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Molecular Rings in Galaxies and a Possible New Cosmic Distance Indicator

Yoshiaki SOFUE

Institute of Astronomy, The University of Tokyo, Mitaka, Tokyo 181

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Abstract

The molecular gas distribution in the nuclear regions of galaxies can be classified into three types: a core (C) type with a high-density peak toward the nucleus; a compact-ring (CR) type with ring radius of ~200 pc; and a broad-ring (BR) type with ring radius of 750 pc. We discuss the possibility of using the ring radius as a cosmic distance indicator for galaxies up to about 100 Mpc. We stress that this geometrical method is independent of such correction factors as extinction and reddening.

Key words: CO gas; Cosmology; Distance scale; Galaxies; Gas rings; Molecular rings.

1. Introduction

The determination of the distances of galaxies is one of the most important subjects of astronomy and cosmology. Current measurements of distances have been based on comparisons of the apparent magnitudes with assumed luminosities of the galaxies or some objects involved therein. Namely, "standard candles" have been used as the distance indicators (e.g., van den Bergh 1989). As has been stressed repeatedly, however, the most problematic factor to be corrected for in such optical measurements is interstellar extinction and reddening, which occur both in concerned galaxies and in our own Galaxy.

Another way of determining distances is, obviously, to have a linear standard scale, the size of which is constant among galaxies. Then, a measurement of the apparent angular size of the scale indicator can immediately give a distance. In this context, a method using the radii of optical inner rings has been proposed by Buta and de Vaucouleurs (1983; and references therein).

In this paper we propose a new possible scale indicator which may be used to measure the distances of galaxies: we use a ring structure of molecular gas in the central regions of galaxies, which are often observed in the CO line emission.

2. High-Resolution CO Observations of Galaxies

During the last decade several high-resolution mm-wave telescopes have become operative. Extensive mappings of nuclear regions of nearby galaxies have been carried out using these facilities (Sofue 1991 for a review). Full mappings of the ^{12}CO ($J=$ 1–0) and ^{12}CO ($J=2$–1) line emissions have been performed by using such large-aperture single dishes as the Nobeyama 45-m and IRAM 30-m telescopes. Higher-resolution maps of the ^{12}CO ($J=1$–0) line with interferometers have also become available: the Owens-Valley mm interferometer has been used to map galaxies at a resolution of a few arc seconds. The Nobeyama mm Array (NMA) has worked at 115 GHz, and CO maps with a resolution of 2 to $8''$ have been obtained. In table 1 we summarize both the observations and references.

Early(S0/Sa)-type galaxies contain a smaller amount of molecular gas compared to Sb and Sc galaxies. No mapping with high angular resolution has yet been made, particularly for the nuclear disk regions. Later-type (Sb/c) galaxies are most extensively studied in the CO line, and many maps have been published. Generally, Sb galaxies show a large-radius ($\sim$ 4 to 10 kpc) molecular ring and a nuclear rotating disk. The distribution of molecular gas in Sc galaxies obeys an exponentially decreasing law with a scale radius of a few kiloparsecs. In both Sb and Sc galaxies a nuclear disk with a smaller scale radius and spiral arms are superimposed (Young and Scoville 1982; Tacconi and Young 1986; Sofue 1987, 1988, 1991). The nuclear disk is usually elongated, showing an oval or bar structure. Generally, the nuclear disk is further resolved either into a high-density core or into a ring surrounding a cavity.

We summarize the typical distribution characteristics of molecular gas (CO line intensity) in nearby galaxies for which high spatial-resolution observations have been made.

The Galaxy: The Milky Way is a typical edge-on Sb galaxy. An entire galactic-plane survey in CO (Dame et al. 1987) has shown that the CO intensity shows broad peaks at $l \sim \pm 20-30^{\circ}$corresponding to the 4-kpc molecular gas ring, and a high concentration within a few hundred pc of the galactic center. Although the molecluar gas distribution near the center is very complicated (e.g., Bally et al. 1987), an expanding ring of 200-pc radius is most conspicuous in the central 1 kpc region (Scoville 1972; Kaifu et al. 1972; Sofue 1990).

NGC 891: This edge-on Sb galaxy has been mapped in CO along the galactic plane (Sofue et al. 1987). The radial CO distribution is similar to that found in our Galaxy: CO emission has a sharp peak near the center, and has a ring-like enhancement at a few kpc radius. The main disk in CO is thin, less than 100 pc (Handa et al. 1991). The nuclear component has not yet been resolved, but is likely to be similar to that in our Galaxy.

NGC 4736: This is an early-type galaxy of Sab. The central region shows intense star-forming activity, and many H II regions are found on a ring of 700-pc radius (Duric and Dittmar 1988). CO observations show a broad ring of 700-pc radius associated with the H II ring (Garman and Young 1986).

Maffey 2: This is a nearby Sbc galaxy. Since the galaxy is located near the galactic plane, no good measurement of the distance is available for a heavy optical extinction: the distance to this galaxy is very uncertain. A CO mapping with the 45-m telescope

Table 1. Nuclear rings and disks of molecular gas for CO bright galaxies.

Galaxy	Type	Dist.[a] (Mpc)	Θ_r [b] ($''$)	r [b]	Ring type[c]	Ref. [d]
M.W.	Sb	8 kpc	$1^\circ\!.3\pm30''$	190-pc ring	CR	By87, Da87 So90a
NGC 891	Sb	14 Mpc	$<17''$	r <500-pc disk	CR?	So87
NGC 4736	Sab	6	$22\pm10''$	700-pc ring	BR	Ga86
Maf. 2	Sbc	5	$9\pm2''$	220-pc ring	CR	Na90, Ig89
M31	Sb	0.7	...	No nucl. disk	...	Sa89
M81	Sb	3.2	...	...	...	Br88
NGC 1068	Sb	18	$10\pm4''$	870-pc ring	BR	Ka89, Pa89
M33	Sc	0.8	$130\pm15''$	640-pc ring	BR	Wi89
M51	Sc	9.6	$18\pm2''$	850-pc hump (+nucl. bar)	BR	Lo87, Na91 Gb90, To91
M100	Sc	7	...	1-kpc nu. disk	...	Sm83
IC 342	Sc	3.9	$7\pm2''$	130-pc ring (cavity + arms)	CR	Yo82, Hy87 Lo84, Iz90a
NGC 6946	Sc	5.5	$<7''$	<80-pc core (+ 500-pc bar)	C	Yo82, We88, So88 Ba85, Iz90b
NGC 4631	Sc/SBd	5.2	$40\pm4''$	1-kpc hump	BR	So89a, So90
			$10\pm4''$	250-pc hump	CR	
M83	SABc	3.7	$< 10''$	<180-pc core	C	Ha90
NGC 4258	SBb	6.6	$< 10''$	<300-pc core	C	So89b, Kr90
NGC 253	SABc	3.4	$14\pm2''$	230-pc hump	CR	Ca88
			$5\pm2''$	82-pc hump	C	
NGC 1097	SBbc	16	$9\pm3''$	700-pc ring	BR	Ge88
M82	Ir/SBG o	3.2	$13\pm2''$	200-pc ring	CR	Lo87, Na87 Ls89, So91

[a] Distances here are those taken from the literature in the last column.
[b] Θ_r = angular radius (see the text for a legend to the error estimation); r = linear radius = Dist.$\times\Theta_r$.
[c] C = Core type; BR= Broad ring type; CR = Compact ring type.
[d] Ba85 = Ball et al. 1985; Br88 = Brouillet et al. 1988 ; By87 = Bally et al. 1987; Ca88 = Canzian et al. 1988; Da87 = Dame et al. 1987; Ga86 = Garman and Young 1986; Gb90 = García-Burillo and Guélin 1991; Ge88 = Gerin et al. 1988; ; Ha90 = Handa et al. 1990; Hy87 = Hayashi et al. 1987; Ig89 = Ishiguro et al. 1989; Iz90 = Ishizuki et al. 1990; Ka89 = Kaneko et al. 1989; Kr90 = Krause et al. 1990; Lo84 = Lo et al. 1984; Lo87=Lo et al 1987; Ls89 = Loiseau et al. 1989; Na87 = Nakai et al. 1987; Na90 = Nakai 1990; Na91 = Nakai et al. 1991; Pa89 = Planesas et al. 1989; Sa89 = Sandqvist et al. 1989; Sm83 = Solomon et al. 1983; So87 = Sofue et al. 1987; So88 = Sofue et al. 1988; So89a = Sofue et al. 1989a; So89b = Sofue et al. 1989b; So90a = Sofue 1990; So90 = Sofue 1991; So91 = Sofue et al. 1991; To91 = Tosaki et al. 1991; We88 = Weliachew et al. 1988; Wi89 = Wilson and Scoville 1989; Yo82 = Young and Scoville 1982.

has shown a bar along the major axis (Nakai 1990), and a recent interferometer image has revealed a compact ring structure with a radius of about 200 pc in this bar-like structure (Ishiguro et al. 1989).

M31: There have been several observations covering segments of spiral arms for this nearby Sb galaxy at low galactic latitude. Generally, the CO intensity is very weak, and the CO gas is distributed mainly on the 10-kpc ring (Dame et al. 1991). No detection of CO gas toward the central region has been reported so far (e.g., Sandqvist et al. 1989).

M81: The CO emission is generally very weak in this typical Sb galaxy (e.g., Brouillet et al. 1988). No good mapping for the central region has been available.

NGC 1068: This is an Sb galaxy of Seyfert I activity. A high-density broad molecular disk has been found near the center. A ring structure with a radius of 870 pc is superimposed on the nuclear disk (Kaneko et al. 1989; Planesas et al. 1989).

M33: This is a nearby Sc galaxy. The CO emission is also weak, and only a few star-forming regions have been mapped in CO. The central region shows a low-intensity nuclear disk, on which a broad ring-like structure of radius about 640 pc is superimposed (Wilson and Scoville 1989). However, the ring radius is uncertain for low angular resolution ($2'$ with the Kitt Peak 12-m telescope) and for the extended structure. Extensive distance measurements have been made in the optical domain, and this galaxy is one of the standard galaxies in the local group used for the cosmic distance scale (Sandage and Tammann 1981; van den Bergh 1989).

M51: A number of CO surveys have been carried out for this almost face-on Sc galaxy. High-resolution ^{12}CO (J = 1–0) mapping of the entire galaxy ($6' \times 6'$ region) was recently completed by Nakai et al. (1991) at a resolution of $17''$ using the 45-m telescope, and by García-Burillo and Guélin (1991) at a resolution of $21''$ using the IRAM 30-m telescope. The CO maps show clear two-armed spirals, tracing the optical (dust lanes) and radio arms. The arms are patchy, and individual clumps correspond to active star-forming regions. The molecular gas is well detected in the interarm regions. The arm-interarm (azimuthal) distribution agrees with the galactic-shock wave theory, while the velocity discontinuity ($\sim$ 70 km s^{-1}) at the shock is much larger than that predicted from theory. These arms are continuously linked to the nuclear high-density region. The gas density rapidly increases toward the center. However, the very nuclear region shows a depression, and a weak bar-like feature is found just toward the nucleus. This situation can be seen better in the higher resolution maps obtained with the Owens Valley ($7''$: Lo et al. 1987) and NMA ($4''$) observations (Tosaki et al. 1991). The annular distribution of gas density shows a peak at a radius of 850 pc.

M100: Few CO mappings have been made for this giant Sc galaxy. A low-resolution CO observation shows a nuclear disk of 1-kpc scale (Solomon et al. 1983).

NGC 6946: The CO distribution in the disk at $r > 2$ kpc obeys an exponentially decreasing law, $I_{\rm CO} = I_{\rm MD}\exp(-r/5\ {\rm kpc})$, while the inner 2 kpc region can be described as $I_{\rm CO} = I_{\rm ND}\exp(-r/0.9\ {\rm kpc})$, where $I_{\rm MD}$ = 20 K km s^{-1} and $I_{\rm ND}$ = 110 K km s^{-1} are the coefficeints for the main disk and the nuclear disk components, respectively (Tacconi and Young 1986; Weliachew et al. 1988; Sofue et al. 1988). The innermost CO gas is distributed in an oval shape, forming a molecular bar. The nuclear region has been mapped with high angular resolution using the NMA

(Ishizuki et al. 1990b). There has been no indication of a ring or a central depression, but the gas distribution shows a sharp peak toward the center. The scale radius of the CO peak is less than 50 pc, and the peak has not been resolved. The intensity of the central core reaches as high as $I_{\rm CO} = 10^3$ K km s^{-1} , an order of magnitude greater than $I_{\rm ND}$. The velocity field shows noncircular motion, suggesting bar-shock accretion.

IC 342: The overall distribution of molecular gas is similar to that observed in NGC 6946 (e.g., Young 1988). The central region shows a molecular bar structure (Lo et al. 1984; Hayashi et al. 1987). Higher resolution observations (Ishizuki et al. 1990a) show that the bar splits into two symmetrical spirals with a large pitch angle. The spirals end near a ring of radius 130 pc. The nuclear $\sim$ 100 pc region has a CO depression. The molecular ring positionally coincides with the radio continuum ring (Turner and Ho 1983). The motion of molecular gas near the center is highly noncircular, suggesting a bar-shock inflow. This may fuel gas toward the central high-density ring, where high star formation is enhanced.

NGC 4631: This is an edge-on Sc/SBd galaxy of the late type, and is disturbed by two companions. Observations of ^{12}CO (J = 1–0) and ^{12}CO (J = 2–1) lines with the 45-m and 30-m telescopes have revealed two nuclear rings of radii 1 kpc and 250 pc (Sofue et al. 1989b, 1990). The rotation in the central 1 kpc is rigid. Because of the edge-on nature, as well as large interstellar absorption, any distance estimates determined by optical measurements must be uncertain.

M83: This is a southern barred galaxy of the SABc type. CO observations with the 45-m telescope have revealed a molecular bar located in the leading edge of the optical bar (Handa et al. 1990). A high-density core exists toward the nucleus, which has not been resolved.

NGC 4258: This is an SBb galaxy and is known for its anomalous radio continuum arms (van Albada and van der Hulst 1982). The central region has an H I bar (van Albada 1980), and a CO core has been detected toward the center; the CO seems to be anticorrelated with H I (Sofue et al. 1989a). The CO emission has also been detected along the anomalous arms (Krause et al. 1990).

NGC 253: This is a giant southern SABc galaxy with large inclination. No detailed CO mapping has been made. Recent interferometer mapping of the central region has shown a bar-like nuclear disk (Canzian et al. 1988). The bar has symmetrical humps with respect to the center, which are likely to be the tangential directions of a ring of radius 230 pc. An unresolved nuclear core of radius less than 80 pc is superimposed on the bar (ring).

NGC 1097: This is an SBbc-type galaxy, and the central region of which shows a high star-forming activity. A ring of molceular gas of radius 700 pc has been found (Gerin et al. 1988).

M82: This is a famous starburst galaxy seen almost edge-on. The nuclear region shows a dense molecular ring of radius 200 pc (Lo et al. 1984; Nakai et al. 1987; Loiseau et al. 1989; Sofue et al. 1991). High-speed molecular outflow with a cylindrical shape has been detected.

There are many other galaxies not listed here, for which CO observations have been made. However, no sufficient data regarding the nuclear regions are available for these galaxies. In this paper we deal only with the galaxies mentioned above.

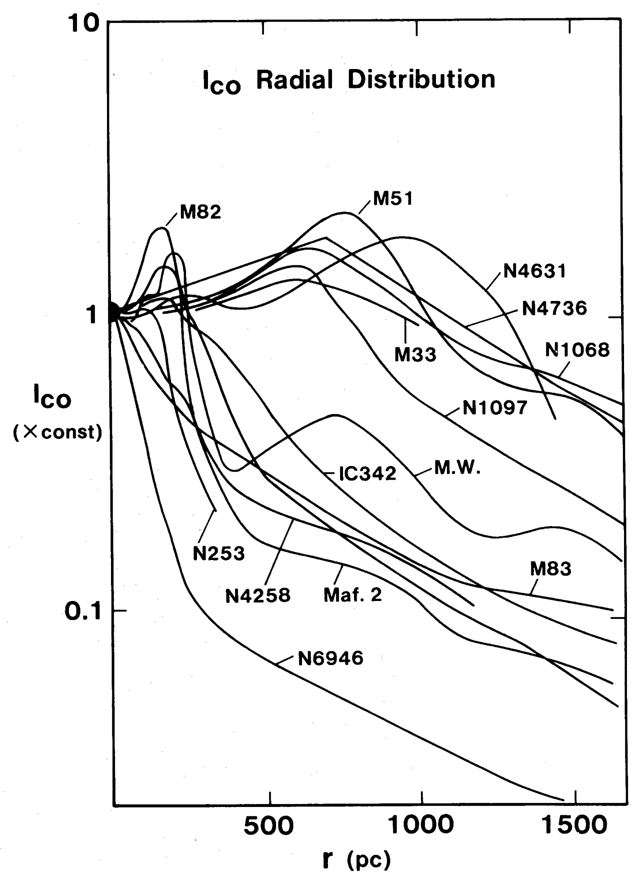

Fig. 1. Averaged variations of the CO line intensity as a function of the distance from the center along the major axis. The intensities are normalized by their central values.

3. Nuclear Rings and Cavity

High-resolution observations of CO bright galaxies have shown that the central regions have a nuclear disk with high concentration of molecular gas. In many cases,the nuclear disks show a ring structure and a central cavity in CO followed by dense molecular arms and/or bars. Only a few galaxies show a filled-center structure, or a core type, having no cavity. Table 1 lists the galaxies for which the central regions have been resolved in the CO line. Figure 1 shows the averaged distributions of the CO intensity along the major axis for these galaxies.

The apparent ring radius, (Θ_r) in table 1 has been estimated by assuming that the angular separation of the observed double peaks of the CO intensity along the major axis represents the ring diameter. The errors in measuring the sepration of the peak-intensity positions arise mainly due to the observational accuracy, and are typically about 50% of the angular resolution for single-dish observations, and even better for interferometers. For example, the Nobeyama 45-m telescope has an angular resolution of $16''$, and the error in measuring the relative separation of peak positions (=diameter) is better than about $\pm 8''$. The error in the radius estimation is thus about

$\pm 4''$. In the case of the Nobeyama millimeter interferometer, the angular resolution is about 4 to $8''$, so that a separation of the peak positions can be determined with an accuracy of better than $2''$. The radius can thus be determined within 1 to $2''$. We, therefore, evaluate the error, ($\delta\Theta_r$) in the angular radius to be equal to 25% of the angular resolution: $\delta\Theta_r \simeq 0.25\Theta$ with Θ being the angular resolution. Table 1 includes the thus-estimated errors of Θ_r. The error in linear radius is more difficult to estimate, since the distance estimates include much larger errors, both systematic and random, which arise mainly from the different methods used by the authors. Therefore, the errors in the linear radius would be much larger. We cannot, however, estimate them properly, so that we here simply assume that the percentage error in linear radius comes simply from the angular size error.

Table 1 and figure 1 can be then used to classify the molecular gas distributions in the following three types:

Core type: The gas is highly concentrated in the central few hundred pc region, and there is no cavity. Examples are NGC 6946, NGC 4258, and M83.

Compact ring (CR) type: Molecular gas forms a ring with a radius of about 200 pc, and a central cavity is found within the ring. Examples are M82, IC 342, and Maf. 2.

Broad ring (BR) type: Molecular gas forms a broad ring with a radius of about 750 pc. Examples are NGC 4631, NGC 1068, and NGC 1097.

We mention that the classification depends on the angular resolution of the observations as well as the distances to the galaxies: Even core-type galaxies might show unresolved inner structures if they were observed at higher resolutions. Also, the BR-type galaxies, most of which are more distant than those of the core and CR-types, might also have unresolved inner core or CR structures. Higher and more sensitive observations in the future will certainly improve the classification and accuracy of measurements of ring radii, etc. in table 1 and figure 1.

Regarding to the formation mechanism of the ring and core structures, we may suggest the following: According to viscosity-driven angular momentum transfer and the on-going star formation model (Yoshii and Sommer-Larsen 1989), the formation of a dense nuclear disk is a natural consequence of exponential-disk formation when a galaxy is born and contracts from a primeval gas sphere. At such a stage when a primeval disk is formed, the radial gas density distribution may be of the core type. In addition to this initial high-density disk, the viscosity and shock-induced angular momentum transfer causes an accretion of gas toward the center. This accretion is enhanced if there exists an oval or a bar-like potential (e.g., Noguchi 1988).

The star-formation efficiency is an increasing function of the gas density, so that the star-formation rate becomes extremely high soon after a nuclear core is formed. As a consequence of intense star formation or a star burst at the center, the gas near the nucleus is rapidly exhausted and partly expands, and a cavity surrounded by a ring is formed. If there exists an AGN, its strong UV will heat and dissociate molecules, forming a cavity around it. The ring radius is then somehow related to the gas disk thickness. A simple numerical simulation has suggested that the ring radius is about twice the scale height of the disk gas; in case that the disk scale height is 100 pc, the ring radius is about 200 pc (Sofue 1976, 1987).

An alternative suggestion is that the ring radius is related to the bar width, as has been shown by a numerical simulation of the bar-induced accretion of gas (Noguchi

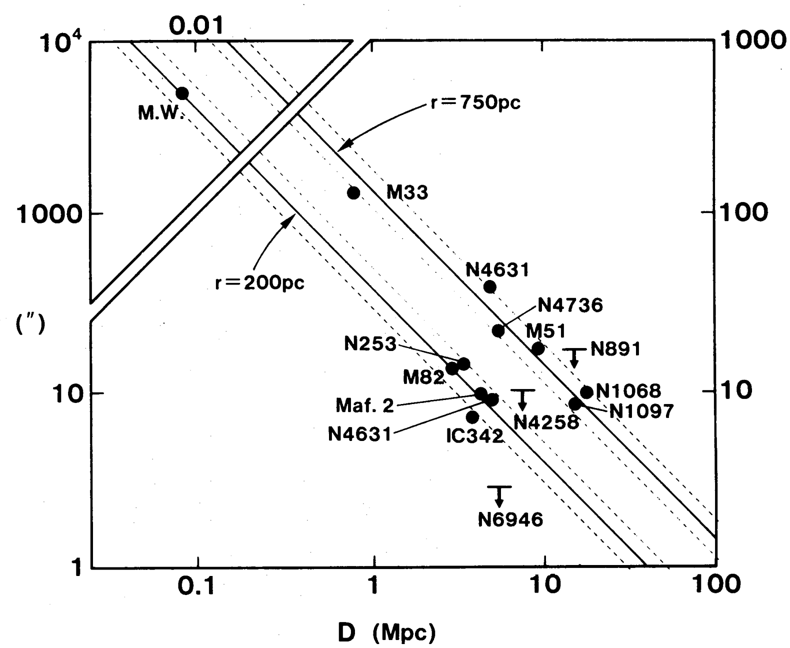

Fig. 2. Plot of the angular radii of molecular rings against the distance from the literature. Note the bimodality of correlations: data fall either around the $r = 200$ pc line enclosed by the dashed lines or around $r = 750$ pc.

1988). Then, if the bar width has a constant dimension for any galaxies, it may be possible that the ring size becomes constant.

4. Ring Size as a Possible Cosmic Distance Indicator

The existence of such nuclear rings in galaxies has an important implication in astrophysics, although the formation mechanism is still not thouroughly understood. It should be emphasized that the ring radius is almost constant, $\sim$ 200 pc for CR (compact ring) type, and 700 to 800 pc for BR (broad ring) type galaxies. If it is established that the ring radius is a constant among galaxies, this characteristics may provide an opportunity to scale the linear dimensions of galaxies, and therefore to scale the distances.

In figure 2 we plot the observed angular radii (apparent sizes) of the molecular rings of the galaxies listed in table 1 against their distances. Here, the distances are those cited in the literature (table 1). As has been shown in section 3, the errors in the angular size are $\pm 10 \sim 20\%$. From this figure we can see that the apparent ring size is inversely proportional to the distance. As readily seen in figure 1, we can also divide the galaxies with resolved CO structures into two groups on this figure: galaxies having compact rings (CR), and those with broad rings (BR). For the six CR-type galaxies in table 1, the ring radii are fitted by the line $r = 200 \pm 40$ pc (the mean and standard deviation). For the five BR type, the radii are fitted by $r = 750 \pm 100$ pc. The "bimodality" (CR or BR) of ring-sizes may be recognized from the fact that the plotted points in figure 2 fall either in the region enclosed by the two dashed-lines

Table 2. Distance and distance modulus estimated from the molecular ring size method.

Galaxy	Distance¶	Dist. modu.	Dist. from literature†	
M. W.	8.4 kpc	...	8 kpc	...
NGC 4736	6.4 Mpc	29.03	6 Mpc	Bo77
Maf. 2	4.6	28.31	5	Sp73
NGC 1068	16	31.02	18	ST75
M33	~ 0.9*	~24.87	0.8	ST81
M51	8.5	29.65	9.6	ST75
IC 342	6.0	28.89	3.9	Tu88
NGC 4631	4.0‡	28.01	5.2	ST74
NGC 253	3.0	27.39	3.4	ST75
NGC 1097	17	31.15	16	Ge88
M82	3.2	27.53	3.2	TS68

¶ The errors are typically ±20%.

† Bo77 = Bosma et al. 1977; Sp73 = Spinrad et al. 1973; ST74, 75, 81 = Sandage and Tammann 1974, 1975, 1981; Tu88 = Tully 1988; Ge88 = Gerin et al. 1988 ($H_0 = 75$); TS68 = Tammann and Sandage 1968.

* The estimated ring radius has large uncertainty because of low resolution of the observations and broad ring structure.

‡ Average of two estimates from the inner and outer rings.

around $r = 750$ pc, or in the region around $r = 200$ pc.

The scatter of data around each line of the two groups can be attributable either to a scatter of the ring radii in individual galaxies, or to errors in the distance determination. The former possibility cannot be excluded at present, since the formation mechanism of the rings are still far from being clarified. It is quite natural that the ring size depends on various circumstances of the individual galaxies.

However, as another extreme case, if we allow for the ring sizes to be a constant and if the scatter comes from errors in the distances, we may be able to use this diagram for an estimation of the galaxy distances. The distances adopted so far have been taken from the literature, as referred in tables 1 and 2. Based on this assumption, we may try to derive the distances to these galaxies. Here, we assume that the "true" ring radius is given by the mean of the values given above: Any compact ring has a radius of 200 pc, and a broad ring has a radius of 750 pc. Then, we can simply calculate the distances from the measured angular sizes. In table 2 we give the thus-estimated distances and the corresponding distance moduli. For a comparison we list the values from both the literture and references. The largest correction was applied to IC 342, for which the new distance is 6.0 Mpc, significantly larger than the old value of 3.9 Mpc.

The sample number of galaxies treated in this paper is still too small for establishing the constant-ring-size characteristics of galaxies, although we have collected almost all available CO data of galaxies useful for the present purpose. In particular, since the galaxies collected here are biased by CO detections, we cannot at present avoid the possibility that the obtained characteristics concerning ring sizes might be due to some selection effects. However, we note that the morphologies and dynamical properties of the sample galaxies are spread over a very wide range, from a small starburst galaxy to a normal giant spiral, and from irregular to Sb and Sc galaxies. Hence, we could say that the present statistical tendency is not a particular characteristic for a specific type of galaxies, but can be applied to a wide range of types of galaxies. Nevertheless, we must emphasize that one may take the method applied here only as a possible trial, and, before obtaining a conclusive result, one should wait for more detailed analyses based on higher-resolution and higher-sensitivity observations in the future for a greater number of sample galaxies. However, if such characteristics are proved to be the case for any or for a certain class of galaxies, it may provide a new possible method to scale galaxy distances independent of the standard-candle methods.

We note that the standard-candle methods are strongly affected by the extinction and reddening in galaxies, particularly for highly tilted galaxies, as well as by those in the foreground interstellar medium in our Galaxy. This is particularly true for galaxies at low galactic latitudes. On the other hand, the present "molecular-ring method" is much simpler: we simply map the molecular (CO) gas disks in the central regions of galaxies with sufficient resolution. Then, the angular sizes of the molecular rings directly give the distance. The molecular-ring method is a simple direct "geometric" method, requiring no additional data, such as luminosity. The method is therfore not affected by uncertainties in intensity and luminosity calibrations. Of course, the ring size, either 200 pc or 750 pc as tentatively given here, should be determined more precisely for a larger number of standard galaxies.

Finally, we compare our molecular-ring method with the Tully-Fisher relation, which also uses radio astronomy techniques, while it is (in principle) a standard-candle method. The Tully-Fisher relation is based on H I line width observations (Tully and Fisher 1977; van den Bergh 1989 for a review) and it measures "integrated" H I line profiles to estimate the absolute luminosity, which is compared with the apparent magnitude after correcting for extinction and reddening, etc. In order to obtain a full H I line width, measurements of the total fluxes are required. Therefore, observations are usually made using single dishes in order that telescope beams can cover the entire extents of the H I distribution in galaxies. For this reason the method is applicable for galaxies with distances less than ~ 100 Mpc for a detection limit at a few mK level of antenna temperature.

On the other hand, the molecular-ring method measures the very central region of galaxies in the CO line emission. The brightness temperature of such central regions is usually a few tens K, much higher than the H I-averaged brightness. If we can resolve the nuclear disk, as is required for this method, the brightness of the region does not depend on the distance. With modern mm-wave interferometers we can achieve an angular resolution of $\sim 1''$. To attain a 100-pc scale resolution with such instruments, which is required for CR type galaxies, objects must be closer than ~ 20 Mpc. If we observe BR-type galaxies, we may be able to go further to ~ 100 Mpc.

Hence, at present the two method can reach about the same distance. However, mm-wave (CO) observing techniques are still under development and will be much improved in the future. If we could use larger mm-wave interferometers, the present method would give a promising way to measure cosmic distances, even beyond 100 Mpc.

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