JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
28: 169 ~ 175, 1995

IS THE PEGASUS DWARF GALAXY A MEMBER OF THE LOCAL GROUP? *

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(Received Oct. 5, 1995; Accepted Oct. 16, 1995)

ABSTRACT

Deep VI CCD photometry of the Pegasus dwarf irregular galaxy shows that the tip of the red giant branch (RGB) is located at $I = 21.15 \pm 0.10$ mag and $(V-I) = 1.58 \pm 0.03$. Using the I magnitude of the tip of the RGB (TRGB), the distance modulus of the Pegasus galaxy is estimated to be $(m-M)_0 = 25.13 \pm 0.11$ mag (corresponding to a distance of $d = 1060 \pm 50$ kpc). This result is in a good agreement with the recent distance estimate based on the TRGB method by Aparicio [1994, ApJ, 437, L27], $(m-M)_0 = 24.9$ ($d = 950$ kpc). However, our distance estimate is much smaller than that based on the Cepheid variable candidates by Hoessel *et al.*[1990, AJ, 100, 1151], $(m-M)_0 = 26.22 \pm 0.20$ ($d = 1750 \pm 160$ kpc) mag. The color-magnitude diagram illustrates that the Cepheid candidates used by Hoessel *et al.*are not located in the Cepheid instability strip, but in the upper part of the giant branch. This result shows that the Cepheid candidates studied by Hoessel *et al.*are probably not Cepheids, but other types of variable stars. Taking the average of our distance estimate and Aparicio's, the distance to the Pegasus galaxy is d= 1000 ± 80 kpc. Considering the distance and velocity of the Pegasus galaxy with respect to the center of the Local Group, we conclude that the Pegasus galaxy is probably a member of the Local Group.

Key Words : galaxies:individual (Pegasus Dwarf Irregular Galaxy: DDO 216) — galaxies:stellar content — galaxies:photometry — Local Group — Cepheid — distance scale

I. INTRODUCTION

The Pegasus dwarf galaxy (DDO 216) is a resolved irregular galaxy. The distance to this galaxy has been controversial in the past. The previous distance estimates for this galaxy based on various methods range significantly from $(m-M)_0 = 25.0$ to $(m-M)_0 = 29.0$ mag (Jacoby & Lesser 1981; Hoessel & Mould 1982; Christian & Tully 1983; Sandage 1986a; Hoessel *et al.* 1990). Among these estimates, Hoessel *et al.* (1990)'s estimate is based on the Cepheid variable candidates: $(m-M)_0 = 26.22 \pm 0.20$ mag. This value has been often used in the literature. This result suggests that the Pegasus dwarf galaxy is located far beyond the boundary of the Local Group which is commonly considered to be ~1 Mpc. However, the velocity data of the Pegasus dwarf indicates that it may be a member of the Local Group (Yahil, Tammann, & Sandage 1977).

During the preparation of this paper, Aparicio (1994) published a new distance estimate for this galaxy based on the tip of the red giant branch, following the description given in Lee, Freedman & Madore (1993): $(m-M)_0 = 24.9$ mag. This value is 1.3 mag smaller than Hoessel *et al.* (1990)'s. He pointed out that independent distance estimates are needed to clarify the significant difference between these two estimates.

In this short paper, we present a new distance estimate for this galaxy using the I magnitude of the tip of the red giant branch (called as TRGB hereafter) which is measured from deep VI CCD photometry, showing that the Pegasus dwarf galaxy is a member of the Local Group. Preliminary results were presented in Lee (1994) and Kim & Lee (1995). Detailed study of the stellar populations in the Pegasus dwarf galaxy will be presented in Lee & Kim (1995).

* This paper is based in part on observations which were made with the Palomar 1.5m telescope which is jointly operated by the California Institute of Technology and the Carnegie Institution of Washington.

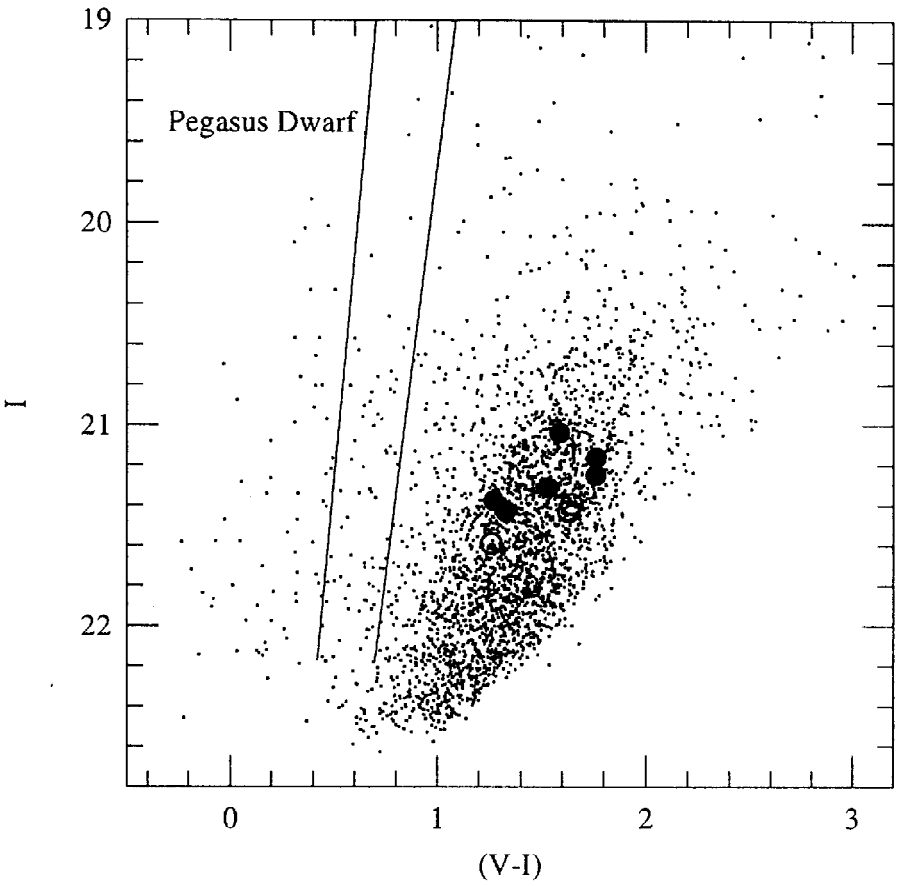

Fig. 1. $I-(V-I)$ diagram of the measured stars in the Pegasus dwarf galaxy. Note that there is a strong concentration of the faint red stars with $I < 21$ mag, which represents the red giant branch of Population II. The Cepheid candidates studied by Hoessel *et al.* (1990) are also plotted: the filled circles represent very likely Cepheid variables and the open circles represent probable Cepheid variables. Two slanted lines represent the schematic position of the Large Magellanic Clouds Cepheids, shifted according to the distance and reddening of the Pegasus dwarf galaxy.

II. THE DATA

Deep VI CCD images of the Pegasus galaxy were obtained using the Palomar 1.5m telescope in three observing runs. The magnitudes of the stars were derived using the digital stellar photometry software DoPHOT (Schechter *et al.* 1993) and DAOPHOTII installed in IRAF. The calibration errors of the photometry are ~ 0.03 mag. Detailed descriptions of the observations and the data reductions are given in Lee & Kim (1995).

Figure 1 displays an $I-$ (V−I) color-magnitude diagram of 3,100 measured stars in the CCD images of the Pegasus dwarf galaxy. In Figure 1 there is a strong concentration of faint red stars with $I < 21$ mag, which represent the red giant branch of Population II.

III. THE DISTANCE TO THE PEGASUS DWARF BASED ON THE TIP OF THE RED GIANT BRANCH

From the luminosity function and the color-magnitude diagram, the TRGB is measured to be at $I = 21.15 \pm 0.10$ mag and (V−I) $= 1.58 \pm 0.03$. The foreground reddening toward the Pegasus galaxy is very small, $E(B-V) = 0.02$ mag (Burstein & Heiles 1984). Using the I magnitude of the TRGB, we estimate the distance to the Pegasus dwarf galaxy: $(m-M)_0 = 25.13 \pm 0.11$ ($d = 1060 \pm 50$ kpc), following the method described in Lee (1993) and Lee, Freedman & Madore (1993). This value is very similar to that given by Aparicio (1994) who used the same method: $(m-M)_0 = 24.9$ ($d = 950$ kpc). Taking the average of our distance estimate and Aparicio's, we obtain a value of

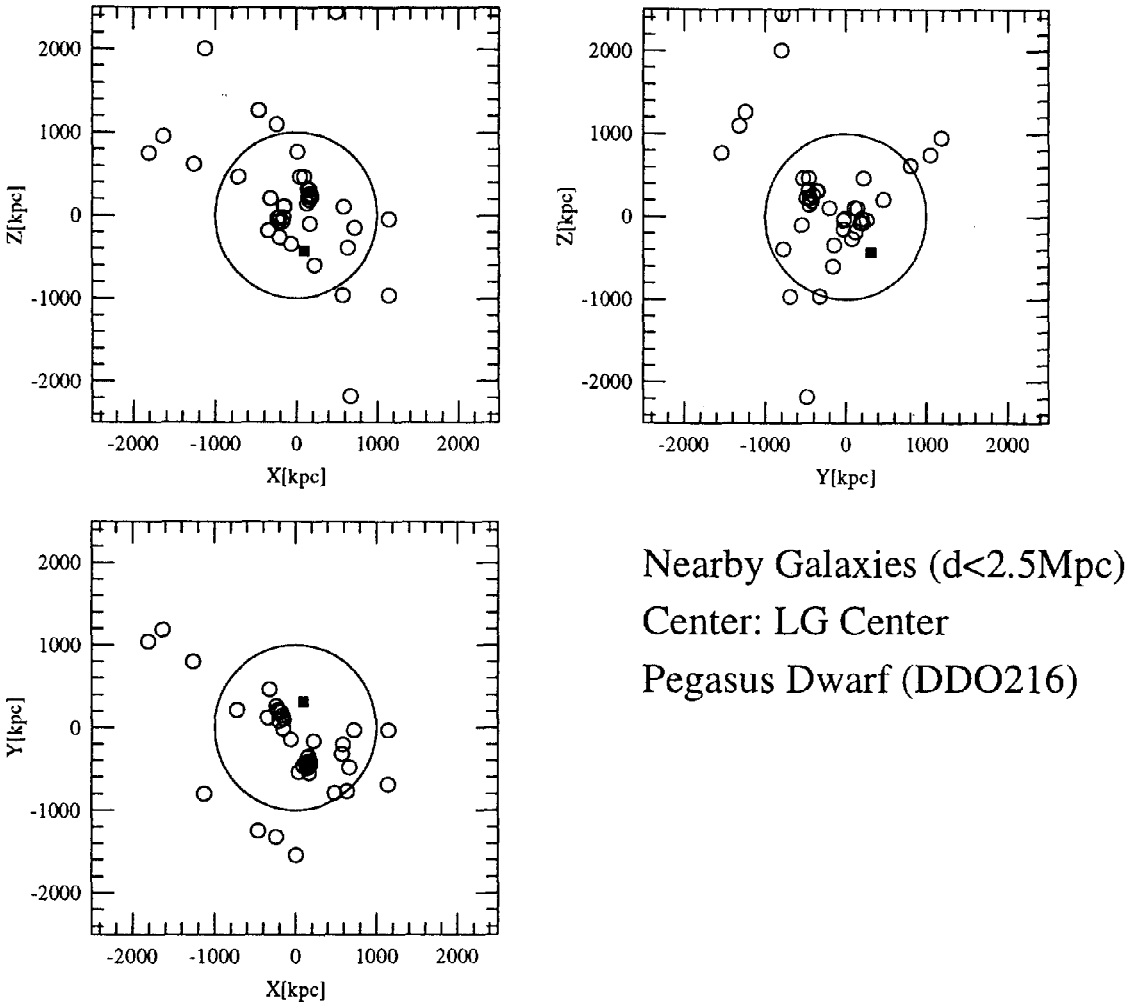

Fig. 2. Projection of the nearby galaxies closer than 2.5 Mpc onto the (X,Y), (Y,Z) and (X,Z) planes. The center is at the center of the Local Group. The direction X is toward the Galactic center, Y toward $l = 90°$. The filled square represents the Pegasus dwarf galaxy. The radius of the circle is 1 Mpc. The centers of the two strong concentrations are at the Milky Way Galaxy and M31.

$(m - M)_0 = 25.00 \pm 0.2$ ($d = 1000 \pm 80$ kpc).

However, our estimate is much smaller than the estimate given by Hoessel *et al.* (1990) who used a one-band photometry of Cepheids in the Pegasus dwarf: $(m - M)_0 = 26.22 \pm 0.20$ ($d = 1750 \pm 160$ kpc). This value is used often for the distance to the Pegasus dwarf galaxy in the literature, because the Cepheids are considered to be one of the most reliable distance indicators. In Figure 1 we have plotted the position of the Cepheid candidates studied by Hoessel *et al.* in order to figure out the large discrepancy between our distance estimate and Hoessel *et al.* (1990)'s. Figure 1 shows surprisingly that Hoessel *et al.* (1990)'s Cepheid candidates are not located in the Cepheid instability strip, but in the position of the upper part of the RGB. This result demonstrates the Cepheid candidates used for the distance estimate by Hoessel *et al.* (1990) are not Cepheids, but other kinds of variables. Therefore the distance estimate obtained using the period – luminosity relation of Cepheids by Hoessel *et al.* (1990) is meaningless.

IV. LOCAL GROUP MEMBERSHIP OF THE PEGASUS DWARF

We have obtained a very accurate distance to the Pegasus dwarf galaxy in the last section: d = 1000 ± 80 kpc. Here we investigate whether the Pegasus dwarf galaxy is a member of the Local Group or not, considering the distance and velocity of this galaxy. The heliocentric velocity of the Pegasus dwarf galaxy is known to be −183 km

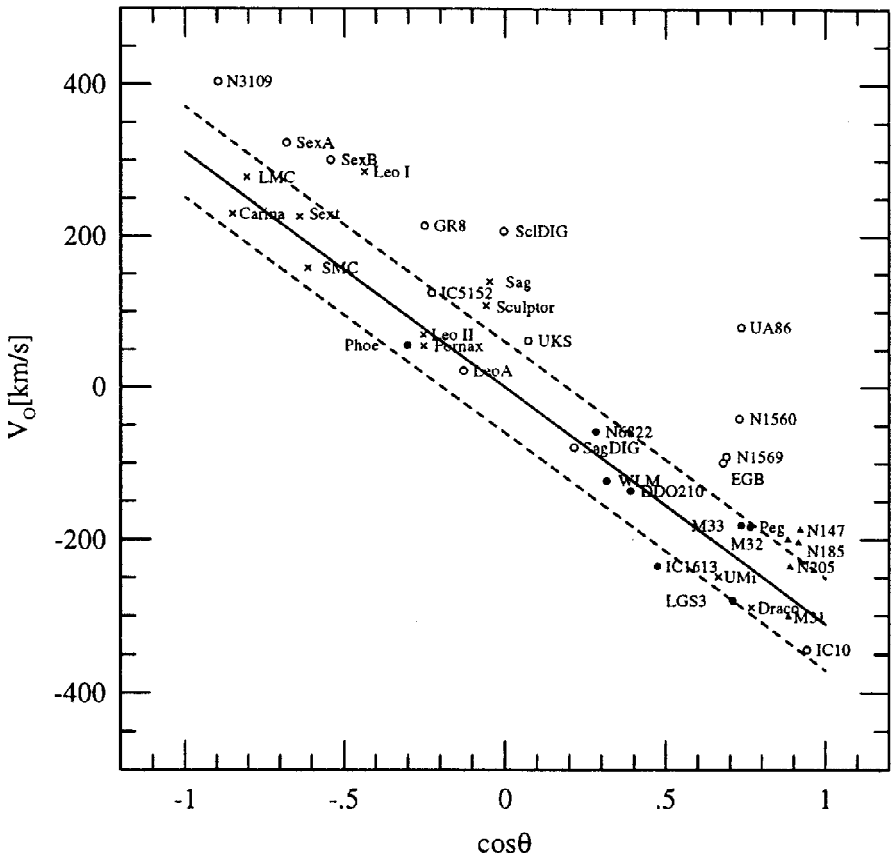

Fig. 3. Heliocentric velocity versus $cos\,\theta$ for nearby galaxies closer than 2.5 Mpc. θ presents an angle subtended between the center of the galaxy and the solar apex. The crosses represent the satellite galaxies of the Milky Way Galaxy, and the triangles represent the satellite galaxies of M31. The filled circles are certain Local Group members which are the satellites neither of the Milky Way Galaxy nor of M31. Local Group envelope lines (dashed lines) are ± 60 km s^{-1} from the center line with $v_\odot(\theta) = -311\,cos\,\theta$.

s^{-1} (Schmidt & Boller 1992).

We have compiled a list of nearby galaxies which are located closer than 2.5 Mpc in Table 1. In Table 1, $\cos\theta$ in the sixth column represents the cosine of the angle which subtends between the galaxies and the solar apex. We adopt the solar motion with respect to the Local Group members of 311 km s^{-1} toward the solar apex ($l = 99°.2$ and $b = -3°.4$) given by Richtler, Tammann & Huchtmeier (1987), which are similar to the values given by Yahil, Tammann & Sandage (1977) and Sandage (1986b). The eighth column v_{CLG} represents the velocity of the galaxies with respect to the center of the Local Group, and the tenth column d_{CLG} represents the distance to the galaxies from the center of the Local Group. The center of the Local Group is assumed to be at a position corresponding to two thirds (= according to the mass ratio of the Milky Way Galaxy and M31 of 0.5) of the distance between the Milky Way Galaxy and M31 in the line connecting the two galaxies. v_{CLG} is calculated using the equation given by Richtler *et al.* (1987): $v_{CLG} = -49.59 \cos l \cos b + 306.95 \sin l \cos b - 18.59 \sin b$.

Figure 2 displays the projection of the galaxies listed in Table 1 onto the (X,Y), (Y,Z) and (X,Z) planes where the (X,Y) plane is defined by the galactic plane. The center is at the center of the Local Group. The direction X is toward the Galactic center, Y toward $l = 90°$. The filled square represents the Pegasus dwarf galaxy. The centers of the two strong concentrations are at the Milky Way Galaxy and M31. The Pegasus dwarf galaxy is located only 539 kpc from the center of the Milky Way Galaxy. The geometrical position of the Pegasus dwarf galaxy in Figure 2 shows that it is probably a member of the Local Group.

Figure 3 illustrates the heliocentric velocity versus $\cos\theta$ for the galaxies in Table 1. The crosses represent the satellite galaxies of the Milky Way Galaxy, and the triangles represent the satellite galaxies of M31. The filled circles are certain Local Group members which are the satellites neither of the Milky Way Galaxy nor of M31.

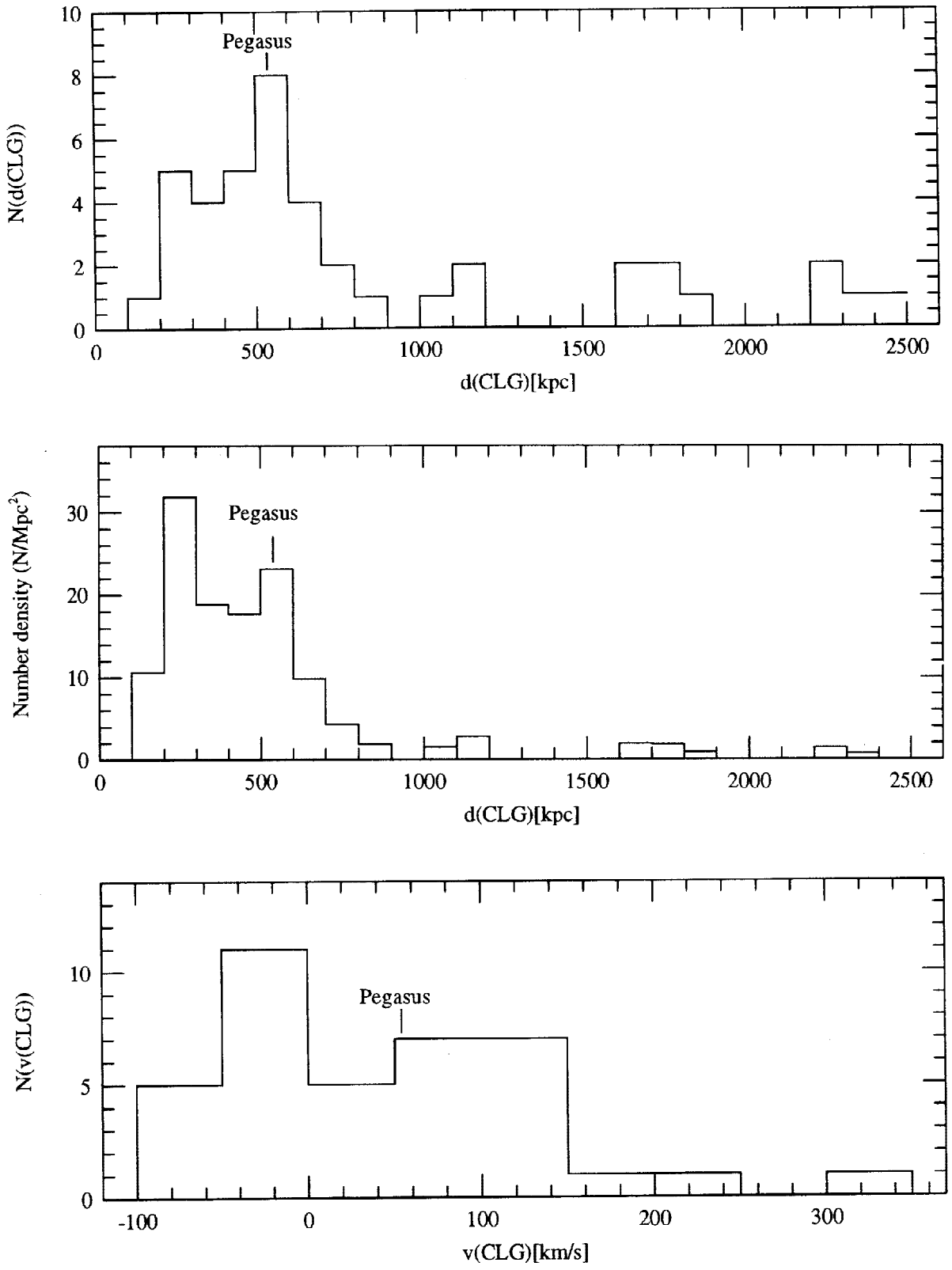

Fig. 4. (Upper panel) The number distribution of the distance with respect to the center of the Local Group for nearby galaxies. (Middle panel) The surface number density variation. (Bottom panel) The number distribution of the velocity with respect to the center of the Local Group.

Table 1. A list of nearby galaxies closer than 2.5 Mpc

Galaxy	α_{2000}	δ_{2000}	l	b	$\cos\theta$	$v_\odot$	v_{CLG}	d	d_{CLG}	M_V	Remark
MWG	17 45 37	−28 56 10	0.00	0.00	−0.160	—	−50	8	515	−20.6	
Sagittarius	18 54 55	−30 34 48	5.50	−14.10	−0.048	140	125	24	515	−13.0	
LMC	5 23 34	−69 45 5	280.46	−32.89	−0.806	278	27	50	535	−18.1	
Ursa Min	15 9 13	67 12 54	104.95	44.80	0.663	−249	−43	65	500	−8.9	
SMC	0 52 42	−72 49 40	302.80	−44.30	−0.613	158	−33	65	532	−16.2	
Draco	17 20 13	57 55 1	86.37	34.72	0.766	−289	−50	76	491	−8.5	
Sculptor	1 0 8	−33 42 21	287.54	−83.16	−0.059	108	90	78	485	−10.7	
Sextans	10 13 8	−1 35 52	243.50	42.30	−0.639	226	27	82	577	−10.0	
Carina	6 41 37	50 57 46	260.11	−22.22	−0.851	230	−35	89	560	−9.4	
Fornax	2 39 55	−34 31 30	237.29	−65.65	−0.252	55	−24	133	494	−13.7	
Leo II	11 13 28	22 9 3	220.17	67.23	−0.253	70	−9	217	662	−9.9	
Leo I	10 8 27	12 18 31	225.98	49.11	−0.436	285	149	270	712	−11.7	
M31	0 42 45	41 16 19	121.18	−21.57	0.883	−301	−26	770	293	−21.1	
And II	1 16 17	33 24 54	128.87	−29.17	0.786	—	—	580	158	−11.8	
NGC 185	0 38 57	48 20 23	120.79	−14.48	0.914	−204	81	620	211	−15.3	
NGC 147	0 33 12	48 30 41	119.82	−14.25	0.920	−187	100	660	237	−15.1	
M32	0 42 41	40 51 41	121.15	−21.98	0.881	−200	74	760	282	−16.4	
And III	0 35 16	36 30 28	119.31	−26.25	0.867	—	—	760	264	−10.3	
And I	0 45 42	38 0 28	121.69	−24.85	0.862	—	—	800	312	−11.8	
LGS 3	1 3 52	21 52 46	126.75	−40.90	0.708	−280	−60	810	347	−10.2	
NGC 205	0 40 23	41 41 3	120.72	−21.14	0.888	−236	40	830	350	−16.3	
M33	1 33 50	30 39 39	133.61	−31.33	0.734	−181	48	860	410	18.9	
Phoenix	1 51 2	−44 37 13	272.49	−68.82	−0.303	56	−38	390	583	−9.9	
NGC 6822	19 44 55	−14 47 57	25.34	−18.39	0.282	−58	30	500	634	−16.4	
IC 1613	1 4 54	2 7 56	129.79	−60.56	0.474	−235	−87	700	380	−14.9	
DDO 210	20 46 53	−12 51 0	34.05	−31.35	0.389	−136	−15	794	739	−11.5	
Tucana	22 41 49	−64 25 5	322.91	−47.37	−0.445	—	—	890	1078	−9.5	
WLM	0 1 58	−15 28 3	75.85	−73.63	0.315	−123	−25	900	661	−14.1	
IC 10	0 20 23	59 17 33	118.97	−3.34	0.941	−344	−51	1000	602	−17.4[a]	
Pegasus	23 28 34	14 44 40	94.77	−43.55	0.762	−183	54	1000	539	−12.51	
Sag DIG	19 29 58	−17 40 21	21.06	−16.28	0.214	−79	−12	1100	1148	−10.5[a]	
EGB 0427+63	4 32 2	63 36 30	144.71	10.51	0.677	−99	112	1100	884	−13.6	
NGC 3109	10 4 53	−25 40 20	262.09	23.70	−0.897	404	124	1250	1722	−16.25	
Sextans A	10 11 2	−4 42 32	246.17	39.87	−0.680	324	112	1300	1734	−14.37	
UKS2323-326	23 26 28	−32 23 30	11.87	-70.84	0.071	62	84	1300:	1170:	−10.4[a]	d:uncertain
Sextans B	9 59 59	5 19 48	233.20	43.78	−0.542	301	132	1450	1837	−14.71	
IC 5152	22 2 40	−51 17 47	343.92	−50.19	−0.227	125	54	1600	1651	−14.8[a]	
UGC-A86	59 48	67 7 41	139.77	10.64	0.734	80	309	1900	1616	−15.1[a]	
Leo A	9 59 22	30 44 50	196.90	52.41	−0.129	22	−18	2200	2434	−14.18	
GR 8	12 58 39	14 13 3	310.72	76.98	−0.249	214	136	2240	2617	−10.98	
Sculptor DIG	0 8 14	−34 34 35	351.48	−78.12	−0.005	207	206	2500	2335	−10.8[a]	
NGC 1560	04 32 50	71 52 52	138.37	16.02	0.728	-41	185	2500	2234	16.9	
NGC 1569	04 30 50	64 50 47	143.68	11.24	0.687	-91	123	2500:	2224:		d:uncertain

[a]: M_B, instead of M_V.

The envelopes of the Local Group are represented by the dashed lines at ± 60 km s^{-1} from the center line with $v_{\odot}(\theta) = -311$ km s^{-1} (Richtler *et al.* 1987; van den Bergh 1994). Figure 3 shows that the Pegasus dwarf galaxy is just inside the envelope of the Local Group.

We plot in Figure 4 the number distribution of the distance with respect to the center of the Local Group for the galaxies in Table 1 and the corresponding surface number density (=number of galaxies/Mpc^2) variation. We also include the number distribution of the velocity with respect to the center of the Local Group in Figure 4. The surface number density profile indicates that the boundary of the Local Group is at 800 – 900 kpc from the center of the Local Group. Figure 4 shows that the Pegasus dwarf galaxy is located in the main concentration of the Local Group members.

Considering both the distance and velocity of the Pegasus dwarf galaxy with respect to the center of the Local Group, we conclude that the Pegasus dwarf galaxy is probably a member of the Local Group.

V. SUMMARY AND CONCLUSION

We have obtained an accurate distance estimate for the Pegasus dwarf galaxy using the TRGB method: d = 1000 ± 80 kpc. Considering the distance and velocity of the Pegasus dwarf galaxy with respect to the center of the Local Group, we have shown that the Pegasus dwarf galaxy is probably a member of the Local Group.

ACKNOWLEDGEMENTS

The author thanks Sang Chul Kim and Eunhyeuk Kim for preparing Table 1. This study was supported in part by the KOSEF grant No. 941-0200-007-2.

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