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CO in Elliptical Galaxies and the Universal CO-to-Dust Ratio

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Abstract

By carrying out a deep survey of ^{12}CO($J = 1$–0) line emission toward elliptical galaxies, we co-added two CO detected ellipticals, NGC 4589 and NGC 4697. These two ellipticals are FIR galaxies, and NGC 4589 has a dust lane across the major axis. Adding data from the literature, we found that the CO-to-dust abundance ratio in elliptical galaxies is approximately the same as that for spirals and for local molecular clouds. We conclude that the CO-to-dust ratio, which is an indicator of the mutual abundance ratios among heavy elements, is universal in interstellar matter in ellipticals, spirals, and in local molecular clouds. This is explained if the ratio is kept constant (frozen), since interstellar heavy elements and dust, which are supplied from late-type stars and their circumstellar shells, have left their parent stars.

Key words: Chemical abundance — CO line — Dust; interstellar — Galaxies; elliptical — Interstellar matter

1. Introduction

Some elliptical and early-type galaxies reveal dust absorption in silhouette against a galaxy's light, suggesting the presence of cool gas (e.g., Sandage 1961; Schweizer 1987; Bertola 1987). Direct evidence for infalling cool gas from outside has been obtained by detecting the H I line emission or absorption, which showed a redshift with respect to the systemic velocity of the galaxy nuclei (e.g., Knapp 1987; van Gorkom et al. 1989). Increasing evidence for interstellar gases in the central regions of elliptical galaxies has been observed in thermal emission lines from ionized gases near to the nuclei (Phillips et al. 1986; Sadler 1987; Danziger and Focardi 1988; Schields 1991), and dust absorptions (Ebneter et al. 1988; Véron-Cetty and Véron 1988; Möllenhoff and Bender 1989). Far-infrared emission has been detected from many ellipticals, and the presence of cold gas in ellipticals appears to be the rule rather than the exeption (Jura et al. 1987; Knapp et al. 1989; Thronson et al. 1989), although the locations of far-IR emitting regions have not yet been well determined.

Observations of molecular gas in CO line emission would give both direct and quantitative information about dense interstellar clouds. CO line emission has been detected in some elliptical galaxies (Huchtmeier et al. 1988; Lees et al. 1991; Bregman et al. 1992; Huchtmeier and Tammann 1992; Wang et al. 1992), although exact location with respect to the nuclei is not clear based on current observations, except for the high-resolution observations by Wang et al. (1992).

The presence of cool interstellar gas in the inner region of elliptical galaxies has implications for understanding various activities in the nuclear region of ellptical galaxies: Interstellar gas is considered to be deeply related to the origin of AGN activity, which is often observed in the nuclei of ellipticals (e.g., Krolik 1989). Recent active star formation is suggested by the presence of strong absorption lines of the Balmer series in the nuclear region of some elliptical galaxies with peculiar morphological features (Carter et al. 1988; Wakamatsu 1991).

The origin of cool interstellar gases in ellipticals is controversial. Cool gases could be formed via instablities of a cooling flow in a hot gaseous halo (e.g., Fabbiano 1989; Hattori and Habe 1990; Fabian 1991), where the gas originates from stars of the galaxy itself. Alternatively, they could be due to Ram-pressure accretion of cool gaseous debris from intergalactic space (e.g., Wakamatsu 1990; Sofue and Wakamatsu 1991, 1992, 1993).

In order to clarify the nature and origin of cold gases in elliptical galaxies, direct observations of molecular gas appear necessary. High-resolution observations of molecular gas in the CO line emission would give more direct and quantitative information concerning the infalling dense clouds. In this paper we report on detection and a search for CO line emission from various kinds of elliptical galaxies, i.e., X-ray ellipticals with cooling flows, radio galaxies, dusty ellipticals, shell ellipticals, normal ellipticals, and dwarf ellipticals. We used the Nobeyama 45-m mm-wave telescope.

Table 1. Parameters for observed elliptical galaxies.

Galaxy (Type)	RA(1950)† (h m s)	Dec(1950)† (° ′ ″)	$V^{\dagger}_{\rm helio}$ (km s^{-1})	Distance‡ (Mpc)
NGC 185 (dE3p)	00 36 11.7	+48 03 43	−251	0.7
NGC 708 (E2)	01 49 50.0	+35 54 20	4827	66.1
NGC 1600 (E3)	04 29 11.8	−05 11 38	4687	61.8
NGC 2974 (E4)	09 40 01.8	−03 28 08	2072	25.7
NGC 3379 (E0) M105	10 45 11.4	+12 50 48	889	10.7
NGC 4374 (E1) M84	12 22 31.6	+13 09 51	910	11.2
NGC 4486 (E0) M87	12 28 17.6	+12 40 02	1282	13.5*
NGC 4589 (E2)	12 35 29.5	+74 28 10	1980	28.0
NGC 4697 (E6)	12 46 00.8	−05 31 41	1236	15.2

† NASA/IPAC Extragalactic Database (NED 1992; operated by Jet Propulsion Laboratory, California Institute of Technology under contract by NASA).

‡ Obtained by dividing galacto-centric velocities by a Hubble constant of 75 km s^{-1} Mpc^{-1}.

* Jura et al. (1987).

2. Observations

Observations of the ^{12}CO(J = 1–0) line of nine elliptical galaxies were made on 1992 April 9 to 11, using the 45-m telescope of the Nobeyama Radio Observatory. The observed galaxies and their parameters are listed in table 1.

The antenna had a HPBW of 15″ at 115.271 GHz, and aperture and main-beam efficiencies of $\eta_{\rm a} = 0.35$ and $\eta_{\rm mb} = 0.50$, respectively. We used an SIS receiver combined with a 2048-channel acousto-optical spectrometer of 250 MHz bandwidth corresponding to a velocity coverage of 650 km s^{-1}. After binding up every 32 to 64 channels in order to increase the signal-to-noise ratio, we obtained spectra with a velocity resolution of 10 to 20 km s^{-1}. The system noise temperature (SSB) was 600 to 800 K. The calibration of the line intensity was made using an absorbing chopper in front of the receiver, yielding the antenna temperature ($T^*_{\rm A}$) corrected for both atmospheric and antenna ohmic losses.

We used an on-off1-on-off2 switching mode, with which we observed the center reference position and two off positions (off1 and off2) at ±5′ east and west in a single sequence of observing run. The on-source total integration time was about 2 to 4 hr per galaxy. The rms noise of the resultant spectra at a velocity resolution of 10 km s^{-1} was typically 5 mK in $T^*_{\rm A}$. Pointing of the antenna was checked every 1 to 1.5 hr by observing nearby SiO maser sources at 43 GHz.

The present observations were made only at one position at the galaxy center, and HPBW=15″; therefore, the extended emission present over a larger area, or at other positions, would have been missed.

3. Results

The obtained spectra are shown in figure 1. Table 2 shows the derived quantities from the observations. The legends to the columns of the table are as follows:

Column 1: Galaxy name.

Column 2 and 3: 100 μm flux and molecular gas mass estimated from the FIR luminosity (Knapp et al. 1989). The mass is derived by using the following formula given by Jura et al. (1987):

$$M(M_{\odot}) = 1.6 \times 10^5 D({\rm Mpc})^2 F(100\ \mu{\rm m})({\rm Jy}). \qquad (1)$$

Column 4: Main-beam temperature ($T_{\rm mb}$) of the ^{12}CO(J = 1–0) line emission, where $T_{\rm mb}$ is related to $T^*_{\rm A}$ by $T_{\rm mb} = T^*_{\rm A}/\eta_{\rm mb} = 2.0T^*_{\rm A}$.

Column 5: Velocity width of the CO emission.

Column 6: Integrated intensity of the CO emission ($I_{\rm CO}$) which is defined as $I_{\rm CO} = \int T_{\rm mb} dV$.

Column 7: Estimated mass of molecular hydrogen gas ($M_{\rm H_2}$) from the CO luminosity. We used the conversion factor from the CO intensity to the H_2 column density, $C = 2.8 \times 10^{20} N_{\rm H_2}/I_{\rm CO}$, with $N_{\rm H_2}$ and $I_{\rm CO}$ being in units of H_2 cm^{-2} and K km s^{-1}, respectively (Bloemen et al. 1985). The mass (in $M_{\odot}$) is calculated by

$$M_{\rm H_2} = C I_{\rm CO} \Omega D^2 (2m_{\rm H}/M_{\odot}), \qquad (2)$$

where $m_{\rm H}$ is the hydrogen atom mass, Ω is the main-beam solid angle, and D is the distance of the galaxy. In the present observation we obtained

$$M(M_{\odot}) = 2.68 \times 10^4 I_{\rm CO}({\rm K\ km\ s^{-1}}) D({\rm Mpc})^2. \qquad (3)$$

Among the observed galaxies, which are mostly far-IR emitting galaxies taken from the list by Jura et al. (1987), we detected CO emission from two ellipticals (NGC 4697

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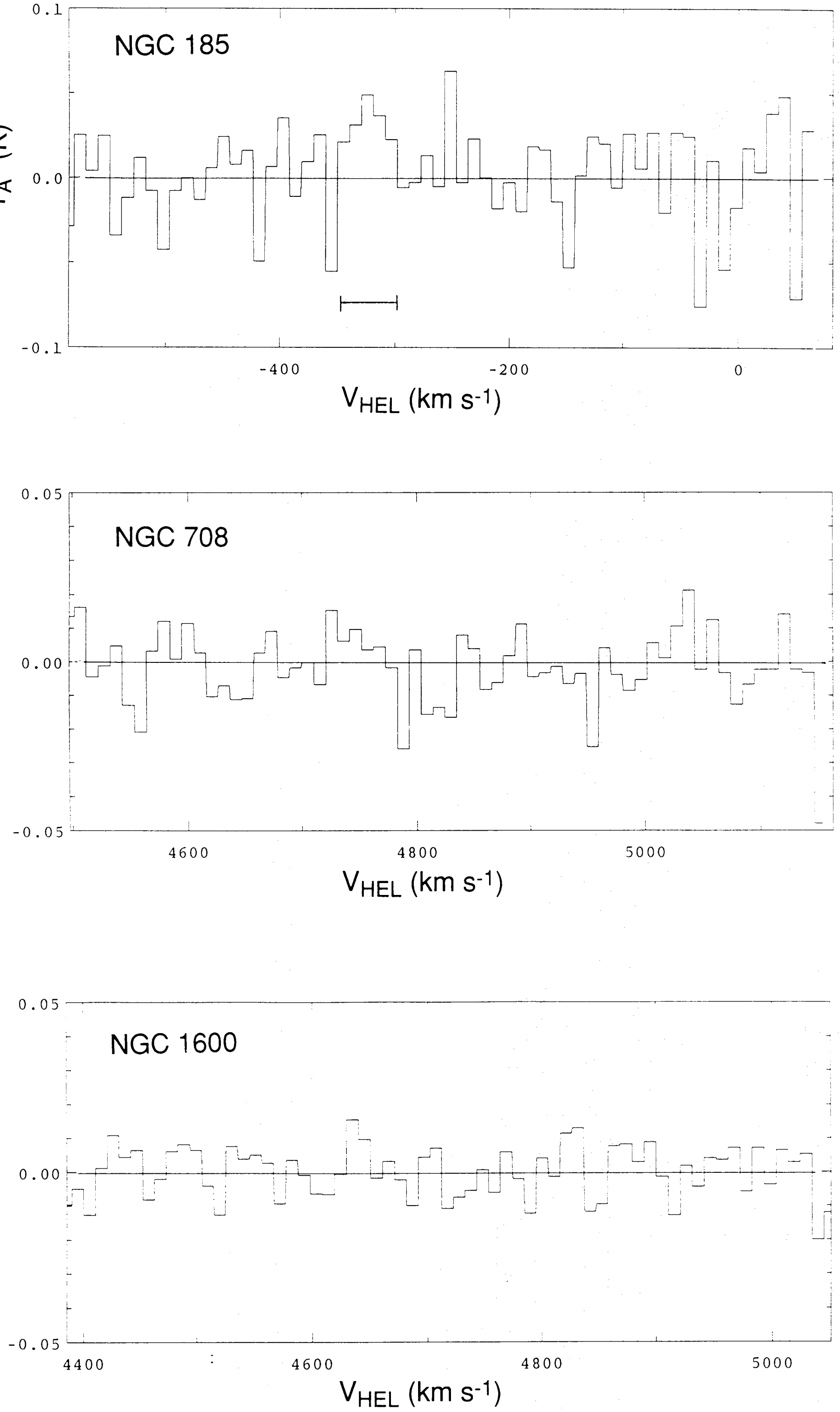
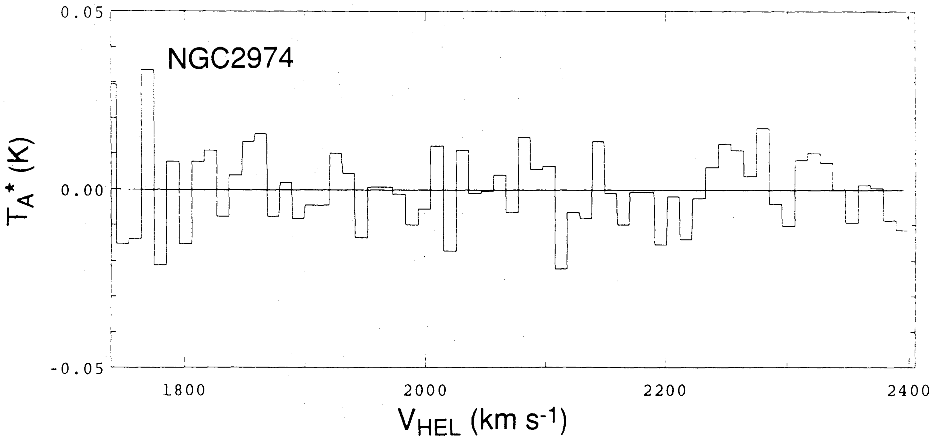
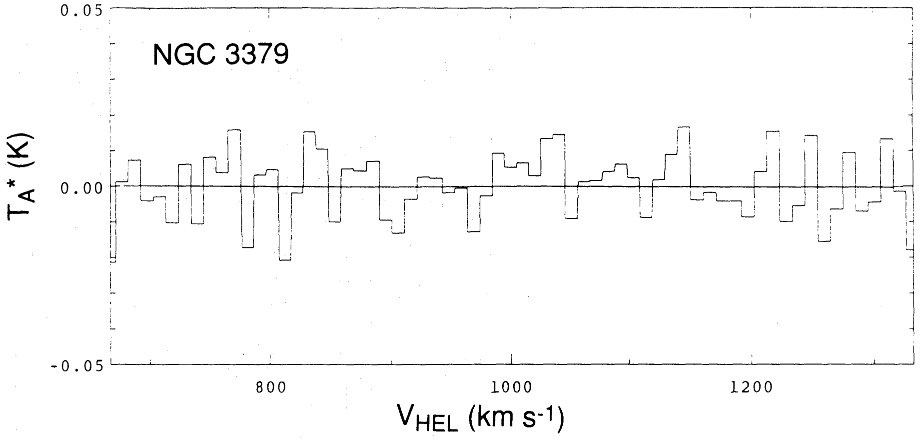


Fig. 1. Obtained spectra of the ^{12}CO(J = 1–0) line for elliptical galaxies using the 45-m telescope at one position at the galaxy center with HPBW=15″. Horizontal bars indicate detection of the CO line.





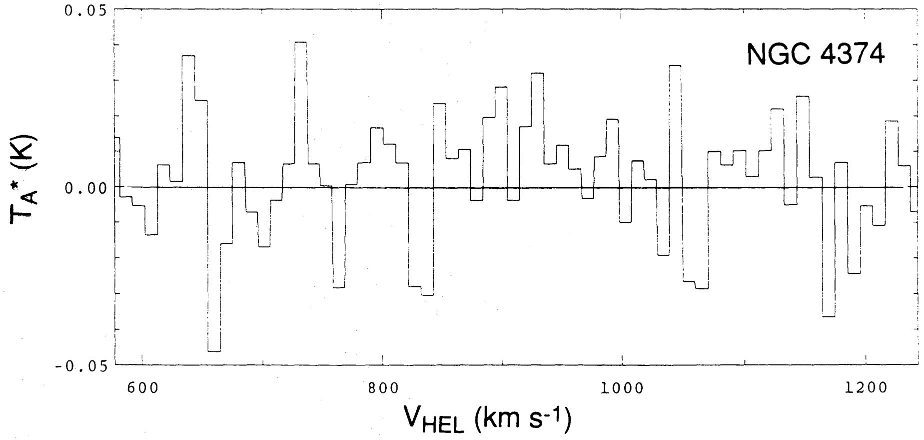
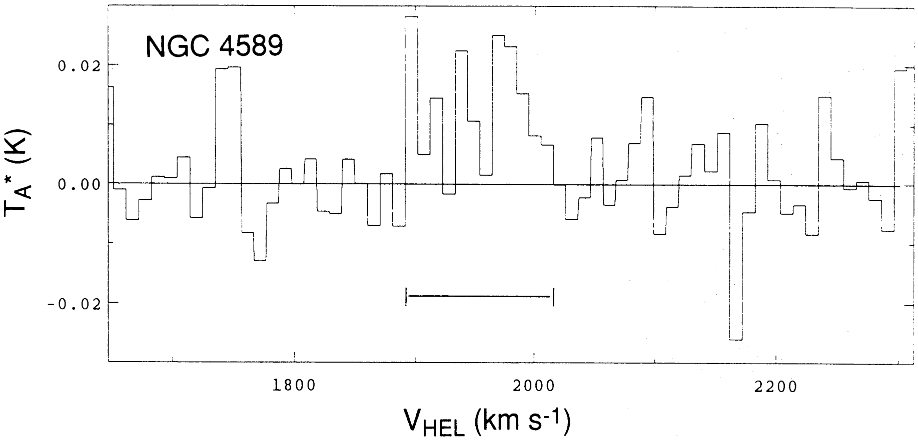
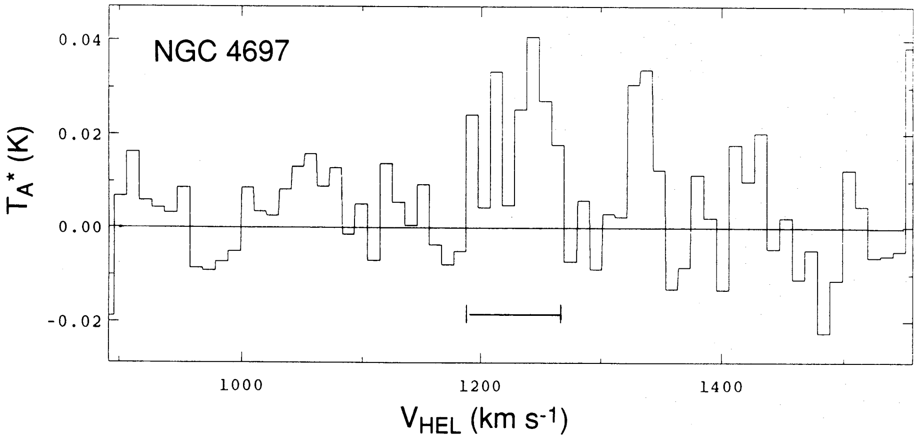


Fig. 1. (Continued)





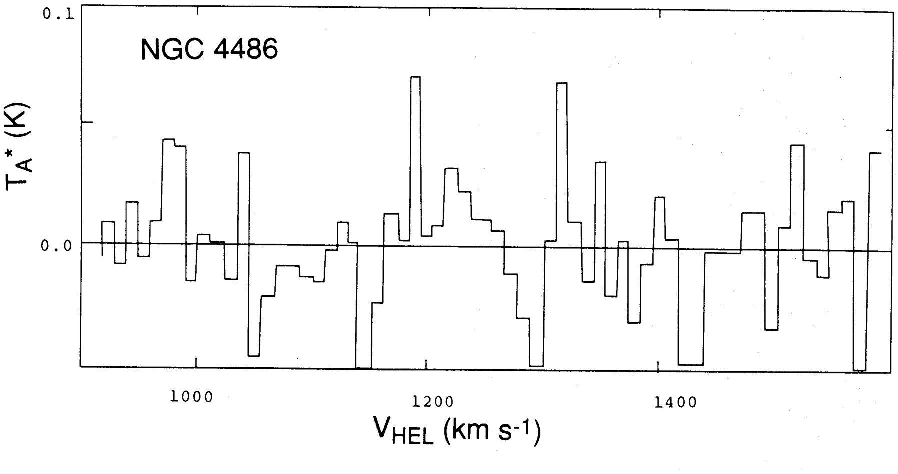


Fig. 1. (Continued)

Table 2. Derived quantities.#

Galaxy	100 μm Flux* (Jy)	$M_{\mathrm{H_2}}$(FIR)* ($10^7 M_{\odot}$)	T_{mb} (mK)	ΔV (km s^{-1})	I_{CO}† (K km s^{-1})	$M_{\mathrm{H_2}}$(CO) ($10^7 M_{\odot}$)
NGC 185	1.72 ± 0.15	0.013 ± 0.001	$\sim 90 \pm 20$	50 ± 10	3.5 ± 1	0.0046 ± 0.002
NGC 708	0.59 ± 0.14	41 ± 10	<20	...	<1.0	<12
NGC 1600	0.17 ± 0.06	10.4 ± 3.6	<20	...	<1.0	<10
NGC 2974	1.69 ± 0.05	18 ± 0.5	< 20	...	< 1	< 1.8
NGC 3379	0 ± 0.01	< 0.2	<30	...	<1.5	<0.5
NGC 4374	1.03 ± 0.11	2.1 ± 0.2	<60	...	<3	<1.0
NGC 4486	0.36 ± 0.09	1.05 ± 0.26	<100	...	<5	<2.4
NGC 4589	0.59 ± 0.14	7.4 ± 1.7	42 ± 10	105 ± 10	3.4 ± 1.2	9.1 ± 3
NGC 4697	1.10 ± 0.07	4.07 ± 0.26	76 ± 15	90 ± 10	4.0 ± 1.5	3.2 ± 1

Errors do not include those arising from distance estimations.

* FIR fluxes were taken from Knapp et al. (1989), and the masses are estimated using equation (1).

† Upper value of I_{CO} is estimated from the 1-σ upper value of T_{mb} by assuming a triangular profile with a velocity width of 100 km s^{-1}.

and NGC 4589); marginal detection was obtained for NGC 185. We discuss the individual galaxies below:

NGC 185: This is a dwarf elliptical, which has patchy dust clouds near the center. A population of blue, presumably young, stars are situated in the center (Gallagher and Hunter 1981). We obtained a marginal detection of $T_{\mathrm{mb}} \sim 90$ mK with a velocity width of about 50 km s^{-1}. The estimated molecular hydrogen mass within our beam is $\sim 4.6 \times 10^4 M_{\odot}$. CO has been detected by Wiklind and Rydbeck (1986) with a 33″ resolution at $T_{\mathrm{mb}} = 37$ mK, who gave a molecular hydrogen mass of about $\sim 10^5 M_{\odot}$. The latter value is consistent with that estimated from FIR observations, which give $1.3 \times 10^5 M_{\odot}$. Our data show a higher temperature, probably because of the smaller beam; it is consistent with this previous observation. The center velocity of the present CO line emission ($V_{\mathrm{helio}} = -325$ km s^{-1}) is different from the previous values by Wiklind and Rydbeck (1986) ($V_{\mathrm{helio}} = -198$ and -287 km s^{-1}). This would suggest some internal velocity structure, which would be expected from the clumpy distribution of dark clouds close to the galaxy center.

NGC 708: This is the central galaxy in the cooling flow cluster Abell 262 (Heckman et al. 1989); it is known as a radio source with mildly bent jets (Smith and Heckman 1989). It is classified as an E2 with clearly twisted isophotos and has a distinct dust lane along its minor axis (Gallagher 1986; Colina and Perez-Fournon 1990). Although the galaxy has weak, extended optical emission lines in its optical spectra (Heckman et al. 1989), it is not detected in H I gas, with an upper limit of the integrated H I flux being 2.0 Jy km s^{-1} , which corresponds to an H I mass of $2.1 \times 10^9 M_{\odot}$ (Heckman et al. 1983). We also obtained an upper limit to CO.

NGC 1600: This is a bright member galaxy in a cluster of Bautz-Morgan type I (Malumuth and Kirshner 1985). It has an extended X-ray halo (Forman et al. 1985), and is listed as one of the cooling flow-type galaxies (Thomas et al. 1986). It is also a strong radio source with a double radio-lobe structure (Birkinshaw and Davies 1985). Hα emission is marginally detected in a region of $r \approx 20''$ (Trincieri and di Serego Alighieri 1991). On isophoto maps of the optical surface photometry, although no isophotal twist can be seen, a boxy-shape structure exists in the outer region (Bender et al. 1989). Forbes and Thomson (1992) have reported a possible detection of a shell structure on deep CCD frames. Although Ebneter et al. (1988) detected dust patches near the nucleus, no H I flux has been detected (Knapp et al. 1985). We otained only an upper limit to CO.

NGC 2974: This is an X-ray source with an extended halo (Forman et al. 1985; Fabbiano et al. 1992), and with a nuclear radio source (Fabbiano et al. 1989). It has an extended dust lane and ionized gas along the major axis of the galaxy (Kim 1989; Schields 1991); its isophotes, however, are of a point type (Bender et al. 1989). Its H I flux is detected with a regular distribution which is consistent with a rotating disk or a ring parallel to the galaxy's major axis (Kim et al. 1988). This galaxy has the strongest 100 μm flux of 1.69 Jy ($2.6 \times 10^8 M_{\odot}$) among the present program galaxies. The FIR estimated molecular gas mass is $1.8 \times 10^8 M_{\odot}$. A CO observation was made by Bregman et al. (1992) at Kitt Peak; however, only an upper limit of 45 Jy km s^{-1} ($3.3 \times 10^8 M_{\odot}$) was given. Our CO observations also give an upper limit to the H_2 mass of $1.8 \times 10^7 M_{\odot}$, which is significantly smaller than the FIR value. Since our beam covers only the central 2 kpc, the discrepancy may be due to a more widely extended molecular gas distribution.

NGC 3379 (M105): This E0 galaxy is a standard classical elliptical in any sense. No isophotal twists, no dust lanes, and no shell structures suggesting recent merging or interacting activities have been detected (Gallagher 1986; Bender et al. 1989; Capaccioli et al. 1990; Forbes 1991). A stringent H I mass upper limit has been obtained for this galaxy, $0.15 \times 10^7 M_{\odot}$ (Bregman et al. 1992). No X-ray flux has been detected with Einstein data (Fabbiano et al. 1992). However, a weak unresolved nuclear radio source is barely detected at 6 cm (Birkinshaw and Davies 1985). No detection of FIR has been reported. The upper limit to the H_2 mass ($< 0.5 \times 10^7 M_{\odot}$), as derived from the CO measurement, is consistent with both the FIR upper limit ($< 0.2 \times 10^7 M_{\odot}$), and the upper limit ($< 0.3 \times 10^7 M_{\odot}$) given from IRAM ^{12}CO($J = 1$–0) observations (Huchtmeier et al. 1988).

NGC 4374 (M84): This is one of the brightest elliptical galaxies in the core region of the Virgo cluster, and is a well-known cooling flow galaxy with an extended X-ray halo (Forman et al. 1985; Thomas et al. 1986). This has been identified as a strong radio source 3C 272.1 with two edge-darkened radio lobes of 2′ and a compact core (Laing and Bridle 1987). This is a well-known dusty elliptical galaxy with boxy isophotes; the dust lane and ionized gas appear to be in an arc along the skewed axis around the nucleus (Ebneter et al. 1988; Véron-Cetty and Véron 1988; Kim 1989; Bender et al. 1989). Although no H I gas has been detected so far (Huchtmeier and Richter 1989), IRAS fluxes have been detected in all four bands (Knapp et al. 1989).

NGC 4486 (M87): This is a strong radio source known as Virgo A, and has prominent radio and optical jets associated with the low surface-brightness radio lobes (Birkinshaw and Davies 1985). The strong X-ray emission surrounding M87 is primarily of thermal origin; the jet, nucleus, and radio lobes account for only 1% in the Einstein energy range (Forman and Jones 1982). No dust lane has been detected (Véron-Cetty and Véron 1988), and its isophoto-shape indicates no deviation from pure elliptical isophotes, except for the core region (Bender et al. 1989). The H I flux could not be measured because of a strong radio continuum emission from the galaxy (Krumm and Salpeter 1979); Jaffe (1987), however, gave an upper limit of $2 \times 10^8 M_{\odot}$. No emission or absorption of the CO line was detected with a brightness temperature upper limit of 33 mK (Jaffe 1987), which is consistent with the present CO observations. Weak IRAS fluxes were detected at 60 μm and 100 μm.

NGC 4589: This E2 galaxy is known for its peculiar, dust-rich rotating disk perpendicular to the major axis; the merging of a gas-rich galaxy has been suggested for the origin of the rotating disk (Möllenhoff and Bender 1989). This is an X-ray source with a compact radio source and an emission line nucleus with a LINER spectrum (Dressel and Wilson 1985; Willner et al. 1985). The molecular hydrogen mass was derived from the present CO observation to be $M_{H_2} = 9.1 \times 10^7 M_{\odot}$. This is consistent within the error with that estimated from the FIR luminosity, $7.4 \times 10^7 M_{\odot}$. The velocity dispersion of the CO line, $\Delta V = 105$ km s^{-1} , is consistent with that expected from the velocity structure observed for the central condensation of the dust ring (Möllenhoff and Bender 1989). The fast rotating disk beyond 7″–8″ from the center, which rotates at 200 km s^{-1} , may not be detected in the present CO observations, not only for its extended structure than the beam, but also for the high-velocity dispersion.

NGC 4697: This is an E6 galaxy with pointed isophotes (Bender et al. 1989), and there is no evidence for the presence of dust (Véron-Cetty and Véron 1988). Although this is a weak X-ray source (Forman et al. 1985) there is possibly a large discrete source component (Canizares et al. 1987). No radio continuum flux has been detected with an upper limit 0.62 mJy at 4.9 GHz (Birkinshaw and Davies 1985). No H I flux has been detected (Roberts et al. 1991). Marginal detection of [N II]λ6583 has been reported by Tirinchieri and di Serego Alighhieri (1991) from innermost region of the galaxy. Though basically an inactive galaxy, NGC 4697 has a 100 μm flux of 1.10 Jy. The estimated molecular gas mass from the FIR emission is $4.1 \times 10^7 M_{\odot}$, while we obtain a smaller value of $3.2 \times 10^7 M_{\odot}$ from CO, which is consistent with the FIR value within the error.

4. Discussion: The Universal CO-to-Dust Ratio

In the present deep survey for CO line emission in elliptical galaxies, we have co-added two CO detected ellipticals, NGC 4589 and NGC 4697, both of which are FIR galaxies.

In figure 2 the CO-estimated H_2 masses (proportional to CO luminosities) are plotted against FIR-estimated H_2 masses (proportional to FIR luminosities) for all of the elliptical galaxies detected in CO. The diagram is consistent with that obtained by Wang et al. (1992) for early-type galaxies. Here, we used our data as well as the masses recalculated from the literature [table 2 of Lees et al. (1991)] using the same formulae as equations (1) to (3). The figure indicates that the masses approximately coincide with each other, and, hence, the CO and FIR luminosities are proportional to each other. Note that we used here the same CO-intensity to H_2 mass conversion factor (Bloemen et al. 1985; Maloney 1990); the dust-to-gas ratio and the dust temperature have been assumed to be similar to those in our Galaxy (Jura et al. 1987).

Therefore, the above coincidence may imply that the CO-to-dust abundance ratio is uniform among elliptical galaxies, and, moreover, that it is not much differ-

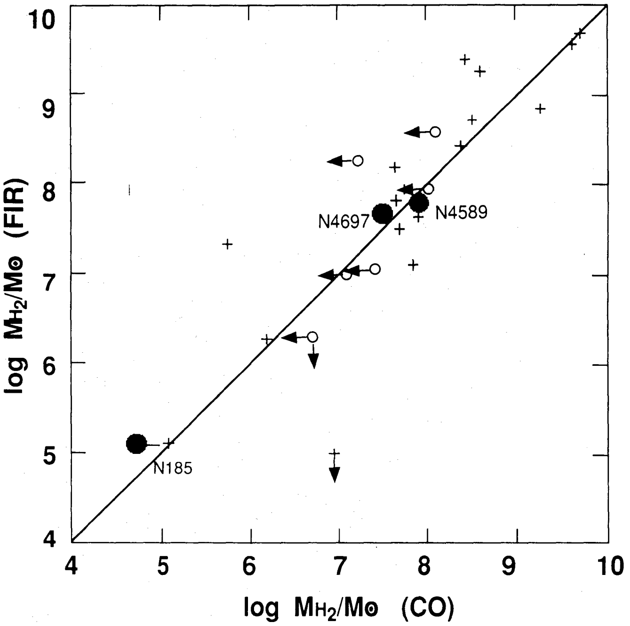


Fig. 2. FIR-estimated H_2 mass (proportional to FIR luminosity) plotted against the CO-estimated H_2 mass (proportional to CO luminosity) for elliptical galaxies. The circles are for present data, and the crosses are for those recalculated from data by Lees et al. (1991) using equations (1) to (3). The solid line represents the relation that the mass calculated from equation (1) is equal to that from equation (3), which applies to local molecular clouds in our Galaxy and probably for normal spiral galaxies as well.

ent from values in spiral galaxies and in local molecular clouds. Note that the straight line in figure 2 approximately gives the correlation between the two masses for spiral galaxies and for molecular clouds in the Milky Way. In other words, the CO-to-dust abundance ratio (more precisely [CO-to-gas]-to-[dust-to-gas] ratio) in interstellar gas is universal, and is not dependent on the stellar metal abundance in ellipticals and spirals.

Since FIR and CO luminosities cannot be independent of each other, the above result does not necessarily imply either that the conversion factor from the CO intensity to H_2 column density used here is universal, or that the dust-to-gas ratio is uniform. In order to clarify this problem, it is necessary to estimate the H_2 mass from other independent observations, such as an estimation of the Virial masses of molecular clouds by measureing their velocity as well as spatial structures.

The problem of the CO-to-gas and dust-to-gas ratios is also beyond the scope of this paper. It is also not straightforwardly understood what the CO intensity represents, since interstellar clouds are opaque against the CO line emission. However, if we here simply assume that the intensity is somehow proportional to the CO content in the galaxy, the uniform CO-to-dust ratio seems to tell us about some universality in the formation processes of CO and dust in elliptical as well as spiral galaxies.

It is known that dust is formed in circumstellar shells, and is distributed to interstellar space by stellar winds (e.g., Knapp 1985; Knapp and Chang 1985; Jura 1986). Carbon and oxygen gases (atoms and molecules) are produced in stars and are supplied to interstellar space via stellar winds, although a small fraction might come from supernovae, whereby, under the normal conditions of stellar evolution, O is richer than C. Through various chemical processes, gaseous carbon is finally combined with oxygen to produce CO almost entirely within a time-scale much smaller than the Hubble time; once CO forms, it is stable (e.g., Morris and Rickard 1982; van Dishoeck and Black 1987). Hence, the observed interstellar CO-to-dust ratio is a manifestation of the ratio of C atoms to dust when they left the stars; the ratio remains “frozen” in the interstellar gas.

We may thus conclude that, wherever and in whatever galaxy it is observed, the interstellar CO-to-dust ratio is determined by the ratio of the gaseous CO-to-dust ratio when heavy-element-abundant gas leaves its parent stars. Since the dominant source of such heavy-element-abundant gas is late-type (polulation II) stars, the CO-to-dust ratio is predominantly determined by the CO-to-dust ratio around late-type stars; the ratio is thus rather universal and independent of galaxy types. Such universality of the mutual abundance ratio among heavy elements (e.g., CO-to-dust ratio) in interstellar gas may apply in any circumstances and conditions such as in ellipticals, spirals, nuclear regions, or in local interstellar molecular clouds.

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