| RA* (K) | FREQUENCY (GHz) | cz= | km/s |
|---------|----------------|-----|------|
| PG0157  | 99.00 99.05 99.10 99.15 99.20 | 48869 | km/s |
| IR02185 | 100.70 100.75 100.80 100.85 100.90 | 29347 | km/s |
| IR02411*| 105.25 105.30 105.35 105.40 105.45 | 43050 | km/s |
| IR07243*| 110.75 110.80 110.85 110.90 110.95 | 28204 | km/s |
| IZW23   | 110.10 110.15 110.20 110.25 110.30 | 12224 | km/s |
| CG1113  | 110.65 110.70 110.75 110.80 110.85  | 13800 | km/s |
| IC2846  | 110.10 110.15 110.20 110.25 110.30 | 12294 | km/s |
| IR14060 | 103.10 103.15 103.20 103.25 103.30 | 35060 | km/s |
| IR14060 | 103.10 103.15 103.20 103.25 103.30 | 35060 | km/s |
Table 1. Galaxies detected in the CO-line using the NRO 45-m telescope.

| Galaxy       | RA(B1950)   | Dec(B1950) | cz  | z         | $D_L$  | Type  |
|--------------|-------------|------------|-----|-----------|-------|-------|
|              | h m s       | ° ′ ″      | km s$^{-1}$ |          | Mpc   |       |
| PG 0157+001  | 01 57 16.3  | +00 09 09  | 48869 | 0.16301   | 676.64 | —     |
| IRAS 02185+0642 | 02 18 40.3 | +06 43 03 | 29347 | 0.09789   | 400.70 | —     |
| IRAS 02411+0354‡ | 02 41 09.3| +03 53 56 | 43050 | 0.14360   | 593.66 | —     |
| IRAS 07243+1215‡ | 07 24 20.6| +12 15 09 | 28204 | 0.09408   | 384.77 | —     |
| I Zw23       | 09 56 01.0  | +52 29 48  | 12224 | 0.04077   | 164.73 | S?    |
| CGCG 1113.7+2936 | 11 13 47.1 | +29 35 58 | 13880 | 0.04630   | 187.29 | SB(s)b|
| IC 2846      | 11 25 24.8  | +11 26 01  | 12294 | 0.04101   | 165.68 | —     |
| IRAS 14060+2919 | 14 06 04.9 | +29 18 59 | 35060 | 0.11695   | 480.72 | —     |
| CGCG 1417.2+4759 | 14 17 14.8 | +47 59 00 | 21465 | 0.07160   | 291.35 | —     |
| IRAS 14210+4829‡ | 14 21 06.2| +48 29 59 | 22690 | 0.07569   | 308.26 | —     |
| CGCG 1448.9+1654 | 14 48 54.5| +16 54 02 | 13700 | 0.04570   | 184.84 | —     |
| NGC 6007     | 15 51 01.6  | +12 06 27  | 10547 | 0.03518   | 141.94 | SABbc:|
| IRAS 16533+6216 | 16 53 19.8 | +62 16 36 | 31808 | 0.10610   | 435.10 | —     |
| PGC 60451    | 17 30 00.6  | +20 09 49  | 14989 | 0.05000   | 202.43 | —     |
| IRAS 17517+6422 | 17 51 45.0| +64 22 14 | 26151 | 0.08723   | 356.22 | —     |
| IRAS 23389+0300 | 23 38 56.9| +03 00 48 | 43470 | 0.14500   | 599.63 | —     |

Col.(1): Galaxy name. A dagger and double dagger denote a galaxy of marginal detection and upper limit of the detection, respectively. Col.(2) and (3): Coordinates in B1950. Col.(4): Heliocentric velocity. Col.(5): Heliocentric redshift from Fisher et al.(1995). Col.(6): Luminosity distance derived from the redshift in Col.(5). Col.(7): Morphological type from RC3 (de Vaucouleurs et al. 1991).
Table 2. CO-line observation results using the NRO 45-m telescope.

| Galaxy          | $cz$   | $t_{int}$ | r.m.s. | $W_{obs}$ | $W_{rest}$ | $T_A^*$ | $I_{CO}$ |
|-----------------|--------|-----------|--------|-----------|------------|---------|----------|
|                 | km s$^{-1}$ | min. | mK     | km s$^{-1}$ | km s$^{-1}$ | mK      | K km s$^{-1}$ |
| PG0157+001      | 48869  | 90        | 2      | 349       | 300        | 15      | 5.11 (0.22) |
| IRAS02185+0642  | 29347  | 90        | 4      | 391       | 356        | 40      | 13.05 (0.48) |
| IRAS02411+0354‡ | 43050  | 60        | 5      | 498       | 435        | 8       | <1.90 (0.66) |
| IRAS07243+1215† | 28204  | 90        | 3      | 237       | 217        | 6       | 1.79 (0.28)  |
| I Zw23          | 12224  | 60        | 4      | 108       | 104        | 39      | 4.82 (0.26)  |
| CGCG1113.7+2936 | 13880  | 60        | 5      | 313       | 299        | 14      | 4.33 (0.55)  |
| IC2846          | 12294  | 30        | 4      | 374       | 360        | 19      | 4.78 (0.48)  |
| IRAS14060+2919  | 35060  | 120       | 3      | 420       | 376        | 8       | 1.91 (0.37)  |
| CGCG1417.2+4759 | 21465  | 180       | 3      | 314       | 293        | 13      | 4.66 (0.32)  |
| IRAS14210+4829† | 22690  | 60        | 4      | 496       | 461        | 11      | 3.08 (0.54)  |
| CGCG1448.9+1654 | 13700  | 60        | 4      | 295       | 282        | 28      | 7.03 (0.42)  |
| NGC6007         | 10547  | 60        | 7      | 360       | 347        | 28      | 11.24 (0.82) |
| IRAS16533+6216  | 31808  | 90        | 3      | 236       | 213        | 10      | 3.54 (0.28)  |
| PGC60451        | 14989  | 60        | 7      | 482       | 459        | 20      | 10.35 (0.95) |
| IRAS17517+6422  | 26151  | 90        | 5      | 522       | 480        | 19      | 4.00 (0.69)  |
| IRAS23389+0300  | 43470  | 180       | 3      | 311       | 272        | 8       | 3.92 (0.31)  |

Col.(1): Galaxy name. A dagger and double dagger denote a galaxy of marginal detection and upper limit of the detection, respectively. Col.(2): Redshift in $cz$. Col.(3): Integration time of on-source in minute. Col.(4): Root mean square of antenna temperature after binning of 10 km s$^{-1}$ in emission-free region of the spectrum. Col.(5): Observed CO linewidth defined as the full width at 20% of the maximum intensity. Col.(6): CO linewidth converted to the rest frame. Col.(7): Antenna temperature at the peak level intensity. Col.(8): Integrated intensity corrected for the main beam efficiency. Col.(9): Uncertainty of 1σ in the integrated intensity.
Table 3. CO properties of the observed sample.

| Galaxy               | $I_{CO}$  | $\log L_{CO}'$ | $\log M_{H_2}$ | $\log (L_{FIR}/L_{CO}')$ |
|----------------------|-----------|----------------|----------------|--------------------------|
|                      | K km s$^{-1}$ | K km s$^{-1}$ pc$^2$ | $M_\odot$     |                          |
| PG0157+001           | 5.11      | 9.85           | 10.50          | 2.56                     |
| IRAS02185+0642       | 13.05     | 9.87           | 10.53          | 1.93                     |
| IRAS02411+0354$^\dagger$ | <1.90    | <9.33          | <9.98          | >2.81                    |
| IRAS07243+1215$^\dagger$ | 1.79     | 8.98           | 9.63           | 2.48                     |
| IZw23                | 4.82      | 8.74           | 9.39           | 2.07                     |
| CGCG1113.7+2936      | 4.33      | 8.80           | 9.45           | 2.16                     |
| IC2846               | 4.78      | 8.74           | 9.39           | 2.79                     |
| IRAS14060+2919       | 1.91      | 9.17           | 9.83           | 2.86                     |
| CGCG1417.2+4759      | 4.66      | 9.18           | 9.84           | 2.10                     |
| IRAS14210+4829$^\dagger$ | 3.08     | 9.05           | 9.70           | 2.05                     |
| CGCG1448.9+1654      | 7.03      | 9.00           | 9.65           | 2.08                     |
| NGC6007              | 11.24     | 8.98           | 9.64           | 1.76                     |
| IRAS16533+6216       | 3.54      | 9.37           | 10.02          | 2.56                     |
| PGC60451             | 10.35     | 9.24           | 9.89           | 1.64                     |
| IRAS17517+6422       | 4.00      | 9.27           | 9.92           | 2.64                     |
| IRAS23389+0300       | 3.92      | 9.65           | 10.30          | 2.39                     |

Col.(1): Galaxy name. A dagger and double dagger denote a galaxy of marginal detection and upper limit of the detection, respectively. Col.(2): CO integrated intensity. Col.(3): CO luminosity in K km s$^{-1}$ pc$^2$. Col.(4): Molecular hydrogen gas mass derived with the CO-to-H$_2$ conversion factor $N$(H$_2$)/$I_{CO} = 3.0 \times 10^{20}$cm$^{-2}$(Kkm$^{-1}$)$^{-1}$, corresponding to $\alpha = M_{H_2}/L_{CO} = 4.5M_\odot$pc$^{-2}$(Kkm$^{-1}$)$^{-1}$. Col.(5): Flux ratio of FIR-to-CO luminosity.
\( \log \text{L}_{\text{fir}} / \log \text{L}'_{\text{co}} \) for GMC

IRAM, NRAO-S, SEST, NRAO-L, NRO
Table 4. IRAS flux densities and dust properties.

| Galaxy            | $S_{12}$ | $S_{25}$ | $S_{60}$ | $S_{100}$ | $S_{25}/S_{60}$ | $S_{60}/S_{100}$ | $T_d$ | $\log M_{\text{dust}}$ | $\log L_{\text{FIR}}$ |
|-------------------|----------|----------|----------|-----------|----------------|------------------|-------|-----------------------|-----------------------|
| PG0157+001        | 0.123    | 0.542    | 2.22     | 2.16      | 0.244          | 1.028            | 48.9  | 7.91                  | 12.41                 |
| IRAS02185+0642    | <0.100   | 0.212    | 1.21     | 2.45      | 0.175          | 0.494            | 35.3  | 8.02                  | 11.80                 |
| IRAS02411+0354†   | <0.085   | 0.224    | 1.37     | 1.95      | 0.164          | 0.703            | 40.6  | 8.03                  | 12.14                 |
| IRAS07243+1215†   | <0.250   | <0.545   | 0.69     | 0.94      | <0.790         | 0.734            | 41.4  | 7.30                  | 11.46                 |
| IZw23             | <0.103   | <0.154   | 0.61     | 1.74      | <0.252         | 0.351            | 31.3  | 7.33                  | 10.81                 |
| CGCG1113.7+2936   | <0.088   | <0.185   | 0.63     | 2.03      | <0.294         | 0.310            | 30.1  | 7.59                  | 10.96                 |
| IC2846            | <0.173   | 0.383    | 4.21     | 6.72      | 0.091          | 0.626            | 38.7  | 7.53                  | 11.53                 |
| IRAS14060+2919    | <0.096   | 0.144    | 1.61     | 2.42      | 0.089          | 0.665            | 39.7  | 7.97                  | 12.03                 |
| CGCG1417.2+4759   | <0.098   | <0.091   | 0.62     | 1.54      | <0.147         | 0.403            | 32.8  | 7.68                  | 11.28                 |
| IRAS14210+4829†   | <0.083   | <0.072   | 0.38     | 0.88      | <0.189         | 0.432            | 33.6  | 7.44                  | 11.10                 |
| CGCG1448.9+1654   | <0.079   | 0.148    | 1.13     | 2.09      | 0.131          | 0.541            | 36.5  | 7.22                  | 11.08                 |
| NGC6007           | <0.105   | 0.123    | 0.69     | 2.03      | 0.178          | 0.340            | 31.0  | 7.29                  | 10.74                 |
| IRAS16533+6216    | <0.059   | 0.169    | 1.48     | 2.50      | 0.358          | 0.592            | 37.8  | 7.98                  | 11.93                 |
| PGC60451          | <0.069   | <0.088   | 0.48     | 1.36      | <0.183         | 0.353            | 31.4  | 7.39                  | 10.88                 |
| IRAS17517+6422    | 0.060    | 0.149    | 2.22     | 3.26      | 0.067          | 0.681            | 40.1  | 7.83                  | 11.91                 |
| IRAS23389+0300    | <0.093   | <0.349   | 1.23     | 1.17      | <0.283         | 1.051            | 49.5  | 7.52                  | 12.04                 |

Col.(1): Galaxy name. Col.(2)–(5): IRAS flux densities at 12, 25, 60 and 100 µm taken from the IRAS Faint Source Catalog (as listed in NED). Col.(6) and (7): IRAS flux ratios. Col.(8): Dust temperature. Col.(9): Dust mass. Col.(10): FIR luminosity in $L_\odot$. 
Table 5. Samples of CO observations at intermediate redshift.

| Sample name        | Reference                  | Telescope | HPBW | No.  | $cz$ | log$L_{\text{FIR}}$ |
|--------------------|----------------------------|-----------|------|------|------|---------------------|
| IRAM Sample\(^a\) | Solomon et al.(1997)       | IRAM 30-m | 30"  | 37   | 10,000 – 60,000     | 11.5 - 12.5          |
| NRAO-S Sample\(^b\) | Sanders et al.(1991)        | NRAO 12-m | 55"  | 58   | 3,000 – 25,000      | 10.5 - 12.0          |
| SEST Sample\(^c\)  | Mirabel et al.(1990)        | SEST 15-m | 44"  | 31   | 5,000 – 25,000      | 11.0 - 12.5          |
| NRAO-L Sample\(^d\) | Lavezzi & Dickey(1998)      | NRAO 12-m | 55"  | 40   | 3,500 – 8,000       | 9.0 - 10.5           |
| NRO Sample\(^e\)   | This work                  | NRO 45-m  | 15"  | 16   | 10,000 – 50,000     | 11.0 - 12.0          |

Col.(1): Sample name used in the text. Remarks and the reference of the samples are mentioned below.
Col.(2): Reference which presents the data. Col.(3): Used telescope. Col.(4): The half power beam width of the antenna. Col.(5): The number of galaxies in the sample. Col.(6): Major range of redshift $cz$ of the sample. Col.(7): Major range of FIR luminosity of the sample.

\(^a\)Higher CO luminosity at father intermediate redshift and mostly mergers or interacting galaxies.
\(^b\)Shallower sample.
\(^c\)Shallower sample in the Southern sky.
\(^d\)Lower $cz$ sample in cluster of galaxies.
\(^e\)Deeper sample with isolated and normal morphology.
\[ \log(S'60/S'100) - \log(S60/S100) \]

- \( T = 55 \text{ K} \)
- \( T = 45 \text{ K} \)
- \( T = 35 \text{ K} \)
- \( T = 25 \text{ K} \)
log \( L_{\text{FIR}} (L_{\text{solar}}) \) vs log \( L'_{\text{CO}} (K \text{ km/s pc}^2) \)

- all samples
- NRO sample
- Seyfert 1
- Seyfert 2
- starburst
- PRG
CO Observations of Luminous IR Galaxies at Intermediate Redshift

Yoshinori Tutui, Yoshiaki Sofue, Mareki Honma, Takashi Ichikawa, and Ken-ichi Wakamatsu

1 Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181-8588, Japan
E-mail (YT): tutui@nmtk.ioa.s.u-tokyo.ac.jp
2 VERA Project Office, National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
3 Mizusawa Astrogeodynamics Observatory, National Astronomical Observatory of Japan, Mizusawa, Iwate 023-0861, Japan
4 Astronomical Institute, Tohoku University, Aoba, Sendai 980-8578, Japan
5 Department of Technology, Gifu University, 1-1 Yanagido, Gifu 501-11, Japan

(Received ; accepted )

Abstract

We present new measurement of $^{12}$CO($J = 1 - 0$) emission from 16 luminous infrared galaxies (LIGs) at intermediate redshift ($cz \sim 10,000 - 50,000$ km s$^{-1}$). These new data were selected by isolated and normal morphology. Although there already exist measurements of CO emission from LIGs in the literature, they are mostly strongly interacting/merging system. The new CO data represent an important new addition to the literature in that they both expand the relatively small sample of LIGs measured in CO, and they include the interesting subset of of LIGs that were selected by isolated and normal morphology. The CO observations were performed using the NRO 45-m telescope. From the measurement of CO emission and the IRAS database, we discuss the molecular gas and dust properties of late-type galaxies at intermediate redshift. Comparison of the CO and dust properties of the new result with those from other CO measurements revealed characteristics of this sample: (1) It is the deepest CO observations of IRAS galaxies at intermediate redshift without strong interaction features. (2) It has typical properties of normal IRAS galaxies in terms of star-formation efficiency, color-color diagrams and galactic nuclear activity. (3) It has smaller gas-to-dust ratio than normal IRAS galaxies. This can be explained by two-component dust model, and our sample consists of most of warm dust.

Key words: Galaxies: spiral — Galaxies: distances and redshifts — ISM: molecules

1. Introduction

The Infrared Astronomical Satellite (IRAS) revealed a number of extragalactic objects with luminosity dominated by FIR emission (e.g. Soifer et al. 1984). IRAS surveyed 96% of the sky, with a completeness limit of $\sim 0.5$ Jy at 12 $\mu$m, 25 $\mu$m and 60 $\mu$m, and $\sim 1.5$ Jy at 100 $\mu$m, and with angular resolution $\sim 0.5$ ' for 12 $\mu$m $\sim 2$ ' for 100 $\mu$m. It discovered $\sim 20,000$ galaxies, which had not been previously cataloged. The majority of IRAS extragalactic galaxies are late-type galaxies. Galaxies detected by IRAS, whose luminosity is dominated by FIR emission, are called IRAS galaxies, and are categorized as luminous infrared galaxies (LIGs) for infrared luminosity of $L_{IR} > 10^{11} L_{\odot}$, ultraluminous infrared galaxies (ULIGs) for $L_{IR} > 10^{12} L_{\odot}$, and hyperluminous infrared galaxies (HyLIGs) for $L_{IR} > 10^{13} L_{\odot}$. Infrared luminous galaxies whose luminosity is more than $10^{11} L_{\odot}$ become the dominant population at the intermediate redshift of $z \lesssim 0.3$ (Sanders & Mirabel 1996). The fraction of merger and interacting systems among IRAS galaxies increases with infrared luminosity; that is $\sim 12\%$ for log($L_{IR}/L_{\odot}$) = 10.5 - 11, $\sim 32\%$ for log($L_{IR}/L_{\odot}$) = 11 - 11.5, $\sim 66\%$ for log($L_{IR}/L_{\odot}$) = 11.5 - 12 and $\sim 95\%$ for log($L_{IR}/L_{\odot}$) > 12 (Sanders & Mirabel 1996).

CO-line observations have revealed that LIGs are extremely rich in molecular gas. Early CO observations of infrared selected galaxies with $L_{IR} = 10^{10} - 10^{11} L_{\odot}$ showed a rough correlation between CO and FIR luminosity (Young et al. 1984; Young et al. 1986). A number of single-dish CO surveys of IRAS galaxies have been performed (Sanders et al. 1991, Mirabel et al. 1990, Tinney et al. 1990, Downes et al. 1993, Mazzarella et al. 1993, Young et al. 1995, Elfhag et al. 1996, Solomon et al. 1997), which consist of galaxies with IR luminosities of $L_{IR} = 10^{10} - 10^{13} L_{\odot}$ from nearby to intermediate redshift. Correlations between CO and IR luminosities are also found for these samples. Furthermore, it is found that the IR-to-CO luminosity ratio ($L_{IR}/L_{CO}$), which represents the star forma-
tion efficiency in a galaxy, increases with the CO luminosity, suggesting that molecular-gas-rich galaxies show a high star-forming efficiency. Assuming the Galactic $^{12}$CO($J = 1 − 0$)-H$_2$ conversion factor of $N_{H_2}/I_{CO} = 3.0 \times 10^{20}$cm$^{-2}$(Kkm$^{-1}$s$^{-1}$)$^{-1}$, the total molecular-gas mass for ULIGs is as high as $M_{H_2} \gtrsim 10^{10} M_\odot$, and the star-formation efficiency in ULIGs is, on average, much higher than any of the most active star-forming Galactic GMC cores.

CO observations of ULIGs at intermediate redshift ($cz ∼ 10,000 − 50,000$km s$^{-1}$) have been performed by Mirabel et al.(1990) using the SEST 15-m telescope, Sanders et al.(1991) using the NRAO 12-m telescope, Solomon et al.(1997) using the IRAM 30-m telescope and Lavezzi & Dickey (1998) using the NRAO 12-m telescope (see Sanders & Mirabel 1996, for more references). In addition to the above, we have performed CO observations using the NRO 45-m telescope. CO observations for ULIGs at intermediate redshift are important for the following points: (1) Objects at intermediate redshift ($z ∼ 0.1−1$) are significant for galactic evolution from the most-active epoch at $z ∼ 1 − 2$, to the local Universe at $z ∼ 0$. (2) Galaxies at intermediate redshift are the most distant targets in which we can detect the CO-line from the galactic disk, which is related to the global properties of the molecular gas in a galaxy. (3) High ratio of merger or interacting systems and high star-formation efficiency of ULIGs can help reveal the star-formation history. (4) Strong CO emission and stable CO linewidths can be used for the Tully-Fisher relation to measure distances to galaxies at intermediate redshift. Photometric observations for the CO-line Tully-Fisher relation have been performed using the Okayama Astrophysical Observatory 1.88-m telescope, and the results will be discussed in a forthcoming paper.

Results of our CO-line observations and definitions of CO and FIR properties discussed in this paper are described in section 2. We compare our sample with these CO observations to evaluate the characteristics of our sample in section 3. The results are discussed in section 4, and summarized in section 5. We also discuss the samples in terms of the IRAS color-color diagrams and galactic activities in appendices 1 and 2. Throughout this paper we use $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$.

2. Data and CO observations

$^{12}$CO($J = 1 − 0$) line observations of galaxies at intermediate redshift were obtained using the Nobeyama Radio Observatory (NRO) 45-m telescope. We also use the data from the literature (Solomon et al. 1997, Sanders et al. 1991, Mirabel et al. 1990 and Lavezzi & Dickey 1998). In comparing these samples, we used given integrated intensities and the same formulae to estimate CO luminosities, or molecular gas mass.

2.1. Sample selection

The main purpose of our CO observations was to obtain CO linewidths in order to apply them to the CO-line Tully-Fisher relation to measure distances to galaxies and determine the Hubble constant at intermediate redshift. The target was late-type galaxies with bright CO-line emission and isolated normal morphology located at intermediate redshift. The sample selection was made using the following criteria.

(1) Redshift criterion. Redshift criterion of the sample was $cz = 10,000 − 20,000$km s$^{-1}$ in 1994/1995 observations, and $cz = 20,000 − 30,000$km s$^{-1}$ in 1995/1996 observations. After we confirmed the possibility of CO detection at such redshift, we set the redshift criterion to $cz = 30,000 − 50,000$km s$^{-1}$ in 1996/1997 observations.

(2) FIR flux density criterion. In order to obtain sufficient CO emission at intermediate redshift we selected relatively strong FIR-emission sources at 60 µm and 100 µm, because FIR emission, which is dominated by thermal emission of dust heated by surrounding starlight in UV, is related to CO emission from dense molecular-gas regions. We selected galaxies whose IRAS flux densities at 60 µm and 100 µm are greater than 1 Jy.

(3) Morphology criterion. Although morphology information at intermediate redshift was not sufficient in catalogs, we judged the morphology of the sample using images from the STScI Digitized Sky Survey (DSS). Strong interacting galaxies and mergers were excluded from the sample. However, weakly interacting galaxies, whose tails or irregular arms were not resolved by the DSS images at the resolution limit of $∼ 1''$, were included, because influences of weak interaction do not affect the CO linewidth so much as for the HI linewidth (Tutui & Sofue 1997).

(4) Position error criterion. Since the half-power beam width (HPBW) of the NRO 45-m telescope was 15'' at the frequency of $^{12}$CO($J = 1 − 0$), 115.271204 GHz in the object rest frame, galaxies whose position error listed in the NASA Extragalactic Database (NED) is less than 10'' were selected. We also cross-checked the position using the DSS images.

(5) Recession velocity error criterion. The band width of the $^{12}$CO($J = 1 − 0$) observation of the NRO 45-m telescope was 250 MHz, corresponding to $650(1 + z)$ km s$^{-1}$. Since linewidths of observed galaxies were expected to be about $200 − 500$km s$^{-1}$, the recession velocity error criterion to select galaxies was less than 100 km s$^{-1}$. The recession velocity was taken from the IRAS redshift surveys by Strauss et al. (1992) and Fisher et al. (1995).

2.2. CO observations

CO-line observations were performed as a NRO 45-m long-term project, and were carried out on January 14 to 23 and December 9 to 12 in 1994, January 6 to 10, March
13 to 17 and December 17, 18, 21, 22 in 1995, January 17 to 22, February 18 to 22 and December 2 to 5 in 1996, and January 8 to 12 in 1997. The HPBW of the NRO 45-m telescope was 15″ at the frequency of $^{12}$CO($J = 1 - 0$) line, and the aperture and main-beam efficiencies were $\eta_a = 0.35$ and $\eta_{mb} = 0.50$, respectively, as measured by observing the planets Mars and Saturn. As the receiver frontends, we used cooled SIS (superconductor-insulator-superconductor) receivers, which could receive two orthogonal polarizations simultaneously, with a SSB filter to select one of the sidebands. The receiver backends were 2048-channel wide-band acousto-optical spectrometers (AOS). The total channel number corresponds to frequency widths of 250 MHz, and therefore, to a velocity coverage in the rest frame of the galaxy of $\sim 650$ km s$^{-1}$. The center frequency was set to the 1024-channel, which corresponded to 115.271204 (1 + z)$^{-1}$ for each galaxy. The system noise temperature was 300 – 800 K in the single side band at the observing frequencies. Calibration of the line intensity was made using an absorbing chopper in front of the receiver, yielding an antenna temperature ($T_A^*$), corrected for both the atmospheric and antenna ohmic losses. The intensity scale of $T_A^*$ was converted to the main-beam brightness temperature by $T_{mb} = T_A^*/\eta_{mb}$. Subtraction of sky emission was performed by on-off position switching, and the offset of the off-position was 5′ away from the on-position. On-source total integration time for each galaxy ranged from 30 minutes to 3 hours. Antenna pointing was performed by observing nearby SiO maser sources at 43 GHz every 60 – 90 minutes. The pointing accuracy was better than ±4″ during all observations. Total observation time for the on/off position integrations and pointing was about 90 minutes to 9 hours for individual galaxies. After flagging bad spectra, subtraction of the baseline was performed by linear-baseline fitting. Adjacent channels were binned to a velocity resolution of 10 km s$^{-1}$. Noise level of the resultant spectra at velocity resolution of 10 km s$^{-1}$ was 2 – 5 mK in $T_A^*$.

2.3. CO-line profiles

We have obtained CO-line spectra of sixteen galaxies at intermediate redshifts, $cz \sim 10,000 - 50,000$ km s$^{-1}$, which are listed in table 1. These galaxies are some of the most distant examples of IRAS galaxies whose CO-line is detected. The observed CO-line profiles are shown in figure 1. Measurement of CO integrated intensities and linewidths were performed carefully, not only by using the final CO-line profiles but also by comparing CO-line profiles between individual spectrometers and each run. In table 2 we list the observed properties of the CO-line profiles; on-source integration time, the r.m.s. antenna temperature, CO linewidths at the observed and rest frames, the antenna temperature at the peak level, and the integrated intensity corrected for the main beam efficiency.

2.4. CO luminosities and molecular gas properties

CO luminosity is expressed mainly in two ways. One is formulated by an integrated flux density with the unit of $L_\odot$. The other is formulated by integrated intensity, or sometimes an integrated flux density, with the unit of K km s$^{-1}$ pc$^2$. Observed integrated intensity is described by

$$I_{v_{obs}} = \int T_{mb} dV_{obs},$$

where $T_{mb}$ is the main beam temperature related to the antenna temperature $T_A^*$ and the main beam efficiency $\eta_{mb}$, as $T_{mb} = T_A^*/\eta_{mb}$. We should note the integrated intensity for a point source object in comparing between different measurements, because the intensity depends on the beamsize and efficiencies. For example, the observed integrated intensity of PG0157 (=Mrk1014), which should essentially be a point source for both the NRO 45-m and IRAM 30-m telescopes, are 5.11 K km s$^{-1}$ for NRO 45-m and 1.8 K km s$^{-1}$ for IRAM 30-m in Solomon et al. (1997), but it is consistent within 50% of the integrated intensity for the efficiency of $\eta_a = 0.35$ and $\eta_{mb} = 0.5$ for NRO 45-m, and $\eta_a = 0.3$ and $\eta_{mb} = 0.6$ for IRAM 30-m.

CO luminosity $L'_\mathrm{CO}$ in the unit of K km s$^{-1}$ pc$^2$ is denoted with the observed integrated intensity $I_{v_{obs}}$ and the beam solid angle $\Omega_v$ as

$$L'_\mathrm{CO} = \frac{\Omega_v I_{v_{obs}} D_L^2}{(1 + z)^3},$$

where $z$ is the redshift and $D_L$ is the luminosity distance formulated using the Hubble constant $H_0$ and the deceleration parameter $q_0$ as

$$D_L = \frac{c}{H_0q_0^{1/2}} \left( q_0 z + (q_0 - 1)(\sqrt{2q_0 z + 1} - 1) \right).$$

Mass of molecular gas is estimated from CO emission assuming the Galactic CO-to-H$_2$ conversion factor. We adopt a conversion factor of $N_{H_2}/I_{CO} = 3.0 \times 10^4$ cm$^{-2}$(K km s$^{-1}$)$^{-1}$ (Strong et al. 1988; Solomon et al. 1991). The correction factor from H$_2$ mass to molecular gas mass including He and other elements is referred from Allen (1973), as

$$M_{\text{gas}} = 1.36 \times M_{\text{H}_2}.$$ (4)

We estimated CO properties of the galaxies with the results of the CO observations listed in table 3. Ranges of the CO luminosity and molecular gas mass of our sample are $L'_\mathrm{CO} = 5.5 \times 10^8 - 7.4 \times 10^9$ and $M_{\text{gas}} = 3.3 \times 10^9 - 4.6 \times 10^{10}$, respectively. These are about 20 times greater than the CO luminosity and molecular gas mass of the Milky Way interior to the solar circle (Solomon & Rivolo 1989).
2.5. FIR luminosities and dust properties

FIR luminosities of LIGs are normally adopted by the formula using the IRAS 60 and 100 µm flux densities,

$$\left( \frac{L_{\text{FIR}}}{L_\odot} \right) = 3.92 \times 10^5 \left\{ 2.58 \left( \frac{S_{60}}{\text{Jy}} \right) + \left( \frac{S_{100}}{\text{Jy}} \right) \right\} C (\frac{\nu_0}{\text{MHz}})^{-1} \left( 1 + \frac{D_c}{58 \text{Mpc}} \right)^{-1} \left( \frac{\nu_0}{100 \text{GHz}} \right)^{-1}$$

where the constant $C$ is a correction factor of the flux density beyond the range of 60–100 µm, which is typically in the range of 1.5 – 2.1 (Solomon et al. 1997), and here we assumed $C = 1.8$.

Dust mass is estimated by the dust temperature $T_d$ derived from flux densities at 60 µm and 100 µm of the blackbody radiation. Assuming that the dust emission follows the emissivity law of $S_\nu \propto \lambda^{-\delta}$, the dust mass $M_{\text{dust}}$ is approximately expressed as (Hildebrand 1983),

$$M_{\text{dust}} = 4.589 \left( \frac{S_{100}}{\text{Jy}} \right) \left( \frac{D_c}{\text{Mpc}} \right)^2 (\exp(144/T_d) - 1)$$

where, $T_d$ is given by the relation,

$$\frac{S_{60}}{S_{100}} = \frac{7.72 \exp(144/T_d) - 1}{\exp(240/T_d) - 1}.$$  \hspace{1cm} (7)

Ranges of FIR luminosity and dust mass of our sample are $L_{\text{FIR}} = 5.5 \times 10^{10} - 2.57 \times 10^{12}$ and $M_{\text{dust}} = 1.7 \times 10^8 - 1.1 \times 10^9 M_\odot$, respectively. The dust properties of our sample are listed in table 4.

3. Comparison with other CO-line samples

3.1. Individual CO-line samples

We compared our results (hereafter NRO sample) with other CO-line observations which had been obtained for a number of IRAS galaxies at intermediate redshift. We used the following four CO samples data for the comparison, and hereafter the samples are denoted as IRAM sample (Solomon et al. 1997), NRAO-S sample (Sanders et al. 1991), SEST sample (Mirabel et al. 1990) NRAO-L sample (Lavezzi & Dickey 1998). Sampling of IRAS galaxies at intermediate redshift is based on the FIR flux density, because FIR flux density is generally correlated with CO flux density. Figures 2 and 3 show plots of redshift $cz$ against FIR luminosity and against CO luminosity for all the samples, respectively. The majority of galaxies in the IRAM sample are ULIGs with higher CO luminosity at farther intermediate redshift, and are interacting galaxies or mergers. NRAO-S sample and SEST sample made pioneering surveys of LIGs in the northern and southern skies, respectively, and they were relatively shallower samples. NRAO-L sample was a sample of IRAS galaxies in clusters of galaxies at relatively lower $cz$. Our NRO sample shows the deepest CO observations at intermediate redshift. The purpose of our observations was obtaining CO line widths of isolated galaxies with normal morphology at intermediate redshift in order to apply them to the CO Tully-Fisher relation. Although the CO emission of normal galaxies is generally not as bright as for ULIGs, deep observations with long integration have obtained CO emission from galaxies at intermediate redshift. Since the purposes of individual CO observations were different, the properties of target galaxies in each sample also show various features. Remarks and details of individual samples are as follows and are also listed in table 5.

3.2. CO and FIR luminosities

A correlation between CO and FIR luminosities for LIGs was found by airborne FIR observations (Rickard & Harvey 1984), and by IRAS observations (Young et al. 1984; Sanders & Mirabel 1985). Figure 4 is a plot of CO luminosity against FIR luminosity for all the samples, showing the correlation between CO and FIR luminosities. The ratio of $L_{\text{FIR}}/L_{CO}$, or $L_{\text{FIR}}/M_{H_2}$, represents the star formation efficiency (SFE). The correlation shows that SFE for LIGs is higher than that for nearby normal spiral galaxies. Nearby samples presented by Sage (1993) and Solomon & Sage (1988) are indicated as a reference by the solid thick line and the solid thin line, respectively. The former is a distance-limited sample, whereas the latter is a flux-limited sample, and the flux-limited sample shows a larger SFE. $L_{\text{FIR}}/L_{CO}$ for giant molecular clouds (GMCs) in the Milky Way is distributed between the two dotted lines (Solomon et al. 1986; Mooney & Solomon 1988). Most of the galaxies in the samples have larger values of $L_{\text{FIR}}/L_{CO}$ than that of the GMCs. As Solomon & Sage (1988) and Solomon et al. (1992) indicated, $L_{\text{FIR}}/L_{CO}$ for LIGs is not constant but increases with the CO luminosity, as seen in figure 4. We fitted all the samples by a power law and obtained a relation between FIR and CO luminosities given by,

$$\log L_{\text{FIR}} = 1.41 \log L_{CO} - 1.60 \quad \text{(all samples)}.$$ \hspace{1cm} (8)

Thus, all the samples which we examined in this paper have systematically larger SFE than the nearby normal spirals. The IRAM sample shows a remarkably higher SFE, whereas NRAO-L sample is not far from that of GMCs. Other samples are distributed between them uniformly. The plots of CO against FIR luminosities for the individual samples are shown in figure 5.

3.3. Gas and Dust Properties

As indicated in equation (7), the dust mass in galaxies is generally estimated using the IRAS flux at 60 and 100 µm, adopting a single-temperature dust model. However, this estimation overlooks cold dust (10 – 20K) radiation, because the radiation of cold dust is dominant
at $\lambda > 100\mu m$, and thus the gas-to-dust ratio is overestimated. The gas-to-dust ratio derived from the IRAS flux for nearby spiral galaxies is typically $\sim 570$ (Young et al. 1986; Young et al. 1989; Stark et al. 1986). On the other hand, the Galactic local gas-to-dust ratio is derived from the gas column density and color excess of nearby stars, and therefore should be close to the real gas-to-dust ratio of 100–150 (e.g. Spitzer 1978; Bohlin et al. 1978). It has been suggested that the discrepancy of the gas-to-dust ratio is explained by two dust components, namely warm and cold dust. The two-component dust model, which consists of cold (10–20K) dust associated with quiescent molecular clouds and warm (30–60K) dust associated with star-forming regions, is considered (e.g. de Jong & Brink 1987). For nearby spiral galaxies the discrepancy can be explained when the dust consists of 10–20% of warm dust and 80–90% of cold dust (Devereux & Young 1990). Figure 6 is a plot of gas mass against dust mass. Although the NRAO-S, SED, and NRAO-L samples follow the gas-to-dust ratio of nearby galaxies ($\sim 570$), the IRAM and NRO samples are distributed between values of nearby galaxies and the Galaxy. It indicates that the warm dust is dominant for IRAM and NRO samples.

3.4. Warm dust fraction

Young et al. (1986) showed that FIR luminosity of a galaxy depends on both CO luminosity and dust temperature. As seen in figure 7, $L_{\text{FIR}}/L_{\text{CO}}$ increases with dust temperature. The IRAM sample and NRO sample have larger values of $L_{\text{FIR}}/L_{\text{CO}}$ at any dust temperature compared to the other samples. We fitted the data in figure 7 by a power law

$$L_{\text{FIR}}/L_{\text{CO}} \propto T_d^{-4.42} \quad \text{(all samples)},$$

$$L_{\text{FIR}}/L_{\text{CO}} \propto T_d^{-4.54} \quad \text{(without IRAM and NRO samples)}.$$ (10)

As discussed in the previous section, dust in galaxies consists of two dust components. However, here we assume simply one dust component whose radiation is dominant in the FIR. Then the FIR luminosity is described by

$$L_{\text{FIR}} \propto M_{\text{dust}} T_d^{4+n},$$

where $n$ is the index of the dust emissivity law of $\lambda^{-n}$. CO luminosity $L_{\text{CO}}$ is proportional to gas mass $M_{\text{gas}}$, and $L_{\text{FIR}}/L_{\text{CO}}$ is described as

$$L_{\text{FIR}}/L_{\text{CO}} \propto f T_d^{4+n},$$

where $f$ is the gas-to-dust ratio. The power of the emissivity law is not well established and usually is adopted as $n = 1$. Therefore, in estimating dust mass and comparing the results with previous work, we used the emissivity law of $n = 1$. In figure 7 the values of $L_{\text{FIR}}/L_{\text{CO}}$ for galaxies in the IRAM and NRO samples are high. It is recognized as due to the fact that the gas-to-dust ratio for these samples is smaller than for the other samples. This is consistent with dominant warm dust in the two-component dust model discussed in the previous section.

4. Discussion

4.1. CO beam coverage

Smaller gas-to-dust ratios for the NRO and IRAM samples may be induced by missing CO flux due to smaller beam size. CO observations were performed by the single dish telescopes and pointed at the centers of target galaxies. Assuming a cosmological model of $h_0 = 0.75$ and $q_0 = 0.5$, the linear scale size $a$ the $^{12}$CO($J = 1 - 0$) beam (HPBW) of the telescope along the redshift against angular size is denoted by,

$$D(\text{kpc}) = 4.0 \times 10^2 \theta(\text{arcsec}) \frac{(1+z)^{1/2}}{(1+z)^{1/2}}.$$ (13)

The beam sizes of the samples are HPBW = 55′′ for NRAO 12-m telescope, 44′′ for SED 15-m telescope, 30′′ for IRAM 30-m telescope, and 15′′ for NRO 45-m telescope. Even for NRO sample, which has the smallest beam, the linear scale size at $cz > 10,000\text{ km s}^{-1}$ is greater than $\sim 10$ kpc, which should cover the whole extent of CO-emitting disk of the galaxies.

4.2. IRAS K-correction

In estimating dust properties we used observed IRAS flux densities without K-correction. We here discuss the effects of K-correction. Assuming a thermal spectral energy distribution and the emissivity law of $S_{\nu} \propto \lambda^{-1}$, we estimate the effect of K-correction on the IRAS flux ratio at 60$\mu$m to 100$\mu$m and on the dust mass. Dust temperature, dust mass and gas-to-dust ratio are derived from flux densities at 60$\mu$m and 100$\mu$m. Figure 8 shows a residual of the IRAS flux ratio of 60$\mu$m to 100$\mu$m to which a K-correction is applied ($S_{60}/S_{100}$) to the observed flux ratio without K-correction ($S_{60}/S_{100}$). Here flux densities to which K-correction is applied are denoted by $S_{60}'$ and $S_{100}'$. The residual for galaxies at redshift $cz$ of 30,000 km s$^{-1}$ with dust temperature of 40 K is estimated to be $-0.1$. Adopting this result, the effect of K-correction is found to be not significant for the discussion of galaxy types in figure 10. Figure 9 shows the dust mass ratio to which K-correction is applied to the observed dust mass without K-correction. The effect of K-correction for most galaxies used in this study is within 10% of the ratio.
5. Summary

1. We have performed long-integration $^{12}$CO($J = 1 \rightarrow 0$) observations for late-type galaxies at intermediate redshift $cz \sim 10,000 - 50,000$ km s$^{-1}$ using the NRO 45-m telescope, and have obtained CO line profiles from 16 galaxies with isolated and normal aspects. We compared the observed NRO sample with other CO observations of IRAS galaxies at intermediate redshift, [i.e. Solomon et al. 1997(IRAM sample); Sanders et al. 1991(NRAO-S sample); Mirabel et al. 1990(SEST sample); Lavezzi & Dickey 1998(NRAO-L sample)], and found that the NRO sample represents the deepest CO observations at intermediate redshift.

2. We compared the samples in terms of molecular gas and dust masses. The gas-to-dust ratio for NRAO-S, SEST and NRAO-L samples are equivalent to the values found in nearby spirals. On the other hand, the gas-to-dust ratio for the IRAM and NRO samples is smaller than for the other samples and is close to the local gas-to-dust ratio of the Galaxy ($\sim 100 - 150$), which is derived from gas column density and color excess of nearby stars, and thus it is close to real gas-to-dust ratio. The method to estimate dust mass using IRAS flux at 100 $\mu$m overlooks cold dust, and the gas-to-dust ratio tends to be overestimated. For nearby spiral galaxies the gas-to-dust ratio is typically 570, and it suggests that the dust components consist of majority of cold dust and minority of warm dust. This discrepancy can be explained if the dust componente of the IRAM and NRO samples is mostly warm dust.

3. We compared the samples in terms of IRAS color-color diagrams and galactic nuclear activity, and found that there is no clear peculiarity for the NRO sample. Although the NRO and IRAM samples show a feature of dominant warm dust, the IRAM sample, which consists of mostly mergers or interacting galaxies, shows evidence of very active star-formation, whereas the NRO sample shows moderate star-formation. Thus properties of the NRO sample are distributed between the IRAM sample and the other samples.

We acknowledge the works of CO-line observations for galaxies at intermediate redshift by Solomon et al., Sanders et al., Mirabel et al. and Lavezzi & Dickey. This research also acknowledge the NASA/IPAC Extragalactic Database to make use of the IRAS data. The authors YT and MH acknowledge the financial support by the Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists.

Appendix 1. IRAS color-color diagram

We discussed the FIR luminosity, dust mass, dust temperature, and gas-to-dust ratio estimated from the IRAS fluxes at 60$\mu$m and 100$\mu$m on the assumption of thermal dust emission with an emissivity law of $n = 1$. In order to test this assumption, we plot a color-color diagram at IRAS wavelengths, of 12$\mu$m, 25$\mu$m, 60$\mu$m and 100$\mu$m. Figure 10a shows IRAS color-color diagrams of $\log(S_{12}/S_{25})$ against $\log(S_{60}/S_{100})$. The top left panel is an IRAS color-color diagram for all the samples. Sauvage & Thuan (1994) examined IRAS color-color diagrams for normal and non-IR luminous galaxies, and discussed the dependency of the morphology of galaxies on a color-color diagram. The dot-and-broken quadrangle box in the top left panel of of figure 10a represents the distribution of the normal and non-IR luminous galaxies with the morphology of Sdm - Im given by Sauvage & Thuan (1994).

Rowan-Robinson & Crawford (1989) also examined IRAS color-color diagrams for starburst, Seyfert and quiescent spiral galaxies. The distributions of these galaxies are shown in figures 10a–c as the solid box (quiescent spirals), the broken box (starburst galaxies) and the dotted box (Seyfert galaxies), respectively. Galaxies whose IRAS fluxes are known at all IRAS bands are denoted by filled symbols. Galaxies whose 12$\mu$m flux is given by an upper limit are denoted by open symbols. Therefore, the real data point of the open symbols will be put leftward. Parts of the regions of the quiescent, starburst and Seyfert galaxies overlap. Comparing each sample with the results of Sauvage & Thuan (1994) and Rowan-Robinson & Crawford (1989) in figure 10a, it is found that the IRAM sample and SEST sample data points fall near the region of Seyfert and starburst galaxies. The NRAO-S sample is distributed within the region of quiescent spiral galaxies, whereas some galaxies in the samples are plotted at the Seyfert and starburst regions. The NRAO-L sample is distributed in the region of quiescent spiral galaxies. Although in the NRO sample there are only two galaxies whose IRAS fluxes are fixed, the real data point of the galaxies denoted by open squares will be plotted leftward. Therefore, the NRO sample has characteristics similar to quiescent spiral galaxies, so far as the color-color diagram is concerned. Figures 10b and c are IRAS color-color diagrams for colors of $\log(S_{12}/S_{25}), \log(S_{25}/S_{60})$ and $\log(S_{60}/S_{100})$. Comparing between them, the same trends as figure 10a are found.

Appendix 2. Galactic active phenomena

Recently it has been recognized that the majority of galaxies, even normal galaxies, have a supermassive black hole including the Milky Way (e.g. van der Marel 1998, and references therein) which is suggestive that they have experienced galactic active phenomena such as starburst, active galactic nuclei (AGN) or powerful radio emission (e.g. Ho et al. 1995) due to supermassive black holes at the galactic center to galaxy interactions. Seyfert
and starburst galaxies, whose CO line has been detected, have been discussed in terms of CO and FIR luminosities (e.g. Mazzarella et al. 1993; Sanders & Mirabel 1996; Rigopoulou et al. 1997). A correlation between CO and FIR luminosities for Seyfert and starburst galaxies shows the same trend as for LIGs and is indistinguishable from them (Heckman et al. 1989; Rigopoulou et al. 1997), and also type 1 and type 2 Seyferts show no difference. This suggests that FIR emission in Seyfert and starburst galaxies is responsible for the similar origin (i.e. dust re-radiation of starlight) of ULIGs and normal galaxies. Furthermore a comparison of the luminosity ratio of FIR to CO, \( L_{\text{FIR}}/L_{\text{CO}}' \), with the dust temperature, \( T_d \), also shows the same trend as ULIGs and normal galaxies, suggesting that the FIR emission is thermal in origin. Mazzarella et al. (1993) examined the CO and FIR properties for powerful radio galaxies whose CO emission had been detected, and also found the same trend between CO and FIR luminosities as ULIGs and normal galaxies, whereas non-thermal radio power showed a large excess compared to those objects. It suggests that the origin of powerful radio galaxies may be closely related to the genesis of dust-enshrouded quasar and classical UV-excess quasars through merging of gas rich disk galaxies (e.g. Sanders et al. 1988a; 1988b). This trend is also clearly found in an examination by Sanders & Mirabel (1996).

In order to discuss the galactic activity for the NRO sample, we compared CO and FIR properties of nearby Seyfert, starburst and powerful radio galaxies with the NRO sample and the ULIGs in figures 11 and 12. The nearby CO data references from the literature are as follows: Seyfert galaxies (Heckman et al. 1989), starburst galaxies (Jackson et al. 1989) and powerful radio galaxies which have been detected in the CO-line (Mazzarella et al. 1993). Figure 12 shows the CO and FIR luminosities for the nearby active galaxies compared to the galaxies at intermediate redshift. Figure 12 shows that the excess of \( L_{\text{FIR}}/L_{\text{CO}}' \) for the NRO sample is not directly related to the galactic activity. The active galaxies are indistinguishable from the galaxies at intermediate redshift.
References

Allen C.W. 1973, in Astrophysical Quantities (3rd ed.), The Athlone Press

Bohlin R.C., Savage B.D., Drake J.F. 1978, ApJ 224, 132
Condon J.J. 1992, ARA&A 30, 575

de Jong T., Brink K. 1987, sfig conf, 323
Devereux N.A., Young J.S. 1990, ApJ 359, 42
Downes D., Solomon P.M., Radford S.J.E. 1993, ApJ 414, L13
Elfhag T., Booth R.S., Hoeglund B., Johansson L.E.B., Sandqvist A. 1996, A&AS 115, 439
Fisher K.B., Huchra J.P., Strauss M.A., Davis M., et al. 1995, ApJS 100, 69
Heckman T.M., Blitz L., Wilson A.S., Armus L., Miley G.K. 1989, ApJ 342, 735
Hildebrand R.H. 1983, Quart.J.R.A.S. 24, 267
Hunt L.K. 1991, ApJ 370, 511
Ho L.C., Filippenko A.V., Sargent W.L. 1995, ApJS 98, 477
Jackson J.M., Snell R.L., Ho P.T.P., Barrett A.H. 1989, ApJ 337, 680
Kim D.C., Sanders D.B. 1998, ApJS 119, 41
Lavezzi T.E., Dickey J.M. 1998, AJ 116, 2672 [NRAO-L sample ]
Lonsdale C.J., Helou G., Good J.C., Rice W. 1985, in Cataloged Galaxies and Quasars Observed in the IRAS Survey (Pasadena, JPL)
Mazzarella J.M., Graham J.R., Sanders D.B., Djorgovski S. 1993, ApJ 409, 170
Mirabel I.F., Booth R.S., Johansson L.E.B., Garay G., Sanders D.B. 1990, A&A 236, 327 [SEST sample ]
Mooney T.J., Solomon P.M. 1988, ApJ 334, L51
Rickard L.J., Harvey P.M. 1984, AJ 89, 1520
Rigopoulou D., Papadakis I., Lawrence A., Ward M. 1997, A&A 327, 493
Rowan-Robinson M., Crawford J. 1989, MNRAS 238, 523
Sage L.J. 1993, A&A 272, 123
Sanders D.B., Soifer B.T., Elias J.H., Madore B.F., Matthews K., Neugebauer G., et al. 1988, ApJ 325, 74
Sanders D.B., Soifer B.T., Elias J.H., Neugebauer G., Matthews K. 1988, ApJ 328, L35
Sanders D.B., Scoville N.Z., Soifer B.T. 1991, ApJ 370, 158 [NRAO-S sample ]
Sanders D.B., Mirabel I.F. 1985, ApJ 298, L31
Sanders D.B., Mirabel I.F. 1996, ARA&A 34, 749
Sauvage M., Thuan T.X. 1994, ApJ 429, 153
Soifer B.T., Rowan-Robinson M., Houck J.R., de Jong T., Neugebauer G., Aumann H.H., et al. 1984, ApJ 278, L71
Solomon P.M., Rivolo A.R., Mooney T.J., Barrett J.W., Sage L.J. 1986, in Proc. of Conference, Star Formation in Galaxies, Pasadena 1986, ed C. Lonsdale, p.37
Solomon P.M., Sage L.J. 1988, ApJ 334, 613
Figure Caption

Figure 1. — CO-line profiles for all galaxies whose CO linewidth was obtained using the NRO 45-m telescope. The scale of intensity is the antenna temperature ($T_A^*\,\text{K}$). The center of abscissa is the heliocentric radial velocity/frequency given by optical redshift determinations.

Figure 2. — Redshift ($cz$) and FIR luminosity ($L'_{\text{FIR}}$) distributions for all the samples. IRAM sample (asterisk), NRAO-S sample (plus), SEST sample (open square), NRAO-L sample (open circle) and NRO sample (filled square). The broken line represents an iso-flux line for a source.

Figure 3. — Redshift ($cz$) and CO luminosity ($L'_{\text{CO}}$) distributions for all the samples. Symbols are the same as Fig. 2. The symbol in parentheses denotes marginal detection, and the symbol with an arrow denotes upper/lower limit. The broken line represents an iso-flux line of a source.

Figure 4. — Diagram of CO and FIR luminosities. Symbols are the same as Fig.2. Solid thick line indicates the average of 65 nearby spiral galaxies as a distance-limited sample presented by Sage (1993), and the solid thin line indicates the average of 93 nearby spiral galaxies as a flux-limited sample presented by Solomon et al. (1988), and the dispersion is about order of 1. The symbol in parentheses denotes marginal detection, and the symbol with a arrow denotes upper/lower limit. The dotted lines represent the range of $L'_{\text{FIR}}/L'_{\text{CO}}$ seen in giant molecular clouds in the Milky Way ($5 \leq L'_{\text{FIR}}/L'_{\text{CO}} \leq 50$).

Figure 5. — Diagrams of CO and FIR luminosities for each sample. Dotted lines represent the ratio of $L'_{\text{FIR}}/L'_{\text{CO}}$ of 5 and 50.

Figure 6. — A diagram of molecular gas mass derived from CO luminosity and dust mass derived from FIR luminosity. Solid line is an observed gas-to-dust ratio ($\sim 570$) for nearby spiral galaxies using IRAS flux at 100 $\mu$m. Broken line represents a typical gas-to-dust ratio of the Galaxy ($\sim 100$) from observations of nearby stars. The symbol in parentheses denotes marginal detection, and the symbol with a arrow denotes upper/lower limit.

Figure 7. — Diagram of dust temperature and a ratio of FIR-to-CO luminosity. The unit of FIR and CO luminosity are $L_\odot$ and $K$ km s$^{-1}$ pc$^2$, respectively. Solid and broken line are fitted by a power law for all the samples and for the data without NRO sample and IRAM sample, respectively. The symbol in parentheses denotes marginal detection, and the symbol with a arrow denotes upper/lower limit.

Figure 8. — Residual of IRAS flux ratio of 60$\mu$m to 100$\mu$m ($S'_{60}\!/S'_{100}$) to which K-correction is applied, to observed flux ratio ($S_{60}\!/S_{100}$). The ordinate is $\log(S'_{60}\!/S'_{100}) - \log(S_{60}\!/S_{100})$. Here we assumed the thermal spectral energy distribution and the emissivity law of $S_\nu \propto \nu^{-1}$. The lines represent different cases of the dust temperature.

Figure 9. — Ratio of dust mass to which K-correction is applied ($M'_{\text{dust}}$) to that without K-correction ($M_{\text{dust}}$) along redshift $cz$, where the thermal spectral energy distribution and the emissivity law of $S_\nu \propto \nu^{-1}$ are assumed. The lines represent different cases of the dust temperature.

Figure 10.(a) — IRAS color-color diagrams of the flux densities at 12 $\mu$m to 25 $\mu$m against 60 $\mu$m to 100 $\mu$m. All the samples are shown in the top left panel, which is overlaid with IRAM sample (middleleft panel), NRAO-S sample (bottomleft), SEST sample (topright), NRAO-L sample (middleright) and NRO sample (bottomright). Filled symbols represent fixed values at all IRAS bands. Open symbols represent that the 12 $\mu$m flux is given as an upper limit, therefore, the real values should be put leftward. The dot-and-broken quadrangle box represents the distribution of the normal and non-IR luminous galaxies with the morphology of Sdm - Im given by Sauvage & Thuan (1994). The distributions of quiescent spiral galaxies, starburst and Seyfert galaxies given by Rowan-Robinson & Crawford (1989) are represented by the solid box, broken box and dotted box, respectively.

Figure 10.(b) — IRAS color-color diagrams of 12 $\mu$m to 25 $\mu$m against 25 $\mu$m to 60 $\mu$m. The solid box, broken box and dotted box represent the distribution of quiescent spiral galaxies, starburst galaxies and Seyfert galaxies, respectively.

Figure 10.(c) — IRAS color-color diagrams of 25 $\mu$m to 60 $\mu$m against 60 $\mu$m to 100 $\mu$m. Boxes represent the same as the previous figures.

Figure 11. — Comparison of Seyfert, starburst and powerful radio galaxies with NRO sample and the other samples plotted in Fig.4 in terms of the CO and FIR luminosities. Type 1 Seyfert (filled triangles) and type 2 Seyfert (open triangles) are referred from Heckman et al. (1989), starburst galaxies (filled diamonds) are referred from Jackson et al. (1989) and powerful radio galaxies (open diamonds) are referred from Mazzarella et al. (1993). NRO sample and the other samples are denoted by crossed and small dots, respectively.

Figure 12. — Comparison of Seyfert, starburst and powerful radio galaxies with NRO sample and the other samples plotted in Fig.7 in terms of the CO-to-FIR luminosity ratio ($L'_{\text{FIR}}/L'_{\text{CO}}$) and the dust temperature ($T_d$). Symbols and the references are the same as Fig.11. The solid line are the regression line fitted by a power law for all the samples used in Fig.7.