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Distance Measurement of Galaxies to a Redshift of ~ 0.1 Using the CO-Line Tully-Fisher Relation

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Abstract

We report on the first results of a long-term project to derive the distances of galaxies at cosmological distances by applying the CO-line width–luminosity relation. We have obtained deep CO-line observations of galaxies at redshifts of up to $cz \sim 29000$ km s^{-1} using the Nobeyama 45-m mm-wave telescope; also, some supplementary data were obtained using the IRAM 30-m telescope. We have detected CO-line emission from several galaxies, and used their CO-line widths to estimate the absolute luminosities based on the line-width–luminosity relation. In order to obtain photometric data and an inclination correction, we also performed optical imaging observations of the CO-detected galaxies using the CFHT 3.6-m telescope at high resolution. The radio and optical data have been combined to derive the distance moduli and distances of the galaxies; also, the Hubble ratios were estimated for these galaxies. We propose that the CO-line width–luminosity relation can be a powerful method to derive the distances of galaxies to redfhifts of $z \sim 0.1$, and to derive the Hubble ratio within a significant volume of the universe.

Key words: Cosmology — Galaxies: distances — Galaxies: general — Galaxies: radio lines — Radio lines: CO molecular

1. Introduction

The H I-line width–luminosity relation (Tully-Fisher relation) is one of the most powerful tools for measuring the distances to galaxies (Tully, Fisher 1977; Aaronson et al. 1986; Pierce, Tully 1988; Kraan-Korteweg et al. 1988; Fouqué et al. 1990; Fukugita et al. 1991). However, distances to galaxies so far reached by H I observations have been limited to around 100 Mpc, or $cz \sim 10000$ to 15000 km s^{-1}, even when using the world's largest telescopes (Schöniger, Sofue 1993). We have no routine method to determine the distances to galaxies beyond this distance, at which the beam sizes of a few arc-minutes at λ21 cm become too large to resolve individual galaxies in a cluster. Interferometers such as the VLA are not very useful for this purpose, because of the limited number of spectral channels (velocity resolution). Furthermore, the red-shifted H I frequency results in increases in the beam size as well as increased interference, which also makes observations of distant cluster galaxies difficult. Moreover, H I line profiles are easily disturbed by interactions among galaxies, which is inevitable in the central region of a cluster, causing an uncertainty in the interpretation of the H I line profiles for the Tully-Fisher relation. On the other hand, since the molecular gas is tightly confined to the luminous stellar disk, it is less affected by tidal interactions and by the ram-pressure distortion due to the intra-cluster gas. Since the molecular gas is distributed within a radius of several to ten kpc, the integrated line profiles manifest the maximum velocity part of the rotation curve (Sofue 1992).

Molecular-line observations at millimeter wavelengths, particularly in the CO-line emission at 115 GHz, can be achieved with much sharper beams. Therefore, we will be able to resolve individual member galaxies in a cluster more easily, which will make it possible to avoid contamination by other member galaxies in a beam. Moreover, the larger is the redshift of an object, the lower is the CO frequency, which results in a decrease in the system noise temperature due to the atmospheric O_2 emission at 118 GHz; the more distant is a galaxy, the lower is the noise temperature.

Dickey and Kazes (1992) have addressed the use of the CO line widths instead of and/or supplemental H I observations, and have proposed the CO-line Tully-Fisher relation as an alternative to the H I Tully-Fisher relation. The CO-line width–luminosity relation has been established for local distance calibrators and tens of nearby galaxies (Sofue 1992; Schöniger, Sofue 1993, 1996). In these studies, we have shown that the CO-line measurements can be used as an alternative to H I by deriving a good linear correlation between the CO and H I linewidths for the galaxies in a sample. The only disadvantage of using the CO line is the sensitivity. Actually, we need a few mK rms noise for line-width measurements at a velocity resolution of 10 km s^{-1} for normal galaxies beyond $cz \sim 10000$ km s^{-1}, which requires long integration times. Such observations are possible only in a long-term project using the world's largest mm-wave telescopes.

On the basis of these studies, we have conducted a long-term project to observe the $^{12}CO(J = 1–0)$ line profiles for distant cluster galaxies at redshifts of up to $z \sim 0.1$ using the Nobeyama 45-m telescope. The targets were chosen so that they include galaxies in clusters of galaxies at $cz \sim 10000$ to 30000 km s^{-1}. Before proceeding to measuring CO in normal galaxies at these distances, we chose far-infrared (FIR) luminous galaxies, so that CO detection would be easier at this first trial. We selected the targets using the NED (NASA Extragalactic Database) searching facility. In this paper, we present the results for the most FIR luminous galaxies with 60 μm and 100 μm fluxes greater than 0.2 and 0.5 Jy, respectively, as well as with redshifts within 10000 and 30000 km s^{-1}. This sample selection may include some possible problems in applying the Tully-Fisher relation because of possible peculiarities in the optical absolute magnitudes for the FIR luminous galaxies. We may need to evaluate the accuracy of the relation for such FIR luminous galaxies, which remains a problem for the future. The result presented here should be taken as a demonstration of the possible use of the CO Tully-Fisher relation for measuring the distances of galaxies of these large distances. However, we mention that such a FIR luminous starburst galaxy as NGC 253 is included in the small number of standard calibrators of the Tully-Fisher relation. It is also known that IRAS galaxies obey a standard Tully-Fisher relation (van Driel et al. 1995).

We obtained additional CO-line spectra for some galaxies using the IRAM 30-m mm-wave telescope. We also obtained high-quality optical imaging of the detected galaxies in CO in order to measure the inclination and magnitude using the Canada-France-Hawaii 3.6-m telescope. In this paper, we report on a first-step result of measuring CO line profiles in order to demonstrate that the line profiles can be obtained in routine work within a reasonable integration time, and that distances can be obtained by applying the Tully-Fisher relation. We also report on the optical imaging observations of several CO-detected galaxies, and try to obtain a possible value of the Hubble ratios.

2. CO-Line Observations

2.1. Observations

We have selected spiral galaxies which satisfy the following criteria using NASA Extragalactic Database (NED): 1) galaxies with red-shift between 10000 km s^{-1} and 30000 km s^{-1} ; 2) with position error of less than 10″; 3) with relatively strong far infrared emission at 60 μm and 100 μm. The first criterion was set to select distant galaxies for which the H I Tully-Fisher relation cannot reach. The highest redshift galaxy was IRAS 08344 + 5105, which had $cz = 29029$ km s^{-1}. The second criterion was set so that the position error be small enough compared to the beam size of CO-line observation. Accurate positions of the sources were measured on the Palomar Sky Survey Prints using the position-measuring facilities at the Kiso Observatory, as well as the STScI Digitized Sky Survey images. The third criterion was to select galaxies which are expected to be bright in CO-line emission. One might suspect that galaxies with bright infrared emission could deviate from the Tully-Fisher relation for normal galaxies. However, van Driel et al. (1995) studied the so-called IRAS Minisurvey galaxies, and showed that there is no significant difference between the Tully-Fisher relation for IRAS selected galaxies and that for normal galaxies. Among the galaxies which satisfy these criteria, interacting galaxies and Seyfert-type galaxies are excluded. Galaxies with a larger error of recession velocity than 100 km s^{-1} are also excluded, though galaxies for which the error of recession velocity is unknown are included. There are some galaxies whose types cannot be known through NED. For such galaxies, we have confirmed that they are disk galaxies and do not show any interaction on the Palomar Sky Survey Prints.

Observations of the $^{12}CO(J = 1–0)$ line of distant cluster galaxies were made on 1994 January 14 to 23, 1994 December 9 to 12, and 1995 January 6 to 10, 1995 March 13 to 17, 1995 December 17, 18, 21, 22, and 1996 February 18 to 22, using the 45-m telescope of the Nobeyama Radio Observatory. The antenna had a HPBW of 15″ at the CO line frequency, and the aperture and main-beam efficiencies were $\eta_a = 0.35$ and $\eta_{mb} = 0.50$, respectively. We used two SIS (superconductor-insulator-superconductor) receivers with orthogonal polarization, which were combined with 2048-channel acousto-optical spectrometers. The total channel number corresponds to a frequency width of 250 MHz, and, therefore, to a velocity coverage in the rest frame at the galaxy of

Table 1. Galaxies detected in the CO line emission.*

Name	RA(1950) (h m s)	Dec(1950) (° ′ ″) (error in ″)	cz (km s^{-1}) (error km s^{-1})	$S_{60\mu m}$ (Jy)	$S_{100\mu m}$ (Jy)	Type	Detection
(1993/94 program)							
CGCG 1113.7 + 2936	11 13 46.9	+29 35 59(4)	13880(33)	0.63	2.03	?	D
CGCG 1448.9 + 1654	14 48 54.4	+16 54 02(4)	13700(51)	0.14	1.13	Sp	D
CGCG 1417.2 + 4759	14 17 14.8	+47 59 00(2)	21465	0.62	1.54	SBb	D
(1994/95 program)							
NGC 6007	15 51 01.6	+12 06 27(10)	10547(6)	0.69	2.03	SBbc	D
CPG 60451	17 30 00.6	+20 09 48.6(5)	14989(?)	0.48	1.36	Scd	D
IC 2846	11 25 24.804	+11 26 00.5(1)	12294(33)	4.21	6.72	Sp	D
(1995/96 program)							
IRAS 17527 + 6422	17 51 44.99	+64 22 14.1(3)	26151(24)	2.22	3.25	?	D
IZw 23	09 56 01.0	+52 29 48.0(1)	12224(57)	0.62	1.74	Sp	D
(Marginal detection)							
IRAS 14210 + 4829	14 21 06.2	+48 29 59.0(1)	22690(?)	0.38	0.88	Sp	?
IRAS 23420 + 2227	23 42 00.60	+22 27 49.8(3)	26022(?)	1.41	2.07	?	?

* Sources of the positions and redshifts is the NED (NASA Extragalactic Database). These velocities were used for the center frequencies of the CO-line detectors.

c (250 MHz/$\nu_{\rm obs}$) = $c(1+z)$(250 MHz/115.2712 GHz) = $650(1+z)$ km s^{-1}. The center frequency was so tuned that the center channel 1024 corresponds to 115.2712 $(1+z)$ GHz for each galaxy.

After combining every 32 channels in order to increase the signal-to-noise ratio, we obtained spectra with a velocity resolution of 10.2 km s^{-1}. The system noise temperature (SSB) was 300 to 400 K at the observing frequencies. The calibration of the line intensity was made using an absorbing chopper in front of the receiver, yielding an antenna temperature ($T_{\rm A}^*$), corrected for both the atmospheric and antenna ohmic losses. We used an on-off switching mode, and the on-source total integration time was 2 to 6 hr for each galaxy. After careful flagging and subtraction of linear baselines, the rms noise of the resultant spectra at a velocity resolution of 10 km s^{-1} was typically 2 mK in $T_{\rm A}^*$. The pointing of the antenna was tested by observing nearby SiO maser sources at 43 GHz every 1 to 1.5 hr, and was typically within $\pm 3''$ during good weather conditions, which were attained during about one fourth of the allocated observing time.

2.2. *CO-Line Profiles and Results*

Among the observed galaxies, sufficient quality data have been obtained for fifteen galaxies, including eight galaxies with CO-line detection. Good CO line profiles were obtained for several galaxies with a sufficient signal-to-noise ratio for determining the velocity width. The CO-detected galaxies were NGC 6007, IZw 23, IC 2846, CGCG 1448.9+1654, CGCG 1113.7 + 2936, CPG 60451, CGCG 1417.2 + 4759, and IRAS 17527 + 6422. We obtained the possible (marginal) detection of two galaxies, IRAS 14210+4829 and IRAS 23420+2227. These galaxies are listed in table 1, and the spectra are shown in figure 1. The intensity scale used in this paper is the antenna temperature ($T_{\rm A}^*$). The abscissa in figure 1 is the relative recession velocity V_0 with respect to the optical redshift (cz) given in table 1. We also performed CO line observations using the IRAM 30-m Telescope, and obtained detection for CGCG 1417.2 + 4759. The observation with the IRAM 30-m telescope was made on 1994 July 9, equipped with an SIS receiver having a system temperature of 270 K and combined with a 256-channel filter-bank spectrometer having a velocity coverage 1400 km s^{-1}. The CO profile from the IRAM 30-m telescope is also shown in figure 1.

The profiles for the detected galaxies show a nearly double-peaked emission, which is characteristic of a rotating disk. From these data we have measured the line width, peak antenna temperature, and line intensity for individual galaxies. The results are listed in table 2. The farthest galaxies for which the CO-line has been detected in the present program are IRAS 23420+2227 and IRAS 17527 + 6422 at cz = 26022 and 26151 km s^{-1}, respectively.

Our program included more distant galaxies with redshift of up to cz = 29000 km s^{-1}. Good data were obtained for several galaxies after integration for a few hours. Some examples are shown in figure 2, which are for IRAS 16305 + 4823 with cz = 26327 km s^{-1}, showing a slight enhancement at a relative velocity

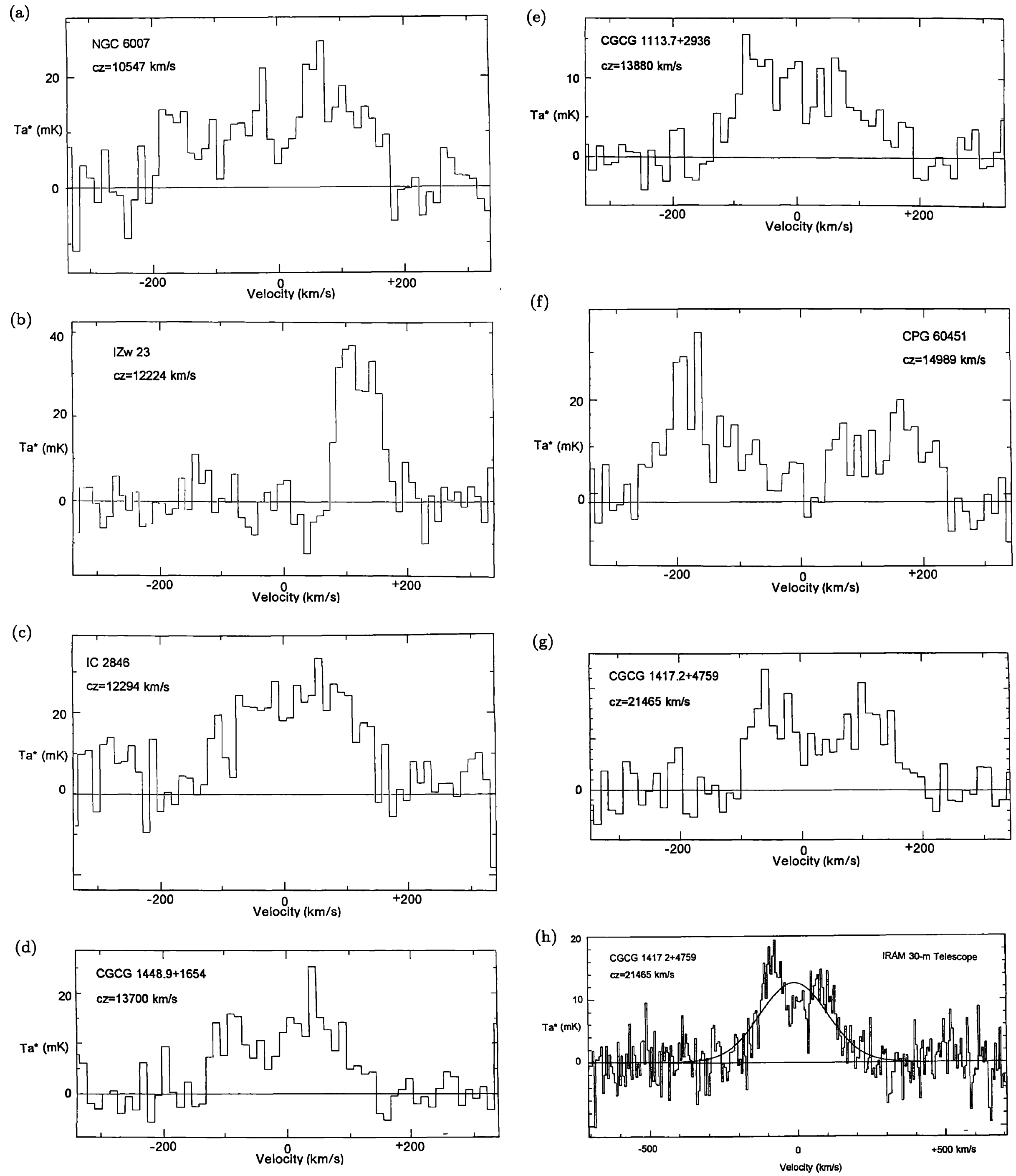

Fig. 1. CO line profiles for the detected galaxies and the marginal detection taken with the Nobeyama 45-m telescope. The CO line profile of galaxy CGCG 1417.2 + 4759, obtained with the IRAM 30-m telescope, is also presented. All of the data are presented in V_0 vs T_A^* plane, where V_0 is radial velocity referred to the galaxy's optical cz.

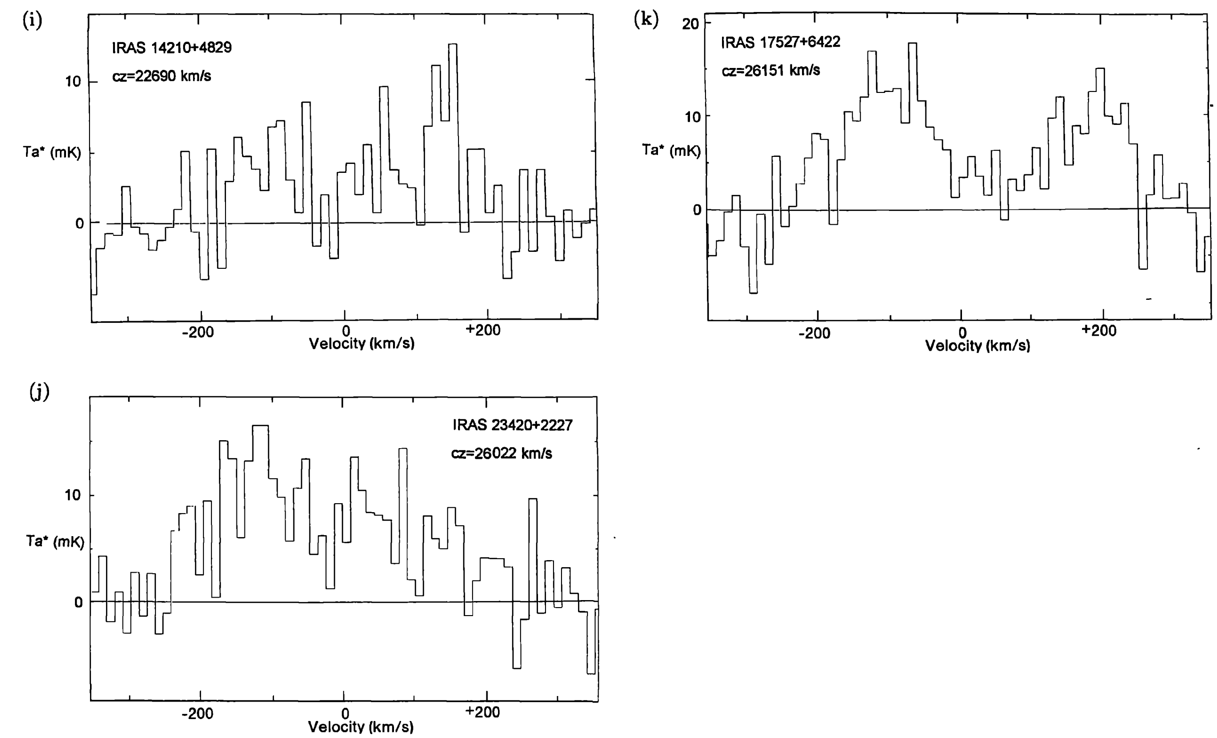

Fig. 1. (continued)

Table 2. CO-line data for the detected galaxies.

Name	cz (km s^{-1})	cz_{CO} (km s^{-1})	$\Delta\nu_{obs}$ (GHz)	W * (km s^{-1})	T_A^* (mK)	$I_{CO,rest}$ (K km s^{-1})	Type
NGC 6007	10547	10542±5	0.129	347±10	23±3	5.1±0.2	SBbc
IZw 23	12224	12364±5	0.0391	106±10	37±5	2.4±0.2	Sp
IC 2846	12294	12302±10	0.0898	243±15	25±4	5.5±0.2	Sp
CGCG 1448.9 + 1654	13700	12693±5	0.0989	269±10	20±3	3.0±0.1	Sp
CGCG 1113.7 + 2936	13880	13910±5	0.117	318±5	16±2	2.5±0.1	SBb
CPG 60451	14989	14984±5	0.168	460±15	25±3	6.3±0.2	Scd
CGCG 1417.2 + 4759	21465	21527±10	0.111	308±15	12±3	1.6±0.2	SBb
(IRAM 30m)			...	380±15	16±3	2.5±0.3	...
IRAS 17527 + 6422	26151	26165±20	0.145	410±20	15±5	4.1±0.4	?

* $W = W_{rest} = c\Delta\nu_{obs}/\nu_{obs;center} = c(1+z)\Delta\nu_{obs}/(115.2712\ \mathrm{GHz})$.

of $V_0 \sim -180$ to 0 km s^{-1}; IRAS 07243 + 1215 with $cz = 28204$ km s^{-1} showed marginal detection at $V_0 \sim +70$ to $+200$ km s^{-1}, while not being conclusive; IRAS 08344+5105 with $cz = 29029$ km s^{-1}, the farthest galaxy in our program, showed a slight sign of enhancement at $V_0 \sim -100$ to $+180$ km s^{-1}.

3. Optical Observations

3.1. Observations

In order to obtain the photometry, morphology, and inclination of the CO detected galaxies, we performed high-quality optical imaging observations of three galaxies: CGCG 1417.2+4759, CGCG 1448.9+1654, and CPG 60451. The galaxies were chosen to be among galaxies

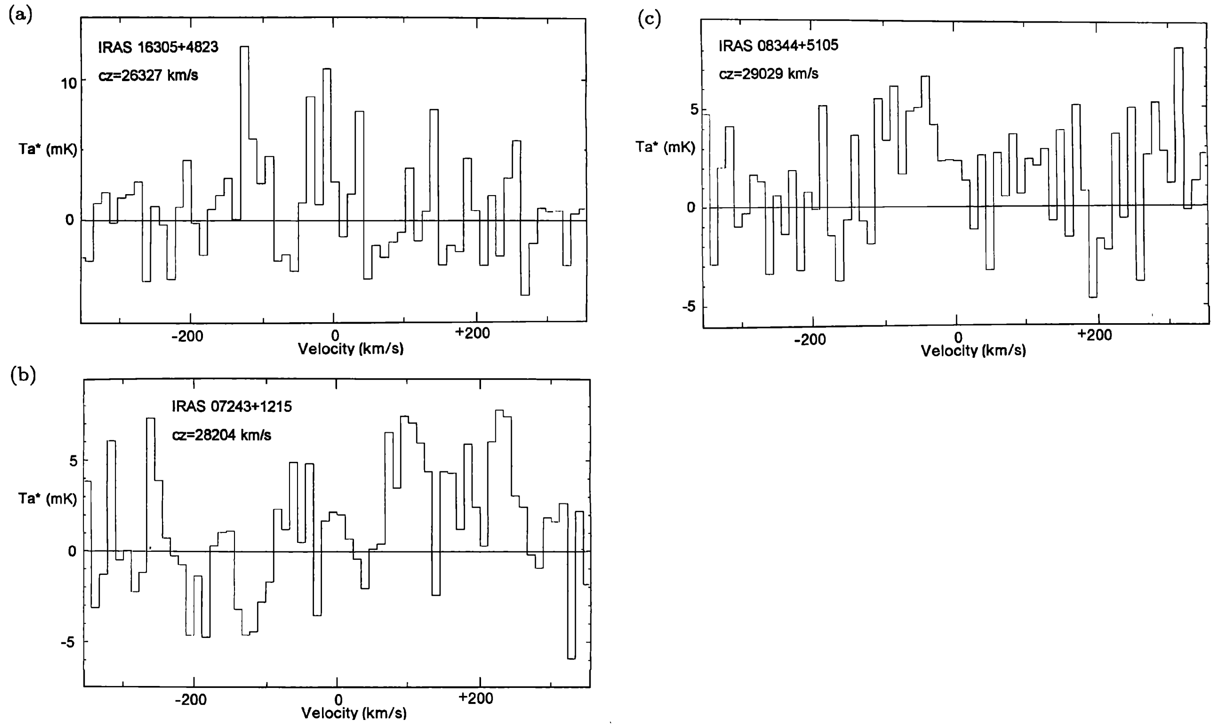

Fig. 2. Same as figure 1, but non-detection or marginal for the farthest galaxies up to cz = 29000 km s^{-1} in the present program obtained under good conditions. Some show a sign of detection, while not yet conclusive.

Table 3. Optical imaging of three galaxies.*

Galaxy	Type	$V_{25.5}$ (mag)	$R_{26.0}$ (mag)	$I_{24.5}$ (mag)	$A_{V_{25.5}}$ ($''$)	$B_{V_{25.5}}$ ($''$)
CGCG 1417.2 + 4759	SBcd	15.34	14.82	14.39	32.2	23.1
CGCG 1448.9 + 1654	Sab	15.00	14.46	13.98	33.5	29.6
CPG 60451	Sc	15.97	15.31	14.72	35.2	13.7

* The errors in the magnitudes are typically 0.03 mag.

showing the best-quality CO line profiles observed during the 1994/1995 missions, and are within the right ascension range observable during the allocated time of the optical observation. The observations were made using the Canada-France-Hawaii 3.6-m Telescope (CFHT) on 1995 June 30–July 1. Additional images were taken with the 105-cm Schmidt telescope of the Kiso Observatory in 1994 January. Using these data, we have determined the apparent magnitudes and inclinations of the galaxies. We summarize the optical data in table 3.

Imaging observations were made in the Johnson V and Kron-Cousins R_C and I_C bands at the Canada-France-Hawaii 3.6-m Telescope with the SIS (Subarcsecond-Imaging-Spectrograph). The Loral3 CCD had an effective imaging area of 2048 × 2048 pixels with a pixel size of 15 μm × 15 μm. The camera covered a sky area of $3' \times 3'$ with a resolution of $0.''086$ per pixel. The exposure times in the V, R_C, and I_C bands were 900, 900, and 300 s, respectively. The observations were performed under photometric sky conditions on 1995 June 30. Standard stars from Landolt (1992) were also observed for a flux calibration. The FWHM seeing size was $0.''6$–$0.''8$, which was small enough to determine the morphology of the observed galaxies. The dome screen was exposed to obtain flat frames.

Standard data processing (bias subtraction and flat fielding) was performed with the IRAF software package. For further image processing and surface photom-

Table 4. Data for the CO-Line TF relation for measured galaxies.*

Galaxy	V_T mag	R_T mag	I_T mag	V_C km s^{-1}	i deg	W_i km s^{-1}
CGCG 1417.2 + 4759	15.31	14.80	14.33	21502	45.3	433±27
(using IRAM 30-m)............						534±33
CGCG 1448.9 + 1654	14.96	14.43	13.93	13483	28.7	560±54
CPG 60451	15.92	15.26	14.66	14840	70.1	489±18

* The errors in the magnitudes are typically 0.1 mag, and inclination errors are ±3°.

etry (e.g., sky subtraction and flux calibration) we used the SPIRAL package developed at Kiso Observatory and installed into the IRAF system. The large field of view gives a sufficiently large sky area around the galaxies to allow accurate sky-subtraction. The flux calibration using the standard star frames resulted in a photometric accuracy of about ±3%. The transformation to the Johnson and Kron-Cousins' standard photometric systems and the atmospheric extinction corrections were determined by analyzing the standard star frames.

3.2. *Surface Photometry*

In figure 3 we present the R_C band images of the three galaxies. The contours are drawn at an interval of 1 mag (arcsec)$^{-2}$, starting from 26.5 mag (arcsec)$^{-2}$. The maps were fitted with ellipses so as to obtain the isophotal magnitudes and axial diameters. The second column of table 3 gives the morphological types of the galaxies. We stress that the galaxies show quite normal morphologies as spirals, and are isolated galaxies. The isophotal magnitudes of the galaxies above 25.5, 26.0, 24.5 mag (arcsec)$^{-2}$ levels in the V, R_C, and I_C bands, respectively are presented in table 3. The major (A) and minor (B) axial diameters at 25.5 mag (arcsec)$^{-2}$ in the V band are given in the last two columns. The typical error in the total magnitude was about 0.03 mag.

We measured the intensity of the galaxies in elliptic annuli of one pixel width centered on the galactic nucleus, after subtracting the sky brightness and stellar images, thus obtaining a growth curve. Since the integrated magnitude in the tail of each growth curve approximately followed an exponential law, asymptotically reaching a constant value, we defined the total magnitudes as the extrapolation of this curve to infinity.

To evaluate the Tully-Fisher relation we need the velocity width corrected for the inclination i and for the redshift effect to an edge-on value at the rest frame. We obtained an intrinsic velocity width in the rest frame referred to the galaxy corrected for the inclination using

$$W_i = W/\sin\ i, \tag{1}$$

Table 5. Distance modulus, distance, and Hubble ratio for the detected galaxies.*

Galaxy	$m-M$ mag	D Mpc	$H=\langle V_C/r\rangle$ km s^{-1}Mpc^{-1}
CGCG 1417.2 + 4759 (IRAM 30-m Telescope)			
(V-band)	37.15±0.40	270±50	80±15
(R_C-band)	37.07±0.53	260±62	83±20
(I_C-band)	37.25±0.57	282±74	76±20
(Average)	37.16±0.51	271±66	80±19
CGCG 1448.0+1654			
(V-band)	36.93±0.64	243±71	55±16
(R_C-band)	36.87±0.84	237±92	57±16
(I_C-band)	37.03±0.89	255±103	53±21
(Average)	36.95±0.79	245±92	55±21
CPG 60451			
(V-band)	37.53±0.23	320±34	46±5
(R_C-band)	37.22±0.31	278±39	53±7
(I_C-band)	37.25±0.33	282±43	53±8
(Average)	37.33±0.34	293±66	51±11

* The errors do not include the systematic errors in the photometric corrections and the internal scatter within the Tully-Fisher relation, itself.

where W is the rest-frame velocity width given by

$$\begin{aligned} W &= W_{\rm rest} = c\Delta\nu_{\rm obs}/\nu_{\rm obs} \\ &= c(1+z)\Delta\nu_{\rm obs}/(115.2712\ {\rm GHz}). \end{aligned} \tag{2}$$

Here, $\Delta\nu_{\rm obs}$ is the observed line width in frequency. We obtained the inclination i of a galaxy from the conventional formula given by Hubble (1926) for oblate spheroid,

$$\cos^2 i = (q^2 - q_0^2)/(1 - q_0^2), \tag{3}$$

with $q = b/a$ and $q_0 = c/a$, where a, b, and c are the lengths of the three axes of the spheroid. Here, we adopt $q_0 = 0.20$ for the present analysis. The measured result is given in table 4. The typical error in the inclination estimate was ±3°.

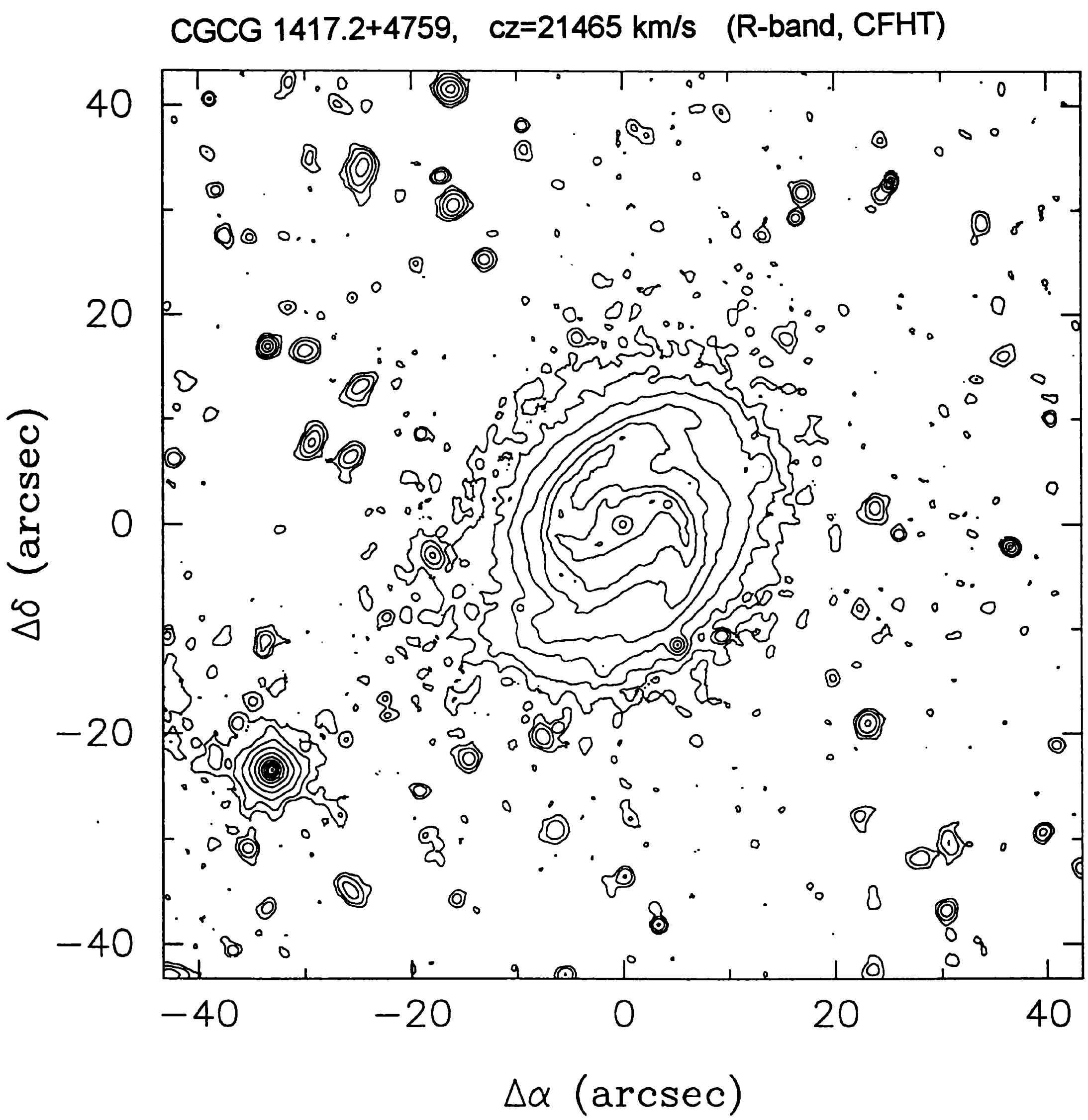

Fig. 3. Optical images taken with the CFHT 3.6-m telescope in the R_C band of galaxies CGCG 1417.2 + 4759, CGCG 1448.9 + 1654, and CPG 60451 in contour map and gray-scale representations. The contours are drawn at an interval of 1 mag arcsec^{-2}, starting at 26.5 mag arcsec^{-2}.

The galactic absorption A_B was taken from Burstein and Heiles (1984). The internal-absorption corrections A_i were computed using the methods given in Pierce and Tully (1992). For the K-correction, we used the correction of Fukugita et al. (1995). The corrected total magnitude is written as

$$m_T^{b,i} = m_T - A_B - A_i - K. \quad (4)$$

The obtained results of the optical measurements are summarized in table 4. Typical errors in the magnitude estimate were about ±0.1 magnitude, except for systematic errors, which might be present in the applied corrections.

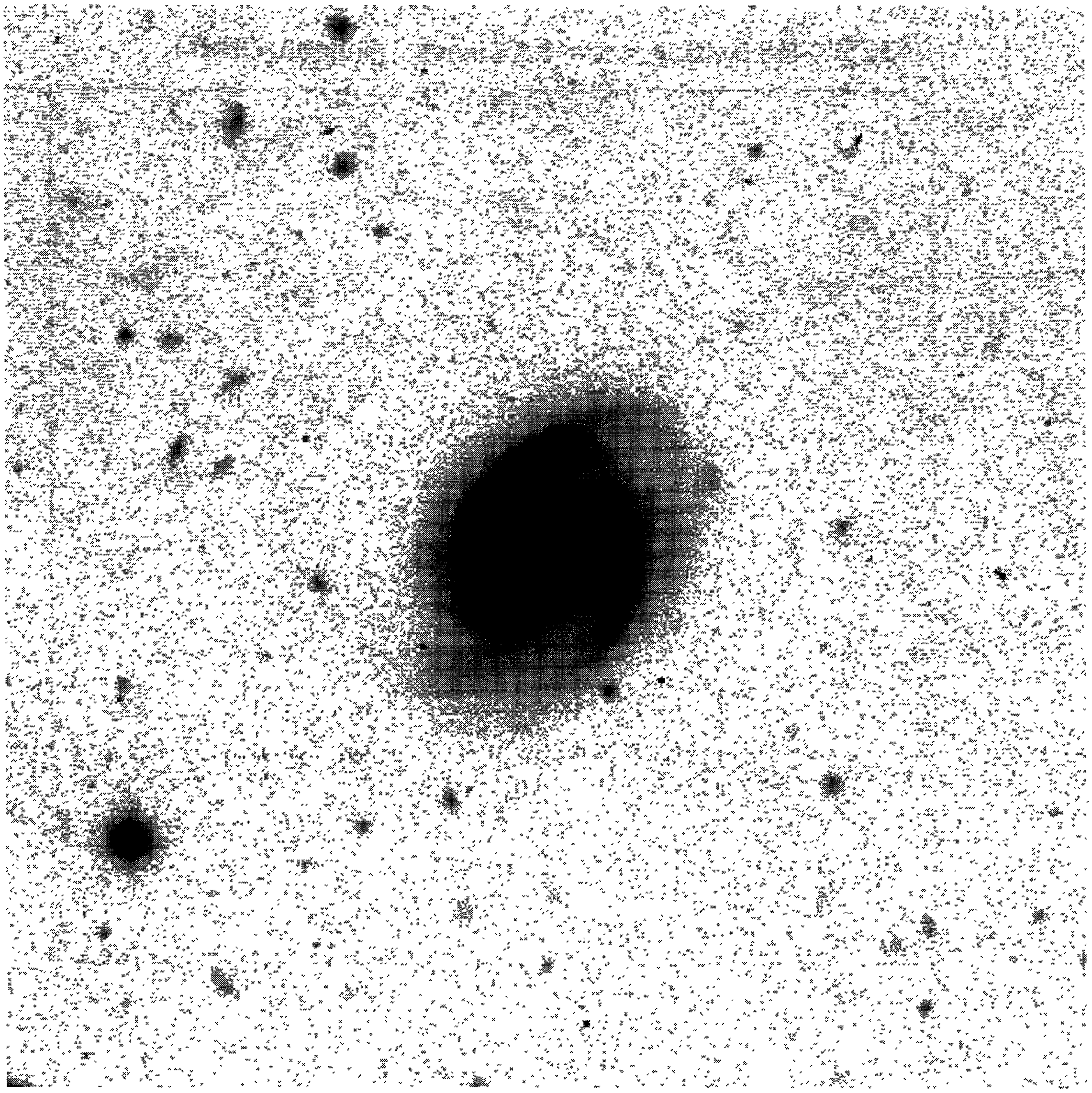

Fig. 3. (Continued)

4. Discussion

4.1. Distances and Hubble Ratios

On the basis of our previous study, in which the CO-line width of a galaxy was equivalent to the H I-line width within the error of the Tully-Fisher relation for local calibrators, we tried to derive the distances to the three galaxies for which the optical photometry and imaging were obtained with the CFHT. We adopted the zero point of the TF relation given by Pierce and Tully (1992) for R and I and by Shimasaku and Okamura (1992) for V band.

$$M_V^{\rm b,i} = -20.43 - 6.21(\log W_i - 2.5) \quad (5)$$

$$M_R^{\rm b,i} = -20.40 - 8.23(\log W_i - 2.5) \quad (6)$$

$$M_I^{\rm b,i} = -20.94 - 8.72(\log W_i - 2.5) \quad (7)$$

We adopted the same scheme for their extinction and inclination corrections. However, the distance moduli of the common local calibrators exhibit large discrepancies.

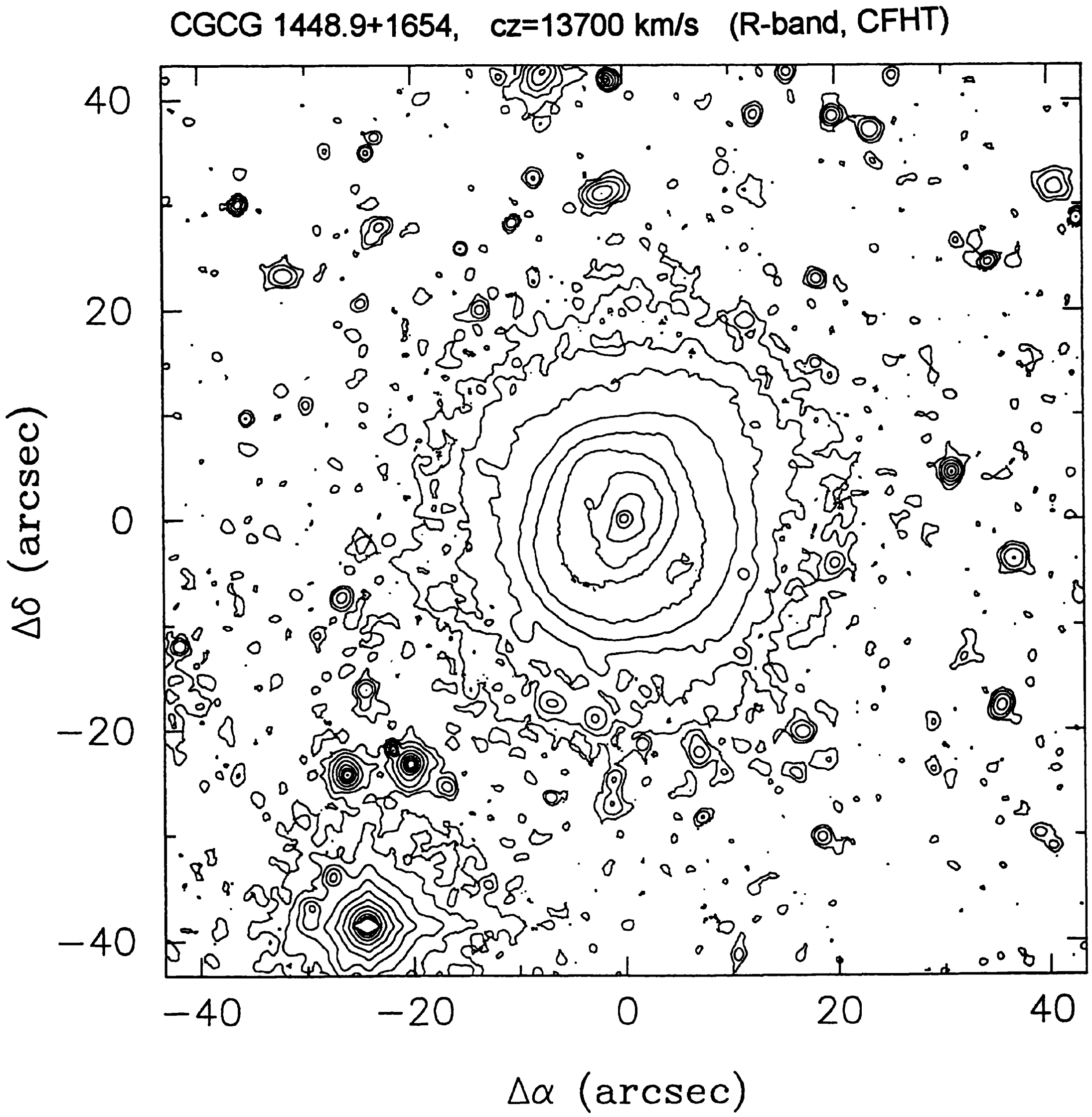

Fig. 3. (Continued)

The differences are −1.0 to +0.1 mag and 0.38 mag on average. (Shimasaku and Okamura's moduli are larger.) Four calibrators (M31, M33, NGC 300, and NGC 2403) have distances well determined by Cepheid variables. The Cepheid distances are in favor of Shimasaku and Okamura's values. We, therefore, adopted the Shimasaku and Okamura's calibration and added 19% to the distance moduli obtained by the Pierce and Tully calibration in the R and I_C bands.

Using the Tully-Fisher relation for the CO-line widths measured in section 2, we derived the distance moduli, distances, and Hubble ratios V_C/r for the three galaxies. Here, the recession velocity V_C has the value with respect to the rest frame referring to the cosmic-background radiation (Smoot et al. 1991). The distance modulus, distance, and Hubble ratio obtained in the individual optical bands (V, R_C, and I_C) are shown in table 5 for each object. The error in the absolute magnitude ΔM arises from the error in the CO line-width measurement ΔW as well as from that due to the error in the inclination

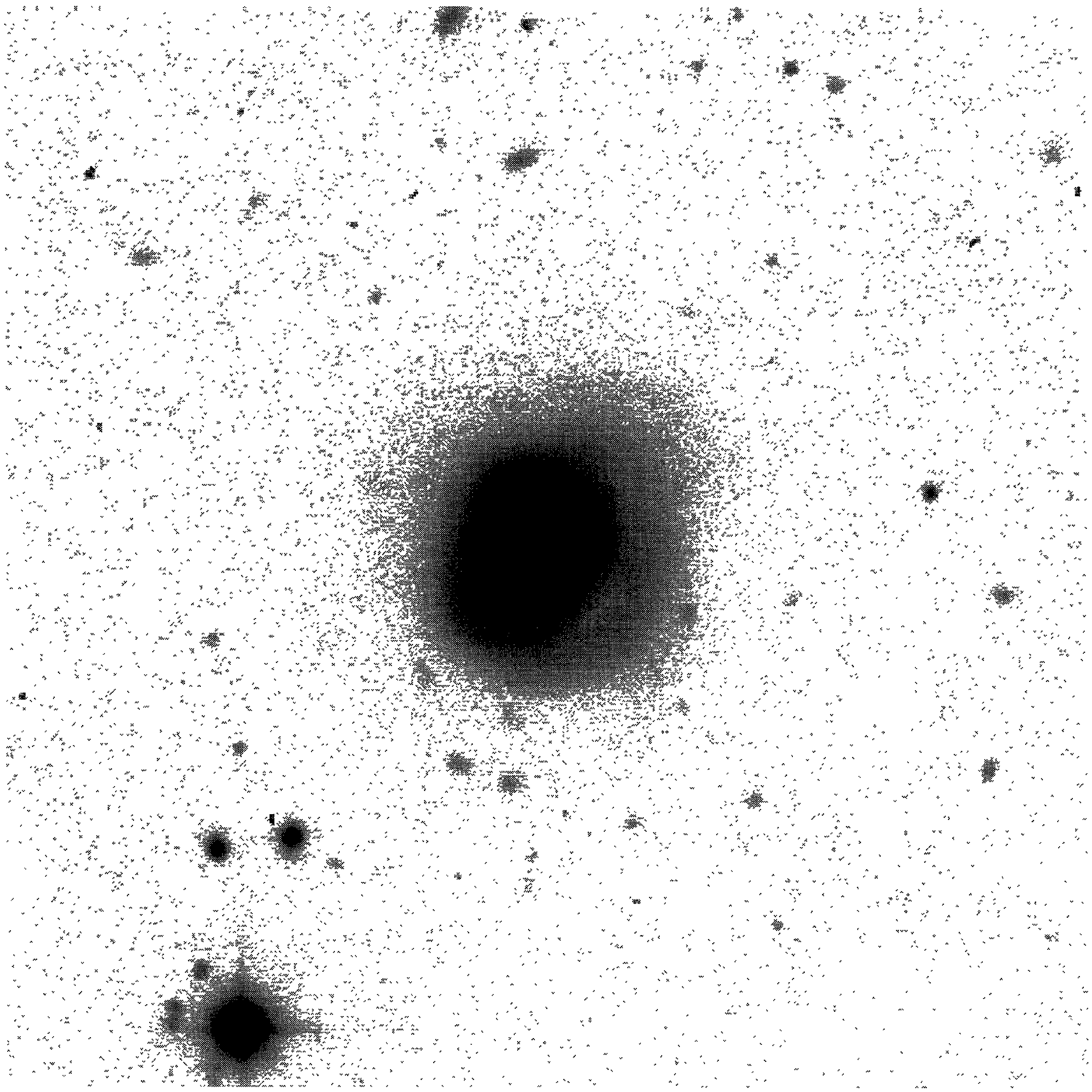

Fig. 3. (Continued)

ΔW_i, which is given by

$$\Delta M \simeq K\sqrt{(\Delta W/W)^2 + (\Delta W_i/W_i)^2}, \tag{8}$$

where K is the coefficient of the Tully-Fisher relation in equations (5) to (7), and

$$\Delta W_i = W\frac{\cot\, i}{\sin\, i}\Delta i = W_i \cot\, i\Delta i. \tag{9}$$

Here, Δi is the error in the inclination measurement, which was typically $\pm 3°$. The distance error is then given by

$$\frac{\Delta D}{D} \simeq \frac{\Delta(m-M)}{5\ \log e} = \frac{1}{5\ \log e}\sqrt{\Delta m^2 + \Delta M^2}. \tag{10}$$

Here, Δm is the error in the photometric measurement of the apparent magnitude. In the present case the error in the apparent magnitude ($\sim$ 0.1 mag) is much smaller than that of the estimate of the absolute magnitude arising from the line-width measurement and inclination correction. Hence, we have

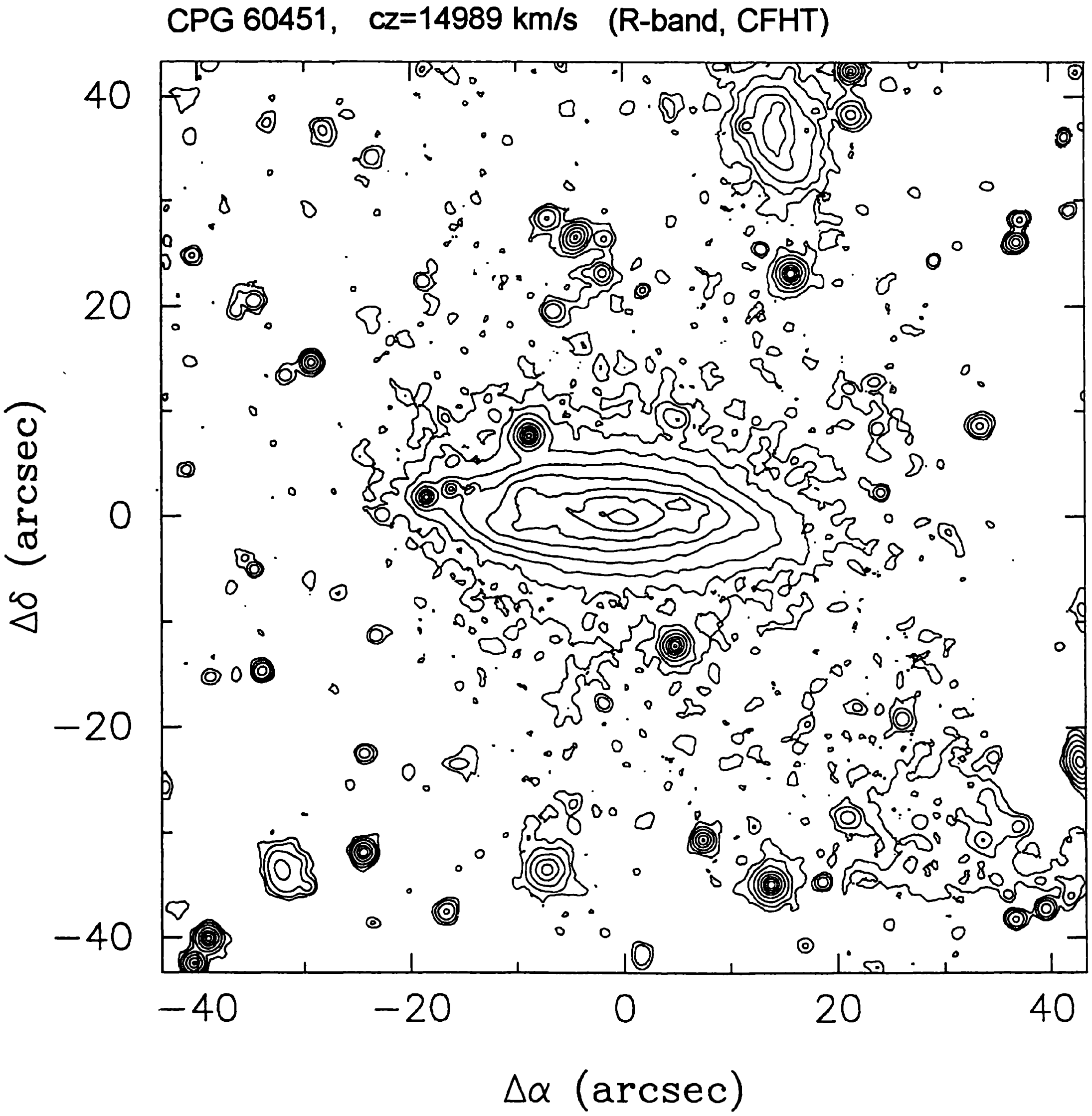

Fig. 3. (Continued)

$$\frac{\Delta D}{D} \simeq \frac{\Delta M}{5\ \log e} \simeq \frac{K}{2.17}\Delta W_i/W_i$$
$$\simeq \frac{K}{2.17}\sqrt{(\Delta W/W)^2 + (\cot\ i\ \Delta i)^2}. \qquad (11)$$

The measured values in the V, $R_{\rm C}$, and $I_{\rm C}$ bands are given in tables 4 and 5. The errors shown here do not include the systematic error in the adopted photometric corrections or the internal scatter within the Tully-Fisher relation, itself. As for the CO line width of CGCG 1417.2 + 4759, we adopted the CO data from IRAM 30-m telescope. The Hubble ratio obtained for CGCG 1417.2 + 4759 from the NRO 45-m telescope data is as large as 110 km s^{-1} Mpc^{-1}, while the data from IRAM 30-m telescope gives a value around 80; we adopted the value from the IRAM data. The larger value of the Hubble ratio from that of NRO data appears to be due to an underestimate of the velocity width, because of the smaller velocity coverage in the spectrometer at NRO

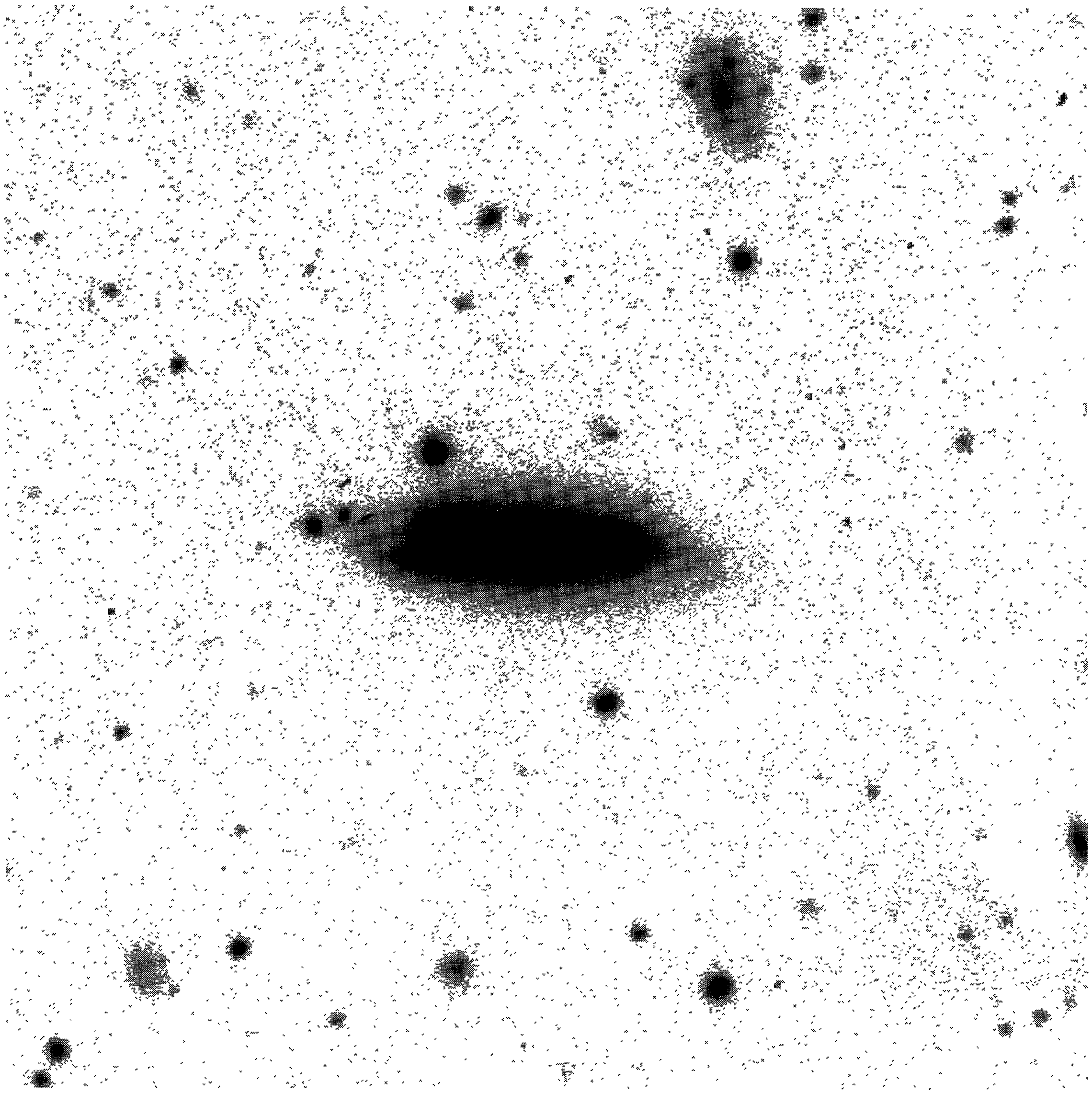

Fig. 3. (Continued)

than at the IRAM 30-m telescope. The obtained Hubble ratios in table 5 are scattered from $\sim$ 50 to $\sim$ 80 km s^{-1} Mpc^{-1}, while the values are within a reasonable range of the current determinations.

4.2. Remarks

We are in the process of conducting a long-term program using the Nobeyama 45-m mm-wave telescope, and partly using the IRAM 30-m telescope, in order to study the CO-line width-luminosity (CO Tully-Fisher) relation. In this program, we have shown that the present method can be a useful technique to derive the distances of galaxies at redshifts greater than $cz \sim 10000$ km s^{-1}, at which the H I-line Tully-Fisher relation becomes more difficult to apply. Although the number of CO detections is not sufficient for any conclusive determination of the Hubble ratio, we have obtained reasonable values for a few galaxies. We, indeed, tried to observe more distant galaxies, whose redshifts are as large as $z \sim 0.1$, in January and

February of 1996. We obtained marginal detection for a few galaxies as listed in tables 1 and 2; their CO line profiles are shown in figures 1 and 2. In order to derive the Hubble ratios of these galaxies, however, high-resolution optical imaging, such as shown in figure 3 is required, which will be performed in the near future.

Our present sample selection may include some problems in applying the Tully-Fisher relation, because of possible peculiarities of FIR luminous galaxies, although optical imaging (figure 3) has shown that the three galaxies used here are of normal morphology. However, we mention that FIR luminous galaxies from the IRAS minisurvey follow the Tully-Fisher relation (van Driel et al. 1995). We also note that such a FIR luminous starburst galaxy as NGC 253 is included in the small number of standard calibrators of the Tully-Fisher relation, indicating that the FIR luminosity does not necessarily disturb this relation.

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