JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
39: 1 ~ 7, 2006

CO OBSERVATIONS OF BARRED SPIRAL GALAXIES

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(Received December 1, 2005; Accepted March 21, 2006)

ABSTRACT

We present the results of a highly sensitive (~10 mK rms) survey toward the central parts of 22 barred spiral galaxies in ^{12}CO(1-0) line using the NRAO 12m telescope at Kitt Peak. Seven of the target galaxies were detected in CO; NGC 3686 has been detected with CO for the first time. We estimated central CO fluxes of 50~1000 Jy km s^{-1} and molecular gas masses of 10^7~10^8 $M_\odot$ for those galaxies.

Key words : galaxies: ISM — ISM: general — surveys

I. INTRODUCTION

Careful studies to understand the formation of barred structure of galaxy and effect of the bar on the galactic evolution have been performed for many years. In general, it has been believed that a barred structure plays an important role in determining star formation history of the galaxy. This idea has been tested by infrared observations. Hawarden et al. (1986) have analyzed Shapley-Ames galaxies (Sandage & Tammann 1981) in the IRAS Point Source Catalogue and found that most luminous ones of the non-Seyfert normal galaxies are invariably barred. For both of interacting and barred galaxies, it has been suggested that non-axisymmetry perturbations in gravitational potential caused by the barred structure give rise to the inflow of interstellar medium towards galactic center (e.g. Combes & Gerin 1985), feeding the compact nuclei and resulting in the increase of star formation rate.

To verify this hypothesis, it is necessary to study the distribution of interstellar medium in galaxies. This study can be best performed by making high spatial resolution maps of galaxies with molecular lines such as ^{12}CO(1-0). This scientific motivation leads to the observations using single dish telescope to select strong CO galaxies. Our observations using the NRAO 12m telescope can provide a fundamental database for the more detailed CO surveys with higher angular resolution. In this paper, we report the results of CO observations of 22 galaxies.

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II. OBSERVATIONS

(a) Sample Selection

Lee et al. (1998) have selected about 100 bright barred galaxies ($B_T \leq 13$) with small inclination angle among galaxies listed in Revised Shapley Ames Catalogue and reported their results of the CO survey of 18 barred galaxies. Our 22 target galaxies are a part of their sample. More details on how the sample was selected are given in Lee et al. (1998). Basic data of sample galaxies are summarized in Table 1. Right ascension and declination are based on NASA Extragalactic Database, and galaxy classifications in Revised Shapley-Ames Catalogue are used. CO observation references are listed in sixth column of Table 1.

(b) Observations

We have observed the central regions of 22 galaxies with the NRAO 12m telescope (now operated by the Arizona Radio Observatory and so called as ARO 12m telescope) between June 5th and 12th, 1998. System temperatures varied from 350 K to 450 K depending on the the system and weather condition. The dual channel 3 mm receivers were used to observe two polarizations which were averaged to get better sensitivity. A filter bank spectrometer with 1MHz resolution and 256 MHz bandwidth covering ~666 km s^{-1} at 115 GHz were used for observations. The beam size (FWHM) of the 12m telescope is ~54″ at 115 GHz. The corrected main beam efficiency η^*_{mb} (0.93 at 115 GHz which is an average value of two measurements given in the NRAO 12m manual) is used to convert from the T^*_R scale - antenna temperature corrected for atmospheric attenuation, radiative loss, rear-ward and forward scattering and hot spillover - to the main beam brightness temperature scale. Integration time ranged from 10 to 90 minutes along the sources resulted in rms sensitivity of ~10 mK at 10 km s^{-1} spectral resolution for all sources. Position switching mode was used by observing 30′ offset sky in azimuth direction for sky subtraction of spectra.

The data reduction of the spectral lines such as a baseline subtraction and an average of several profile scans was performed with one of GILDAS (Grenoble Image and Line Data Analysis Software) packages, CLASS (Continuum and Line Analysis Single-dish Software).

III. RESULTS

Out of 22 galaxies, we have detected CO emission toward 7 galaxies. NGC 3412 (Welch & Sage 2003), NGC 4245 (Sage 1993; Gerin & Casoli 1994), NGC 4314 (Roberts & Hogg 1991; Sage 1993; Gerin & Casoli 1994) and NGC 4435 (Roberts & Hogg 1991; Bregman et al. 1992) have been detected, but they were not detected in our observations. Our detected galaxies such as NGC 3346 (Boker et al. 2003), NGC 4123 (Kandalyan 2003), NGC 4293 (Roberts & Hogg 1991), NGC 4424, NGC 4691 and NGC 5194 (Young et al. 1995) have been also detected. Only NGC 3686 has never been detected in CO before. The optical images and CO line profiles toward the detected galaxies are shown in Fig. 1(a)-(g).

The observational results of sample galaxies are summarized in Table 2. The CO spectra are presented in unit of T_R^*. We have listed the peak antenna temperature $T^*_{R,peak}$ and its rms in the second and third column of Table 2.

Most of galaxies show that corrected antenna temperatures range from 20 mK to 380 mK. In case of NGC 4691 and NGC 5194, they show strong, and well-developed peaks of CO emissions. This suggests that these galaxies have high CO luminosity in their central regions.

(a) Central CO Flux

The basic equation relating total CO line flux S_{CO} to the main beam brightness temperature distribution $T_{mb}(\Omega, v)$ of a source is given by Kenny & Young, (1988)

$$S_{CO} = \frac{2k}{\lambda^2} \int\int T_{mb}(\Omega, v)\ d\Omega\ dv, \qquad (1)$$

where Ω is the solid angle, v is the velocity, λ is the observed wavelength and k is Boltzman's constant. For the NRAO 12m telescope, calibration factor G=30 Jy K^{-1} is used to convert antenna temperature to Jansky (Lavezzi & Dickey 1998). The calculated CO fluxes of each observed galaxies are listed in fifth column of Table 2.

It is interesting to compare our calculated CO fluxes with results of other CO observations including FCRAO Extragalactic CO Survey (Young et al. 1995, hereafter FCRAO CO Survey) and IRAM 30m observations.

The commonly detected galaxies in both NRAO and FCRAO CO Surveys are NGC 4293, NGC 4424, NGC 4691 and NGC 5194. The CO fluxes of NGC 4293, NGC 4424 and NGC 4691 given in the FCRAO CO Survey are 270±40 Jy km s^{-1}, 60.0±30.0 Jy km s^{-1} and 160.0±30.0 Jy km s^{-1}, respectively. Our calculated CO flux for NGC 4424 is 30.5±10.1 Jy km s^{-1} which is similar to that of the FCRAO CO survey within its observational uncertainty. However, the CO fluxes of other two NGC 4293 (169.7±8.3 Jy km s^{-1}) and NGC 4691 (252.2±8.8 Jy km s^{-1}) are a bit different from the results of the FCRAO CO survey. In the case of NGC 4293, the FCRAO CO survey presents CO fluxes at the three points around the central position of the galaxy, showing that only the central part has strong CO emissions. Therefore, it is possible that CO gases of NGC 4293 are concentrated in the central part and so larger beam of the NRAO 12m telescope than that of the FCRAO telescope (about 45″) might cause more beam dilution effect.

In case of NGC 4691, our estimation of CO flux is higher than that of FCRAO CO survey. It is noticed that the CO profile of NGC 4691 in higher spectral resolution, has actually two velocity components of ~ 44 km s^{-1} and ~ 88 km s^{-1}. The FCRAO CO flux of NGC 4691 given in their table might be only for the component of ~ 44 km s^{-1}. In fact, the CO profiles between two observations, smoothed in ~ 15 km s^{-1} velocity resolution, are very similar in their peak temperature and line width.

NGC 3346 (Boker et al. 2003) and NGC 4123 (Kandalyan 2003) have been observed at the IRAM 30m telescope. CO fluxes of these galaxies are estimated as 17.2 ± 1.1 Jy km s^{-1} and 85 Jy km s^{-1}. In our observations, CO fluxes of these galaxies are estimated as 54.3±10.2 Jy km s^{-1} and 141.7 ± 13.4Jy km s^{-1}. Our results show a bit higher CO fluxes. This is probably because gaseous material of two galaxies may be spread enough over the NRAO 12m beam and, if so, the larger beam of the 12m telescope may collect more CO fluxes than the 30m telescope.

(b) Central Molecular Gas Mass

Molecular gas mass in galaxy can be estimated using the relation between integrated CO brightness temperature and molecular hydrogen column density by Strong et al. (1988), $N(H_2) = 2.3 \times I_{CO}$ cm^{-2}, where $I_{CO} \equiv \int T_{mb}\, dv$. We used

$$M(H_2)(M_\odot) = 97.8 \times\ \theta_b^2\ I_{CO}\ D_{Mpc}^2, \qquad (2)$$

where θ_b is beam FWHM in arcseconds and D_{Mpc} is distance in megaparsec. (Lavezzi et al. 1999). Distances are calculated assuming $H_0 = 75$ km s^{-1}Mpc^{-1}.

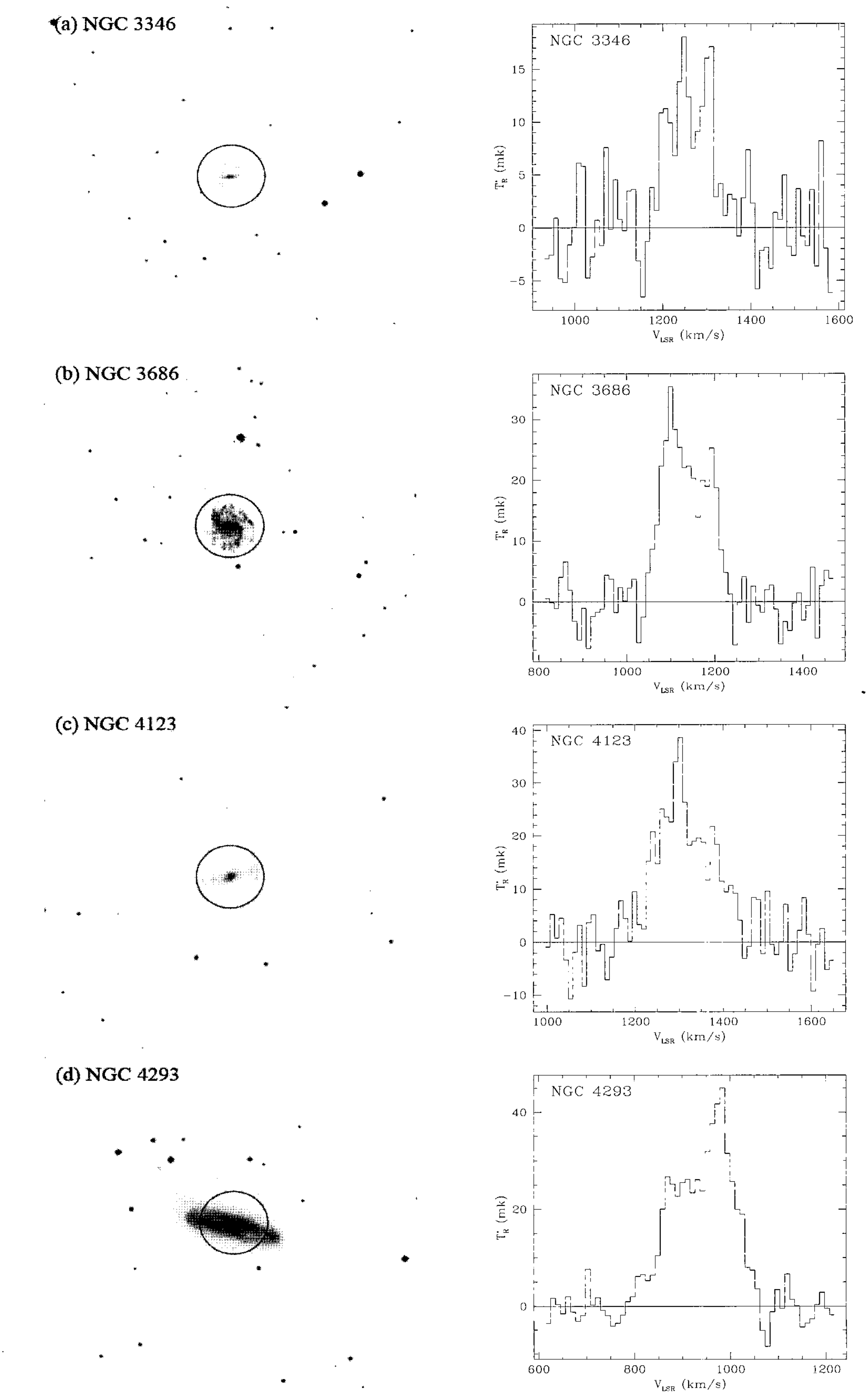

Fig. 1.— Optical images and CO profiles of (a) NGC 3346, (b) NGC 3686, (c) NGC 4123 and (d) NGC 4293.

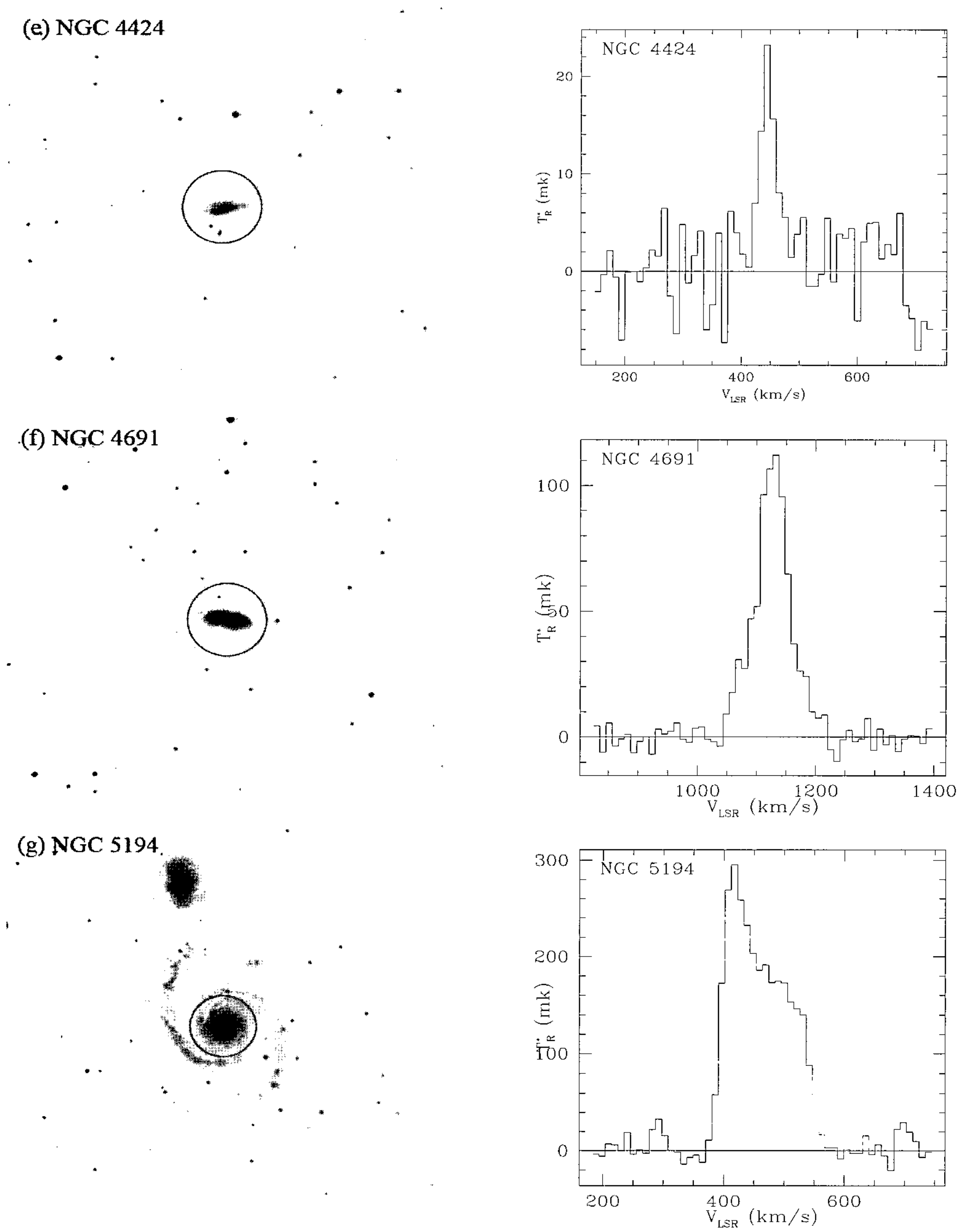

Fig. 1. continued — Optical images and CO profiles of (e) NGC 4424, (f) NGC 4691 and (g) NGC 5194. Scale of all images except NGC 5194 is 10 arcmin × 10 arcmin. Scale of NGC 5194 image is 12 arcmin × 12 arcmin. 54″ beam of the NRAO 12m telescope is displayed on the center of each images. All optical images are taken from Digitized Sky Survey.

TABLE 1.
BASIC DATA OF SAMPLE GALAXIES

Galaxy	Classification[b]	α [h:m:s]	δ [d:m:s]	V_{LST} (km s^{-1})	Previous CO observation (Ref.)[c]
NGC 2950	R LB4	9:41:36	4:51:09.3	1375	No
NGC 3145	SB T4	10:10:10	-12:26:04.9	3651	No
NGC 3319	SB S5	10:39:09	41:41:09.7	758	No
NGC 3346	SB T5	10:43:39	14:52:17.8	1260	Yes (6)
NGC 3412	LB25	10:50:54	13:24:45.7	861	Yes (8)
NGC 3637	R SB4 0	11:20:40	-10:15:26.6	1855	No
NGC 3686[a]	SB S4	11:27:44	17:13:28.5	1143	No
NGC 3718	S 1 G	11:32:35	53:04:07.6	1002	No
NGC 3729	SB P	11:43:45	53:07:28.7	1035	No
NGC 3992	SB T3	11:57:36	53:22:35.9	1049	No
NGC 4123	SB T4	12:08:12	2:52:36.2	1325	Yes (7)
NGC 4245	SB S1	12:17:36	29:36:14.3	890	Yes (3), (4)
NGC 4293	S 1 P	12:21:14	18:23:03.5	933	Yes (5)
NGC 4314	SB T1 P	12:22:33	29:53:28.1	883	Yes (1), (3), (4)
NGC 4394	SB Q3	12:25:56	18:12:47.6	944	No
NGC 4424	S 1U P	12:27:12	9:25:12.2	456	Yes (5)
NGC 4435	LB17	12:27:40	13:04:48.4	869	Yes (1), (2)
NGC 4665	SB6 0	12:45:06	3:03:26.0	785	No
NGC 4688	SB S5	12:47:47	4:20:05.3	981	No
NGC 4691	SB 3 P	12:48:13	-3:19:49.3	1123	Yes (5)
NGC 4781	S S5	12:54:24	-10:32:09.5	895	No
NGC 5194	S S4	13:29:53	47:11:48.1	460	Yes (5)

Note : Right ascension and declination are presented in J2000.0.
[a] First reported galaxy in this observation.
[b] Galaxy classifications in Revised Shapley-Ames Catalogue are used.
[c] CO observation references.— (1)Roberts & Hogg 1991; (2)Bregman et al. 1992; (3)Sage 1993; (4)Gerin & Casoli 1994; (5)Young et al. 1995; (6)Boker et al. 2003; (7)Kandalyan 2003; (8) Welch & Sage 2003

The calculated molecular gas masses are listed in seventh column of Table 2.

Averaged molecular gas mass of our detected galaxies is $\sim 2.8\times10^8 M_\odot$. Compared with the gas masses of normal nearby spiral galaxies (e.g., Sage 1993), we note that there is no obvious difference in the distribution of molecular gas mass between barred and unbarred spirals. This is consistent with large single dish surveys of molecular gas in galaxies (Young et al. 1995).

(c) Notes on Individual Galaxies

In this section, we describe briefly the galaxies which are detected in our observations.

NGC 3346 shows typical multiple arm structures. This galaxy has a very bright, short segment in a bar (0.14 arcmin × 0.03 arcmin), and many branching arms are partially resolved. The CO line profile with peak intensity of 30 mK represents strong emission from central part. Calculated CO line flux and molecular gas mass are individually 54.3±10.2 Jy km s^{-1} and $1.46(\pm0.27)\times10^8 M_\odot$. This galaxy has been observed with the IRAM 30m telescope (Boker et al. 2003). In their observations, CO flux and molecular gas mass were estimated as 17.18± 1.10 Jy km s^{-1} and 54.2×10^6 $M_\odot$, respectively. They also calculated atomic gas mass of this galaxy as 1.4×10^9 $M_\odot$ by using 21 cm fluxes from LEDA (Lyon Meudon Extragalactic Database).

NGC 3686 has a very small, extremely bright nucleus, and 0.4 arcmin × 0.13 arcmin size bar. This galaxy shows 2 main knotty arms and faint, smooth outer whorls. The CO line profile has its peak intensity of 40 mK at around 1100 km s^{-1}.

NGC 4123 has a very small, very bright nucleus on a faint bar with dark lanes. This galaxy shows noninteracting pair with NGC 4116 14 arcmin apart, and several filamentary arms are partially resolved. The peak CO intensity of 40 mK appears at around 1300 km s^{-1}. This galaxy has the abundant molecular gas mass among our sample. Also, this galaxy has been studied as a Markarian galaxy which shows a variety of activities (Kandalyan 2003). Kandalyan (2003) investigated gas properties and star burst phenomenon of this galaxy by using CO(1-0) line which was observed with the IRAM 30m telescope. He calculated CO flux, molecular gas mass and atomic gas mass as 85.4 Jy km s^{-1}, 2.95×10^8 $M_\odot$ and 2.34×10^8 $M_\odot$, respectively.

NGC 4293 has a bright nucleus hidden by strong dark lanes. This galaxy shows the peak CO intensity of 50 mK at around 1000 km s^{-1}. Also, this galaxy has been observed with the FCRAO 14m telescope (Young et al. 1995). In their observations, CO flux was calculated as 270±40 Jy km s^{-1}.

NGC 4424 is classed as a possible Sa, based on the smooth, massive, and semi-spiral outer envelope. The peak CO intensity is only around 20 mK, which is

TABLE 2.
OBSERVATIONAL RESULTS OF SAMPLE GALAXIES

Galaxy	$T^*_{R,peak}$ (mK)[a]	rms (mK)	Distance (Mpc)[b]	CO flux (Jy km s^{-1})	$M(H_2)(M_\odot)$
NGC 2950	< 18	6	18		
NGC 3145	< 21	7	49		
NGC 3319	< 27	9	10		
NGC 3346	30	4	17	54.3 ± 10.2	$1.46(\pm0.27) \times 10^8$
NGC 3412	< 21	7	11		
NGC 3637	< 36	12	25		
NGC 3686	40	4	16	108.5 ± 10.0	$2.40(\pm0.21) \times 10^8$
NGC 3718	< 12	4	13		
NGC 3729	< 12	4	14		
NGC 3992	< 18	6	14		
NGC 4123	40	5	18	141.7 ± 13.4	$4.20(\pm0.40) \times 10^8$
NGC 4245	< 21	7	12		
NGC 4293	50	3	12	169.7 ± 8.3	$2.50(\pm0.12) \times 10^8$
NGC 4314	< 18	6	12		
NGC 4394	< 18	6	13		
NGC 4424	20	4	6	30.5 ± 10.1	$1.07(\pm0.03) \times 10^7$
NGC 4435	< 18	6	12		
NGC 4665	< 21	7	10		
NGC 4688	< 21	7	13		
NGC 4691	140	4	15	252.2 ± 8.8	$5.38(\pm0.19) \times 10^8$
NGC 4781	< 27	9	12		
NGC 5194	380	7	6	1031.3 ± 31.8	$3.70(\pm0.11) \times 10^8$

Note : [a] Upper limit is 3σ.
[b] Distance is calculated assuming $H_0 = 75$ km $s^{-1}Mpc^{-1}$.

the weakest among our sample. This galaxy has been observed with the FCRAO 14m telescope (Young et al. 1995). In their observations, CO flux was calculated as 60±30 Jy km s^{-1}.

NGC 4691 has a very bright, complex bar with dark markings, and very faint asymmetric rings. This galaxy is compact (2.5 arcmin × 1.4 arcmin) but has the strong CO emission ($T^*_{R,peak}$ = 140 mK). Molecular gas mass of this galaxy is the largest amount among our detected galaxies. This galaxy has been observed with the FCRAO 14m telescope (Young et al. 1995). In their observations, CO flux was calculated as 160±30 Jy km s^{-1}.

NGC 5194 is one of the most magnificent spirals in the sky. The entire spiral pattern is dominated by the dust lanes. The two most opaque dust lanes lie on the inside of the two brightest spiral arms. These two principal arms plus their associated dust lanes wind into the central region along an almost perfect spiral path. This grand design galaxy has the strongest CO emission ($T^*_{R,peak}$ = 380 mK) among our sample. This galaxy has been observed with the FCRAO 14m telescope (Young et al. 1995). In their observations, CO flux was calculated as 9210±3000 Jy km s^{-1}.

IV. CONCLUSION

In this paper, we present the results of the CO survey for optically selected barred spiral galaxies. We have observed 22 galaxies by using the NRAO 12m telescope, and 7 of them were detected in CO. Each galaxy has been observed with 54″ beam. We note that NGC 3686 has been detected in CO for the first time from this survey. The peaks of corrected antenna temperature range from 20 mK to 380 mK in unit of T^*_R. Especially NGC 4691 and NGC 5194 show strong CO emissions of ~140 mK and ~380 mK, respectively. Central CO fluxes and molecular gases of sample galaxies are also calculated. The results presented in this paper will serve as a groundwork for the more detailed CO surveys with higher angular resolution.

ACKNOWLEDGEMENTS

C.W.L. acknowledges supports from grant KOSEF R01-2003-000-10513-0 of the Basic Research Program of the Korea Science and Engineering Foundation.

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