

LEO I: THE YOUNGEST MILKY WAY DWARF SPHEROIDAL GALAXY?

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ABSTRACT

We have obtained deep CCD photometry of $\sim 16\,000$ stars in the Leo I dwarf spheroidal galaxy (dSph), the most distant known satellite of the Milky Way Galaxy. The resulting color-magnitude diagrams (CMDs) of Leo I reveal several striking features. (1) There is a well-defined red giant branch (RGB) which is very blue and has a flatter slope than all other dwarf dSphs and Galactic globular clusters. The tip of the RGB is at $I_{\text{TRGB}} = 18.25 \pm 0.10$ mag and $(V-I)_{\text{TRGB}} = 1.43 \pm 0.02$ mag. (2) Unlike all of the other known dSphs, Leo I has no obvious horizontal branch; however, it does show a strong clump of red giants at $V \approx 22.4$ mag and $(V-I) \approx 0.8$ mag. (3) The CMD of Leo I shows ~ 50 anomalous Cepheid candidates. (4) There are ~ 50 asymptotic giant branch stars above the tip of the RGB, including 15 known carbon stars. (5) A large number of stars is seen at $V \gtrsim 23$ mag ($M_V \gtrsim +1$ mag) and $0 < (V-I) < 1$ mag. The present data do not go sufficiently deep to determine conclusively the nature of these faint stars. However, despite increasing crowding effects, the number density of these stars increases from $V=23$ mag to $V=24$ mag, consistent with the presence of a young population of ~ 3 Gyr. From the I magnitude of the tip of the RGB we estimate the distance modulus of Leo I to be $(m-M)_0 = 22.18 \pm 0.11$ mag, corresponding to a distance of 270 ± 10 kpc for an adopted I -band extinction of 0.04 mag. We estimate the mean color of the RGB at $M_I = -3.5$ mag to be $(V-I)_{-3.5} = 1.29 \pm 0.02$ mag with an intrinsic dispersion of ± 0.07 mag. These results suggest that the mean metallicity of the RGB stars is $[\text{Fe}/\text{H}] = -2.0 \pm 0.1$ dex with a dispersion of ~ 0.3 dex. Applying timing arguments to the pair of our Galaxy and Leo I, we obtain an estimate for the mass of our Galaxy of $M = 1.7 \times 10^{12} M_\odot$ for an assumed age of the Universe of $t = 14$ Gyr.

1. INTRODUCTION

There are eight known dwarf spheroidal galaxies (dSphs) in the halo of the Milky Way Galaxy (Draco, Ursa Minor, Sculptor, Sextans, Carina, Fornax, Leo II, and Leo I). Color-magnitude diagrams (CMDs) reaching the main-sequence turnoff based on deep CCD photometry have been published for all of these galaxies except the Leo I dSph (Draco: Stetson *et al.* 1985, Carney & Seitzer 1986; Ursa Minor: Olszewski & Aaronson 1985; Carina: Mould & Aaronson 1983, Mighell 1990, Mateo & Nemec 1993; Leo II: Demers & Irwin 1992; Sextans: Mateo *et al.* 1991; Sculptor: Da Costa 1984; Fornax: Buonanno *et al.* 1985). These studies have revealed that significant intermediate-age populations (3–10 Gyr) are present in Fornax and Carina. In the other five dSphs, the stellar populations appear to be dominated by stars older than 10 Gyr. The giant branch in Leo I has been studied by Fox & Pritchett (1987) and Reid & Mould (1991), but the main-sequence turnoff has not been reached for this galaxy.

Leo I (DDO 74) is a dSph discovered by Harrington & Wilson (1950) during the course of the first Palomar sky survey. Basic information on Leo I is summarized in Table 1. It has been considered to be the most distant satellite galaxy bound to the Milky Way Galaxy (Hodge 1971; Zaritsky *et al.* 1989; Zaritsky 1991), and therefore accurate distance and velocity determinations are important for estimates of the mass of the Milky Way Galaxy using the timing argument (e.g., Kahn & Woltjer 1959; Zaritsky *et al.* 1989; Zaritsky 1991). In spite of its importance, there have been fewer studies of Leo I compared with other dSphs in the halo of our Galaxy because it is relatively distant and because it happens to be located inconveniently close to the very bright Galactic foreground star Regulus. Consequently, the distance and metallicity for Leo I are not well established (Fox & Pritchett 1987; Reid & Mould 1991).

In this paper we present a study of the stellar populations in the central (5.6×5.6) area of Leo I based on deep VI CCD photometry and shallower B CCD photometry, arguing that Leo I may be the youngest dSph among the known satellites of our Galaxy. A preliminary progress

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TABLE 1. Basic information for Leo I.

Parameter	Information	Reference
α_{1950}	$10^h 05^m 46^s.0$	Webbink 1985
δ_{1950}	$+12^\circ 33' 12''$	Webbink 1985
l, b	226.0, 49.1 deg	Webbink 1985
$v_\odot$	285 km s^{-1}	Zaritsky 1991
v_{GC}	177 km s^{-1}	Zaritsky 1991
$E(B - V)$ (Foreground)	0.02	Burstein & Heiles 1982
[Fe/H]	$-2.0 \pm 0.1 \text{ dex}$	This study
$(m - M)_0$	22.18 ± 0.11	This study
Distance	$270 \pm 10 \text{ kpc}$	This study
V_T	$10.2 \pm 0.1 \text{ mag}$	Caldwell <i>et al.</i> 1992
M_V^T	-12.0 mag	Caldwell <i>et al.</i> 1992
Central Surface Brightness, $S_V(0)$	$22.3 \pm 0.2 \text{ mag/arcsec}^2$	Caldwell <i>et al.</i> 1992
Core radius, r_c	$3'.3 \pm 0'.3$ (260 pc)	Irwin & Hatzidimitriou 1993
Tidal radius, r_t	$12'.6 \pm 0'.3$ (990 pc)	Irwin & Hatzidimitriou 1993
Ellipticity, e	0.21 ± 0.03	Irwin & Hatzidimitriou 1993
Position Angle, PA	$79 \pm 3 \text{ deg}$	Irwin & Hatzidimitriou 1993
N(carbon star)	19	Azzopardi <i>et al.</i> 1986

report of this study was given in Lee *et al.* (1992a). A companion study of variable stars in Leo I will be given elsewhere.

2. OBSERVATIONS AND DATA REDUCTIONS

2.1 Observations

CCD images of the Leo I dSph were obtained in two different observing runs in 1991. First, a set of *BVI* CCD data of the central area was obtained under photometric conditions on 1991 January 10 using the Tektronix (hereafter referred to as TEK) 1024×1024 pixel CCD camera on the du Pont 2.5 m telescope of the Las Campanas Observatory. Second, a series of *VI* CCD images of the central area were obtained on three photometric nights (1991

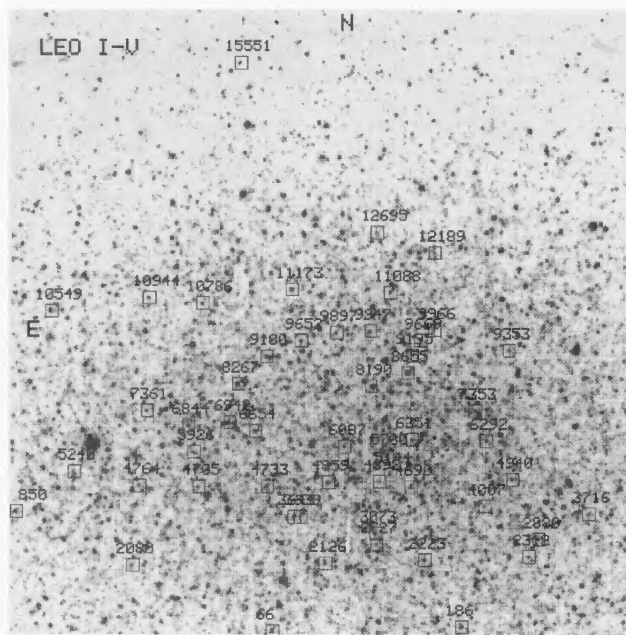
January 24–26) using the Ford 2048×2048 pixel CCD chip at the same telescope. The original pixel scales were $0.23''/\text{pixel}$ for the TEK CCD and $0.164''/\text{pixel}$ for the Ford CCD, giving field sizes of 3.9 and 5.6 arcmin, respectively. The Ford CCD images were obtained in a 2×2 pixel binning mode. The journal of observations of Leo I is given in Table 2. Greyscale maps of *V* and *I* Ford CCD images are shown in Fig. 1.

2.2 Data Reduction

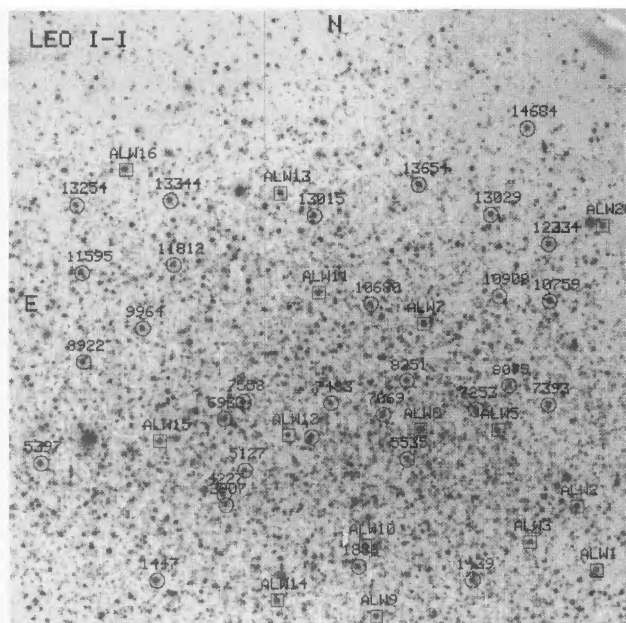
All of the Ford CCD frames from each night were combined to create three *V* and *I* pairs to compare each night's photometry. We then combined all of the Ford CCD frames of similar quality for each filter to create a *V* and *I*

TABLE 2. Journal of observations for Leo I.

Filters	T_{exp}	Air Mass	FWHM	U.T.(Start)	CCD
<i>B</i>	1203 sec	1.40	$1''.5$	1991 Jan 11 08:31	TEK
<i>V</i>	600 sec	1.35	$1''.5$	1991 Jan 11 07:55	TEK
<i>I</i>	400 sec	1.38	$1''.2$	1991 Jan 11 08:15	TEK
<i>V</i>	$28 \times 300 \text{ sec}$	1.35	$1''.3$	1991 Jan 25,26,27	Ford
<i>I</i>	$39 \times 300 \text{ sec}$	1.40	$1''.2$	1991 Jan 25,26,27	Ford



(a)



(b)

FIG. 1. (a) A V CCD image of Leo I. North is at the top and east is to the left. The size of the frame is 5.6×5.6 . Anomalous Cepheid candidates are labeled. (b) An I CCD image of Leo I. Carbon stars (squares) and noncarbon AGB stars (circles) are labeled.

pair, resulting in 28×300 s for the V frame and 39×300 s for the I frame. These master frames were used for the final photometry of stars in Leo I.

Instrumental magnitudes of stars in Leo I were obtained using the digital photometry reduction program DOPHOT (Schechter *et al.* 1993). The instrumental magnitudes were transformed onto the standard Kron-Cousins system using standards from Graham (1981) and Landolt (1983). Transformation equations for the TEK photometry are

$$V = v - 0.028(b - v) - 0.148X + \text{constant},$$

$$(B - V) = 1.254(b - v) - 0.041X + \text{constant},$$

$$I = i + 0.018(v - i) - 0.099X + \text{constant},$$

The color and extinction terms for the three independent sets of observations with the Ford CCD were averaged, and the adopted transformation equations are

$$V = v + 0.029(v - i) - 0.144X + \text{constant},$$

$$I = v + 0.033(v - i) - 0.094X + \text{constant},$$

where the lower-case symbols represent the instrumental magnitudes normalized to 1 s exposure times and the upper-case symbols represent the standard magnitudes.

Since we have VI photometry obtained on four independent photometric nights, we can check the external calibration error. The master VI Ford CCD photometry is calibrated using a median value of the three nights' photometry. A comparison between the final Ford CCD photometry and the TEK CCD photometry shows excellent agreement with mean differences of ΔV (Ford-TEK) = 0.012 mag and $\Delta(V - I)$ (Ford-TEK) = -0.009 for ~ 250 stars with $V < 21$ mag common to both datasets. This agreement between data taken on different nights and with different CCDs lends confidence to the precision of our photometric calibration. The total number of stars which were measured in at least two colors using the TEK CCD is ~ 2800 , while the total number of stars with VI photometry using the Ford CCD is $\sim 16\,000$. We listed the photometry of asymptotic giant branch stars in Table 3(a), and the photometry of anomalous Cepheid candidates in Table 3(b). The X and Y coordinates in Table 3 are given in units of CCD pixel (1 pixel = $0''.33$). The table for the photometry of all the measured stars is available from the authors upon request. Mean photometric errors for stars (formal errors from DOPHOT) are given in Table 4.

2.3 Comparisons with Previous Photometry

Fox & Pritchett (1987) published BV CCD photometry of 12 carbon stars in Leo I (their Table 3). We have compared our photometry of 10 stars in common with theirs, as shown in Fig. 2. The crosses in Fig. 2 represent the difference in V and $(B - V)$ between this study and that of Fox and Pritchett. Figure 2 illustrates that there is a significant systematic difference in the V magnitude between the two studies in the sense that magnitudes of Fox & Pritchett are fainter than ours by -0.60 ± 0.15 mag. The $(B - V)$ colors are in agreement with $\Delta(B - V) = -0.06 \pm 0.12$ mag, where Δ represents ours minus that of Fox and Pritchett. We have also compared our V magnitudes of four carbon stars (ALW 2, 3, 5, and 7) with those by Olszewski *et al.* (1984) quoted in Aaronson & Mould (1985), as plotted by open circles in Fig. 2. The mean difference between our photometry and theirs is $\Delta V = 0.30 \pm 0.36$ mag, where Δ represents ours minus theirs.

Soon after completing this study, we received information on new BV CCD photometry of Leo I from Demers (Demers & Irwin 1993). A comparison of the carbon stars in common between the two studies is plotted as filled

TABLE 3(a). Photometry of AGB stars in Leo I.

ID	X	Y	V	(V - I)	ID	X	Y	V	(V - I)
342	409.9	26.6	19.23	1.81	8075	196.7	401.9	19.04	1.55
824	571.6	53.5	18.93	1.77	8251	361.3	411.4	20.08	2.51
1439	253.7	85.9	19.36	1.68	8922	886.0	444.4	19.22	1.45
1447	767.1	86.4	19.46	1.71	9058	398.6	451.0	19.05	1.22
1752	54.2	101.3	19.63	1.80	9176	573.9	457.2	19.58	1.41
1886	439.8	108.0	19.25	1.32	9964	790.9	499.0	19.45	1.57
2534	428.6	141.7	19.55	1.87	10102	334.0	506.0	19.06	1.95
2621	161.2	146.3	20.05	2.31	10680	420.5	537.8	19.21	1.29
3809	85.7	204.1	19.45	2.03	10759	130.4	541.7	19.06	2.06
3907	655.6	208.3	19.38	1.37	10908	212.6	550.1	19.42	1.61
3989	110.2	212.5	19.69	1.51	10976	984.5	554.6	19.56	1.39
4052	447.4	215.8	19.60	1.42	11017	505.3	556.6	19.50	1.85
4227	659.3	224.8	19.22	1.47	11334	618.6	575.3	19.56	1.39
5127	624.3	265.4	20.06	2.14	11595	888.8	589.6	19.24	1.58
5397	954.5	277.2	19.39	1.70	11812	741.8	602.7	19.55	1.67
5535	360.6	282.5	19.12	1.32	12334	132.5	635.0	20.87	3.10
6130	762.9	312.5	19.35	2.02	12763	44.8	664.4	19.30	1.82
6281	516.3	318.6	19.02	1.60	13015	512.5	681.6	19.67	1.55
6523	214.5	329.2	19.48	2.07	13029	226.4	682.8	19.30	1.40
6553	338.6	331.0	19.22	2.08	13254	897.5	699.5	19.95	1.91
6933	659.2	349.0	19.81	2.59	13344	747.2	706.8	19.50	1.41
7069	399.4	355.2	19.40	1.42	13499	567.4	718.4	19.53	1.80
7253	249.8	363.4	19.35	1.60	13654	342.5	730.9	19.15	1.65
7393	132.4	370.0	20.66	2.99	13972	818.6	756.5	19.27	1.82
7483	485.2	374.3	19.29	1.40	14684	167.4	821.1	19.50	1.48
7483	485.2	374.3	19.29	1.40					

TABLE 3(b). Photometry of anomalous Cepheid candidates in Leo I.

ID	X	Y	V	(V - I)	ID	X	Y	V	(V - I)
66	583.3	11.5	20.27	0.54	6351	356.3	321.7	20.59	0.32
186	275.7	18.2	20.24	0.19	6654	612.0	336.0	20.34	0.36
2126	497.6	121.4	20.96	0.56	6844	721.9	344.9	20.61	0.24
2223	335.1	126.6	20.18	0.27	6942	653.8	349.4	20.80	0.52
2312	167.6	131.3	20.90	0.54	7353	255.6	368.1	20.81	0.23
2727	413.9	152.1	20.69	0.18	8190	423.9	408.3	21.08	0.45
2880	151.8	159.9	20.76	0.33	9180	594.1	457.2	20.80	0.41
3073	415.6	169.4	20.28	0.34	9195	356.5	457.9	21.13	0.57
3643	548.2	196.9	20.94	0.55	9652	536.8	482.2	20.47	0.60
3716	70.9	200.1	20.81	0.23	9669	343.1	483.2	20.78	0.32
3850	997.8	205.8	20.65	0.57	9897	480.9	495.6	21.12	0.28
4007	240.0	213.3	21.02	0.23	9947	425.2	498.0	20.70	0.21
4690	358.5	245.1	20.59	0.19	9966	321.4	499.0	20.99	0.35
4705	705.0	245.8	21.07	0.43	10549	941.9	531.2	20.64	0.34
4733	592.6	246.9	20.61	0.43	10786	699.0	543.5	20.75	0.21
4764	800.7	248.1	20.80	0.32	10944	785.0	552.7	20.93	0.29
4859	493.0	252.8	19.85	0.33	11088	392.3	561.0	20.90	0.55
4940	195.3	256.7	20.64	0.51	11173	552.2	565.8	20.18	0.09
5144	392.0	265.9	20.84	0.60	12189	320.6	625.8	21.06	0.51
5240	904.8	270.6	20.97	0.50	12695	414.5	659.3	21.16	0.41
5780	398.1	295.5	20.14	0.17	14679	895.4	820.0	21.14	-0.13
5926	713.7	302.2	20.87	0.26	15551	637.0	930.3	21.08	0.46
5926	713.7	302.2	20.87	0.26					

TABLE 4. Mean photometric errors for stars in Leo I.

V	σ_V	$\sigma_{(V-I)}$	I	σ_I	$\sigma_{(V-I)}$
19.25	0.004	0.005	18.25	0.004	0.006
19.75	0.005	0.006	18.75	0.004	0.007
20.25	0.007	0.008	19.25	0.006	0.009
20.75	0.009	0.012	19.75	0.008	0.013
21.25	0.012	0.017	20.25	0.012	0.017
21.75	0.018	0.027	20.75	0.017	0.025
22.25	0.028	0.041	21.25	0.025	0.038
22.75	0.042	0.067	21.75	0.037	0.056
23.25	0.068	0.120	22.25	0.062	0.089
23.75	0.102	0.176	22.75	0.097	0.131
24.25	0.150	0.238	23.25	0.146	0.188
24.75	0.214	0.304	23.75	0.216	0.264

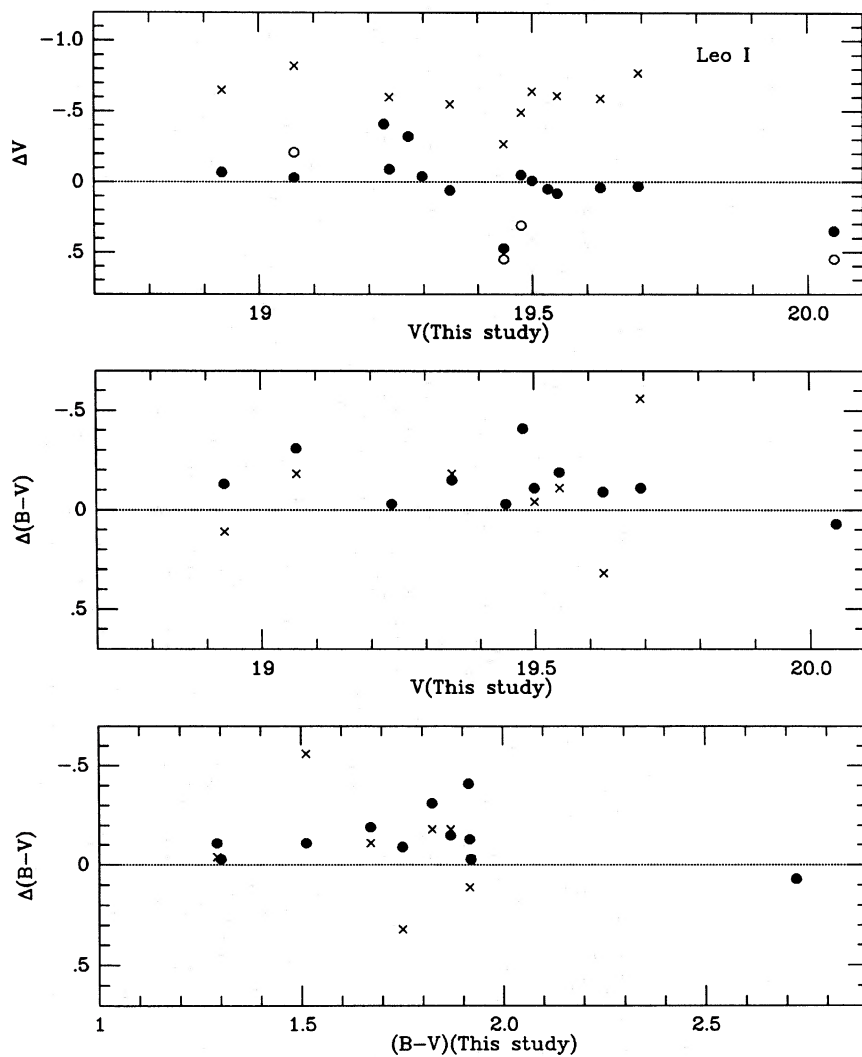
FIG. 2. Comparisons of our photometry with Fox & Pritchett (1987) (crosses), Olszewski *et al.* (1984) (open circles), and Demers & Irwin (1993) (filled circles).

TABLE 5. Mean VI locus for the giant branch of Leo I.

I	$(V-I)$	I	$(V-I)$
18.25	1.37	20.25	1.00
18.75	1.28	20.75	0.92
19.25	1.16	21.25	0.84
19.75	1.08	21.75	0.79

circles in Fig. 2, showing reasonably good agreement between the two sets of photometry. The mean differences in V and $(B-V)$ are $\Delta V = 0.00 \pm 0.06$ mag for 11 stars and $\Delta(B-V) = -0.09 \pm 0.08$ mag for 9 stars, where Δ represents ours minus theirs.

3. CMDS OF LEO I

3.1 General Morphology

We display $V-(V-I)$ and $I-(V-I)$ diagrams based on the Ford CCD photometry of $\sim 16\,000$ stars in Figs. 3(a) and 3(b), and a $V-(B-V)$ diagram based on the TEK CCD photometry of ~ 2800 stars in Fig. 3(c). The TEK CCD data are 2 mag shallower than the Ford CCD data, and cover a smaller section of Leo I. For this reason we used it only for the comparison of the zero point with previous photometry in the literature (see Sec. 2) and we will discuss the Ford CCD data only in the following. Since the galactic latitude of Leo I is relatively high ($b = 49^\circ$), the contamination by Galactic foreground stars in our CMDs is likely to be minor (see also Ratnatunga & Bahcall 1985). We adopt the foreground reddening for Leo I of $E(B-V) = 0.02$ mag, as given by Burstein & Heiles (1984).

The CMDs show several interesting features. These features are summarized here and discussed in more detail in Sec. 6 below.

RGB stars. Leo I has a well-defined red giant branch (RGB) extending to $I \sim 18.2$ mag and $(V-I) \sim 1.4$ mag. The mean locus of the RGB for $I = 17.25$ – 22.75 mag is derived using the median of the colors as a function of magnitude. This locus is listed in Table 5. The RGB of Leo I is very blue and its slope is flatter than all other dSphs and Galactic globular clusters.

Lack of horizontal branch. Surprisingly Leo I shows no suggestion of any horizontal branch (HB) typical of Galactic globular clusters or other dSphs. However, Leo I does show a strong clump of red giant stars at $V \approx 22.4$ mag and $(V-I) \approx 0.8$ mag. Similar red giant clump stars are observed in the CMDs of Galactic open clusters with ages of a few Gyr and in the general fields in the Magellanic Clouds. However, Leo I appears to be the most metal-poor among these.

AGB stars. There are ~ 50 asymptotic giant branch (AGB) stars located above the tip of the RGB (TRGB) in the $I-(V-I)$ diagram. These include the 15 known carbon stars which will be described in detail later in this section.

Possible anomalous Cepheids. There is a group of 45 stars at $21.2 < V < 19$ mag and $0 < (V-I) < 0.6$ mag [see Table 4(b)]. As shown in Fig. 1(a), these stars are located

mostly in the central area of Leo I. This feature is not clearly seen in the published CMDs of other dSphs in the halo of our Galaxy. Our preliminary study for variability shows that a significant fraction of these stars are variables,

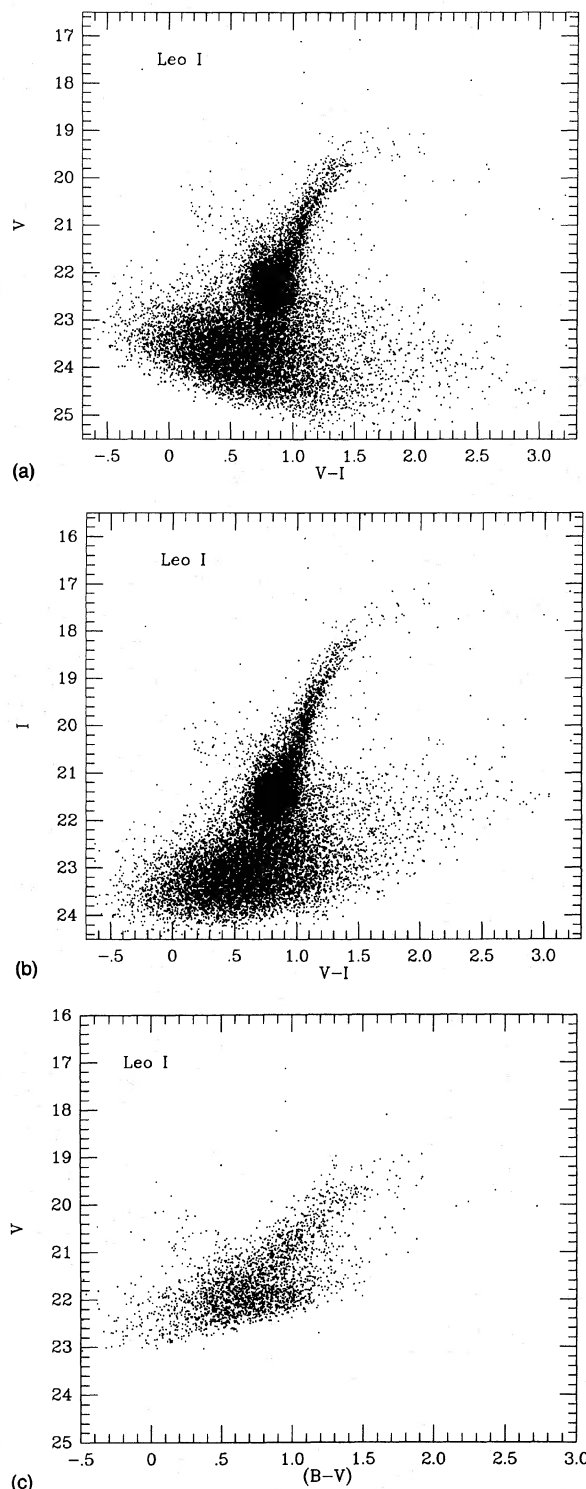


FIG. 3. CMDs for Leo I. (a) $V-(V-I)$ diagram for $\sim 16\,000$ stars. (b) $I-(V-I)$ diagram for $\sim 16\,000$ stars. (c) $V-(B-V)$ diagram for ~ 2800 stars.

TABLE 6. Photometry of carbon stars in Leo I.

ALW	ID	V	σ_V	$(V-I)$	$\sigma_{(V-I)}$	$(B-V)$	$\sigma_{(B-V)}$	M_{bol}
ALW1	1752	19.619	0.005	1.805	0.006	1.750	0.041	-3.86
ALW2	3809	19.443	0.005	2.030	0.006	1.920	0.034	-4.30
ALW3	2621	20.045	0.005	2.305	0.006	2.724	0.101	-4.03
ALW5	6523	19.476	0.005	2.070	0.005	1.914	0.029	-4.31
ALW7	10102	19.059	0.003	1.948	0.004	1.823	0.020	-4.57
ALW8	6553	19.238	0.009	2.084	0.010	1.301	0.023	-4.70
ALW9	342	19.222	0.004	1.811	0.005	—	—	-4.27
ALW10	2534	19.540	0.006	1.867	0.007	1.671	0.031	-4.01
ALW11	11017	19.494	0.004	1.849	0.005	1.292	0.022	-4.04
ALW12	6359	19.685	0.006	1.430	0.007	1.512	0.026	-3.40
ALW13	13499	19.523	0.005	1.804	0.006	—	—	-3.96
ALW14	824	18.926	0.003	1.772	0.004	1.917	0.022	-4.52
ALW15	6130	19.345	0.004	2.022	0.005	1.869	0.031	-4.39
ALW16	13972	19.267	0.004	1.819	0.006	—	—	-4.23
ALW20	12763	19.292	0.005	1.822	0.006	—	—	-4.21

and we propose that these stars are anomalous Cepheid candidates. This interpretation is supported by the fact that the two anomalous Cepheids listed in Hodge & Wright (1978), V17 [our ID:66, $V=20.27$ mag and $(V-I)=0.54$ mag] and V23 [our ID:5144, $V=20.84$ mag and $(V-I)=0.54$ mag], are included in this group. The position of these stars in the CMD of Leo I and the large number of stars in the galaxy may provide clues for investigating the origin of anomalous Cepheids (see Nemec *et al.* 1988; Nemec 1989).

Possible main-sequence stars. A large number of stars with $0 < (V-I) < 1$ mag is seen at $V \gtrsim 23$ mag, ~ 0.5 mag below the position of the red giant clump. These stars may be main-sequence turnoff stars.

3.2 Carbon Stars

Previous surveys for carbon stars in Leo I found 18 carbon stars and one further additional candidate (Aaronson *et al.* 1983; Aaronson & Mould 1985; Azzopardi *et al.* 1985, 1986). We have identified 15 known carbon stars in our CCD field [see Fig. 1(b) for the identification of these stars]. Four carbon stars (ALW 4, 6, 17, and 19) are outside the boundary of our CCD field. The photometry of the carbon stars in our CCD field is listed in Table 6. Bolometric magnitudes for these carbon stars are derived using a formula for the bolometric correction to the V and I magnitudes given by Bessell & Wood (1984), and listed in Table 6. A distance modulus of $(m-M)_0=22.18$ was assumed (see Sec. 4 below).

Figure 4 displays the $V-(V-I)$, $I-(V-I)$, $V-(B-V)$, and $M_{\text{bol}}-(V-I)_0$ diagrams for the known carbon stars (Azzopardi *et al.* 1985, 1986) as well as the noncarbon AGB stars listed in Table 3(a). Figure 4 shows several features of note. (1) There is a sharp blue boundary between the carbon stars and the noncarbon AGB stars at $(V-I) \approx 1.7$ mag. (2) Most of the carbon stars are concentrated in the area of $1.8 < (V-I) < 2.1$ mag and $17.1 < I < 17.8$ mag. (3) There are 7 noncarbon AGB stars and 14 carbon stars redward of $(V-I)=1.7$ mag. (4) One carbon star (ALW 12) is fainter and much bluer than the

majority of the other carbon stars, and it is located very close to the position of the TRGB [$I=18.22$ mag and $(V-I)=1.38$ mag]. It is 0.41 mag bluer and 0.45 mag fainter than the second faintest carbon star (ALW 1). (5) The bolometric magnitudes of carbon stars in Leo I range from $M_{\text{bol}} = -3.4$ to -4.6 mag.

Carbon stars are in general divided into three classes: (a) the normal carbon stars in the AGB stage, (b) the blue and low-luminosity carbon stars discovered in the Galactic bulge, and (c) dwarf carbon stars (Azzopardi & Lequeux 1992; Green 1992). Azzopardi & Lequeux (1992) state that in their survey for carbon stars in dSphs they have not found any carbon stars of the second class described above; however, our photometry of ALW 12 suggests that it may belong to the second class of carbon stars.

4. DISTANCE

Lee *et al.* (1993a) showed recently that the I magnitude of the TRGB is an excellent distance indicator for resolved galaxies with metal-poor populations ($[\text{Fe}/\text{H}] < -0.7$ dex) older than a few Gyr, with an accuracy comparable to that of RR Lyraes and Cepheids. The I magnitude of the TRGB is estimated using the $I-(V-I)$ diagram and the stellar luminosity functions. Figure 5 shows the I and V luminosity functions from the Ford CCD data, and these are listed in Table 7. These data show that there is a sudden discontinuity at $I=18.25 \pm 0.10$ mag and $V=19.65 \pm 0.10$ mag, corresponding to the TRGB. The median value for the color of the TRGB is estimated to be $(V-I)_{\text{TRGB}}=1.43 \pm 0.02$ mag for 19 RGB stars with $18.2 < I < 18.3$ mag [see Fig. 3(b)]. The bolometric magnitude of the TRGB is calculated from $M_{\text{bol}} = -0.19[\text{Fe}/\text{H}] - 3.81$ (Da Costa & Armandroff 1990). Adopting a mean metallicity of $[\text{Fe}/\text{H}] = -2.0 \pm 0.1$ dex as estimated in the next section, we obtain a value for the bolometric magnitude of $M_{\text{bol}} = -3.43$ mag. The bolometric correction at I for the TRGB is estimated to be $\text{BC}_I = 0.54$ mag, adopting $\text{BC}_I = 0.881 - 0.243(V-I)_{\text{TRGB}}$ (Da Costa & Armandroff 1990). The intrinsic I

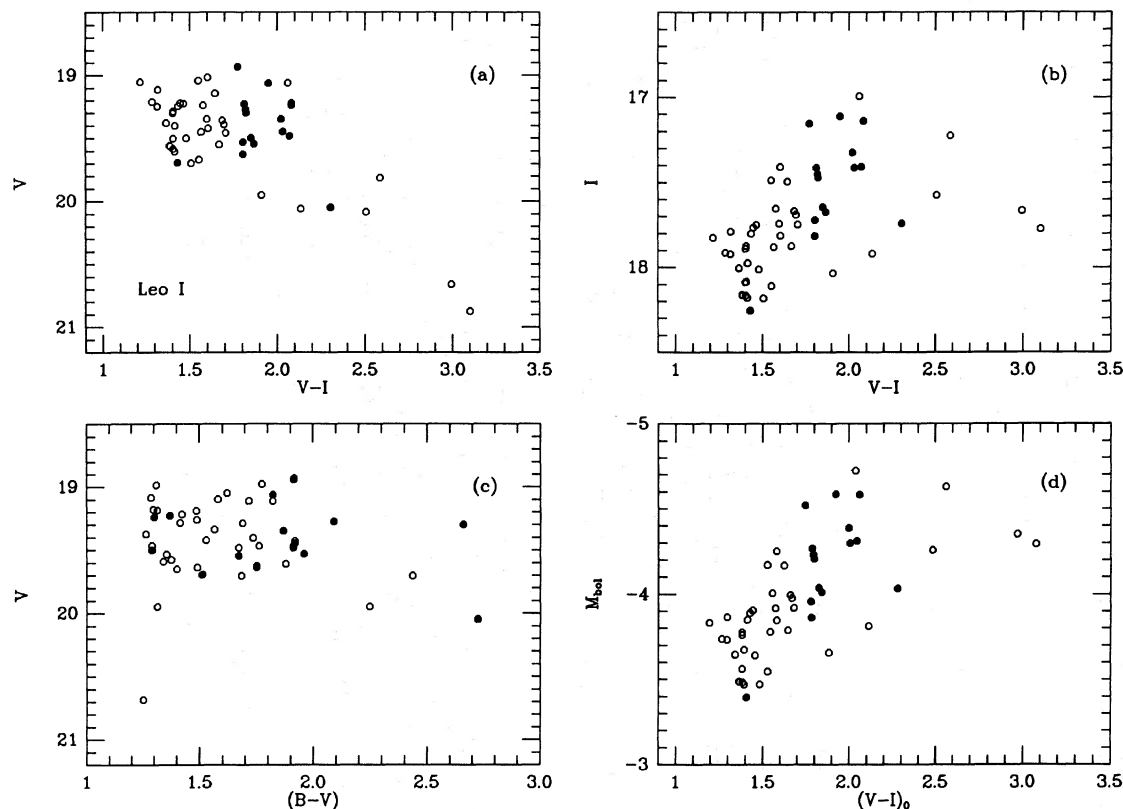


FIG. 4. CMDs for AGB stars in Leo I. Filled circles represent carbon stars and open circles represent noncarbon AGB stars. (a) $V-(V-I)$ diagram. (b) $I-(V-I)$ diagram. (c) $V-(B-V)$ diagram. (d) $M_{\text{bol}}-(V-I)_0$ diagram.

magnitude of the TRGB is then given by $M_I = M_{\text{bol}} - BC_I = -3.97$ mag.

Finally the apparent I distance modulus to Leo I is obtained: $(m-M)_I = 18.25 - (-3.97) = 22.22$ mag. Note that the estimate is almost insensitive to the change in the adopted metallicity of the range of $-2.2 < [\text{Fe}/\text{H}] < -0.7$ dex (Da Costa & Armandroff 1990; Lee *et al.* 1993a). Adopting a foreground extinction of $A_I = 0.04$ mag, we obtain a value for the intrinsic distance modulus of $(m-M)_0 = 22.18 \pm 0.11$ mag, corresponding to a distance of 270 ± 10 kpc.

There have been two recent estimates for the distance to Leo I based on CCD photometry: Fox & Pritchett (1987) and Reid & Mould (1991). Fox & Pritchett (1987) gave a distance estimate of $(m-M)_0 = 21.8 \pm 0.2$ mag which is based on the TRGB and their nondetection of the HB in their $V-(B-V)$ CMD.

Reid & Mould (1991) presented Gunn ri photometry of a $2' \times 2'$ central field in Leo I, measuring the TRGB to be at $I = 17.8$ mag and $(R-I) = 0.8$ mag. They derived from this a distance modulus of 21.85 ± 0.15 mag, adopting a metallicity of $[\text{Fe}/\text{H}] = -1.0$ dex. Their estimate for the I magnitude of the TRGB is 0.45 mag brighter than ours. The agreement between our measurement of the distance modulus and the values from Fox and Pritchett and Reid and Mould is poor, and the reason for the discrepancy is unknown. We prefer our value because of greater depth of

our observations and the excellent agreement between our four independent photometric calibrations.

5. METALLICITY

We have estimated the mean metallicity and metallicity dispersion of the RGB stars in Leo I using the $(V-I)$ colors at $M_I = -3.5$ mag (~ 0.5 mag fainter than the TRGB) (see Da Costa & Armandroff 1990; Lee 1993; Lee *et al.* 1993a). The 44 stars with $18.6 < I < 18.8$ mag and $(V-I) > 0.8$ mag, have a mean $(V-I)_{-3.5} = 1.29 \pm 0.02$ mag [$(V-I)_{0,-3.5} = 1.27$ mag assuming a reddening of $E(V-I) = 0.02$] and $\Delta(V-I)_{-3.5} = 0.08$ mag. Using the calibration based on the RGB colors of Galactic globular clusters (Da Costa & Armandroff 1990; Lee *et al.* 1993a), we obtain a value for the mean metallicity of $[\text{Fe}/\text{H}] = -2.02 \pm 0.10$ dex.

A dispersion of the observed color of the RGB stars can be caused by sources such as photometric errors, an intrinsic metallicity dispersion, and perhaps an age spread. The contribution from an age spread to the $(V-I)$ color in the $I-(V-I)$ diagram is expected to be much smaller than a contribution from the metallicity dispersion (Da Costa & Armandroff 1990). For example, the $(V-I)$ color at $M_I = -3.5$ is only 0.03 mag bluer for an age of 3.5 Gyr than for an age of 15 Gyr, according to the Revised Yale Isochrones (Green *et al.* 1987). If the RGB stars in the

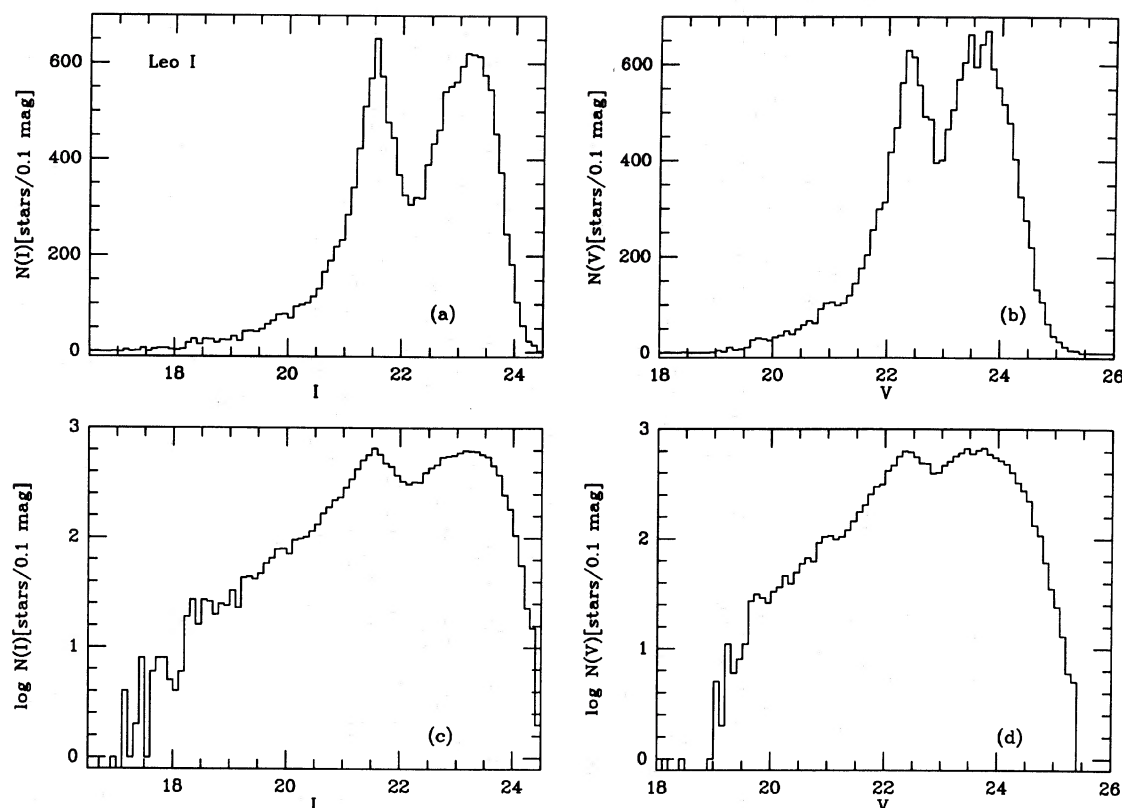


FIG. 5. Luminosity functions for the stars in Leo I. (a) V luminosity function. (b) I luminosity function. (c) Logarithmic V luminosity function. (d) Logarithmic I luminosity function. The TRGB is seen at $I_{\text{TRGB}} = 18.25$ mag and $V_{\text{TRGB}} = 19.65$ mag.

Leo I are as young as 3.5 Gyr, the mean metallicity will be increased slightly from the previous estimate of $[\text{Fe}/\text{H}] = -2.0$ dex to $[\text{Fe}/\text{H}] = -1.9$ dex. The mean photometric error of $(V-I)$ for $I = 18.7$ mag is $\sigma_{(V-I)} = 0.02$ mag. Then the intrinsic dispersion of the color is $\Delta(V-I)_{-3.5} = \sqrt{0.08^2 - 0.03^2 - 0.02^2} = 0.07$ mag, indicating a metallicity dispersion of $-2.3 < [\text{Fe}/\text{H}] < -1.8$ dex.

Previous estimates for the mean metallicity of the stars in Leo I vary from $[\text{Fe}/\text{H}] = -1.0$ to -1.9 dex. Aaronson & Mould (1985) used JHK photometry of eight giant stars in Leo I to estimate the metallicity of the stars. They derived $[\text{Fe}/\text{H}] = -1.85$ dex from $(J-K)$ colors of the RGB at $M_K = -5.5$ mag and $[\text{Fe}/\text{H}] = -1.45$ dex from $(V-K)$ colors in comparison with the Galactic globular clusters. However, all of the stars they used in Leo I are brighter at K than the brightest point (the TRGB) of any of the Galactic globular clusters in their sample. Therefore their estimates for the metallicity of Leo I are based on an extrapolation of the mean colors of the RGB at $M_K = -5.5$ mag. Suntzeff *et al.* (1986) obtained moderate resolution spectra of two red giants in Leo I and three giants in Leo II. From the calcium and magnesium line strengths they derived that the mean metallicities are $[\text{Fe}/\text{H}] = -1.5 \pm 0.25$ dex for Leo I and -1.9 ± 0.2 dex for Leo II. However, their estimate for the mean metallicity for Leo I may be in error

for the following reasons. First, the number of stars used for Leo I is too small to derive a reliable mean metallicity. Second, a later analysis of the same data showed that the metallicity of Leo I is $[\text{Fe}/\text{H}] \approx -1.8$ dex (Suntzeff 1992). Fox & Pritchett (1987) suggested from the $(B-V)$ color of the RGB of Leo I that the mean metallicity is $[\text{Fe}/\text{H}] = -1.4$ dex and that the dispersion in metallicity is as large as ~ 1 dex. Finally Reid & Mould (1991) used Gunn ri photometry of the RGB stars in Leo I to estimate the mean metallicity of the galaxy. From a comparison of the $(r-i)$ color of the relatively narrow RGB of Leo I with the Revised Yale isochrones (Green *et al.* 1987), they derived a mean metallicity of $[\text{Fe}/\text{H}] = -1.0$ dex and a metallicity dispersion of $\lesssim 0.3$ dex, much smaller than the dispersion claimed by Fox & Pritchett (1987). Their estimate for the mean metallicity is higher by ~ 1 dex than ours, while their estimate for the metallicity dispersion is the same as ours. The significant difference for the mean metallicity is not clearly understood. However, we believe that our estimate of the metallicity is to be preferred, because it is based on a firm calibration of photometry (see Sec. 2.2), and on a metallicity-color relation of stars with similar luminosities in well-observed Galactic globular clusters.

TABLE 7(a). I luminosity function for stars in Leo I.

I	$N(I)$	I	$N(I)$
16.95	1	20.45	115
17.05	0	20.55	132
17.15	4	20.65	167
17.25	1	20.75	190
17.35	2	20.85	219
17.45	8	20.95	233
17.55	1	21.05	285
17.65	6	21.15	342
17.75	8	21.25	423
17.85	8	21.35	510
17.95	5	21.45	570
18.05	4	21.55	652
18.15	6	21.65	573
18.25	19	21.75	478
18.35	27	21.85	446
18.45	16	21.95	369
18.55	27	22.05	326
18.65	26	22.15	307
18.75	20	22.25	322
18.85	25	22.35	320
18.95	24	22.45	390
19.05	33	22.55	434
19.15	23	22.65	462
19.25	43	22.75	542
19.35	44	22.85	553
19.45	42	22.95	562
19.55	47	23.05	595
19.65	58	23.15	622
19.75	65	23.25	619
19.85	78	23.35	615
19.95	79	23.45	576
20.05	71	23.55	547
20.15	95	23.65	454
20.25	98	23.75	373
20.35	102	23.85	246

6. DISCUSSION

6.1 Stellar Populations in Leo I

6.1.1 Leo I: the youngest Milky Way dSph?

A large number of stars with $V > 23$ and $(V-I) < 1$ are seen in the CMD of Leo I in Fig. 3. While the stars observed at $V > 23$ mag are near to the limit of the photometry and thus subject to large photometric uncertainty, we argue that these stars are main-sequence (MS) turnoff stars including subgiant branch stars for two reasons: a reversal in the luminosity function at $V \approx 23$ mag and an asymmetric distribution of stars in the CMD. First, in Fig. 5 the stellar luminosity functions show a bright peak at $V \approx 22.4$, a local minimum at $V \approx 23$ mag, and then a fainter second peak at $V \approx 23.5$ mag. The bright peak is largely made of red giant clump stars. The increase after the local minimum is consistent with a contribution by MS stars, where the subsequent fall-off is due to the incompleteness of our photometry at the faint end. Second, if the observed distribution were due to errors in photometry, then a symmetric distribution would be expected about the subgiant branch. The expected mean color of the subgiant branch is $(V-I) \approx 0.85$ mag, based on the mean color of the red giant clump. We listed in Table 8 the number density of stars with $21 < V < 24$ mag in the $V-(V-I)$ CMD.

TABLE 7(b). (b) V luminosity function for stars in Leo I.

V	$N(V)$	V	$N(V)$
18.95	1	21.75	256
19.05	5	21.85	299
19.15	2	21.95	313
19.25	11	22.05	418
19.35	6	22.15	469
19.45	8	22.25	562
19.55	11	22.35	630
19.65	27	22.45	616
19.75	31	22.55	558
19.85	29	22.65	492
19.95	26	22.75	486
20.05	33	22.85	396
20.15	36	22.95	401
20.25	46	23.05	466
20.35	39	23.15	507
20.45	49	23.25	570
20.55	59	23.35	605
20.65	67	23.45	663
20.75	62	23.55	596
20.85	92	23.65	643
20.95	104	23.75	671
21.05	106	23.85	592
21.15	99	23.95	553
21.25	104	24.05	518
21.35	120	24.15	479
21.45	145	24.25	404
21.55	176	24.35	325
21.65	204	24.45	276

Table 8 shows that ~ 3 times more stars are observed with $(V-I) < 0.85$ mag than for $(V-I) > 0.85$ mag for $23 < V < 24$ mag. And, given the limit of the V photometry in this table, one could expect more, rather than fewer, stars with $(V-I) > 0.85$ mag, if the distribution were due to errors alone.

Figure 7 shows a $V-(V-I)$ CMD together with the Revised Yale theoretical isochrones for a metallicity of $[\text{Fe}/\text{H}] = -2.0$ dex and a helium abundance of $Y = 0.23$ (Green *et al.* 1987). The solid lines represent isochrones for ages of 0, 0.2, 0.5, 1, 2, 4, 8, and 15 Gyr. The isochrones shown in Fig. 7 are consistent with the stars with $V \geq 23$ mag ($M_V \gtrsim +1$ mag) being MS turnoff stars with ages of ~ 3 Gyr. These stars may be the progenitors of the carbon stars seen above the TRGB and of the anomalous Cepheids.

Similar MS populations are seen in the Carina and Fornax dSphs, but at fainter absolute magnitudes. In the Carina dSph MS stars are visible at $M_V \gtrsim +2.5$ mag (Mould & Aaronson 1983; Mighell 1990; Mateo & Nemec 1993), while in Fornax they are detected at $M_V \gtrsim +2$ mag (Buonanno Metal 1985). It is known that the MS populations seen in the CMDs for the other dSphs in the halo of the Milky Way Galaxy are older than 10 Gyr; therefore the faint stars in Leo I, if they belong to a MS population, appear to be the youngest among these dSphs.

6.1.2 RGB, red giant clump, and HB

In Figs. 6 and 7, the RGB of Leo I is compared with the RGBs of the Galactic globular clusters M15 and M2,

TABLE 8. Number density of stars in the $V-(V-I)$ diagram.

$V, (V-I)$	-0.4	-0.2	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
20.1	0	0	1	2	0	1	1	3	36	20	2	0	0
20.3	0	0	0	1	2	2	0	8	67	4	0	0	0
20.5	0	0	0	2	1	1	2	23	76	0	2	0	1
20.7	0	0	0	4	4	3	6	56	53	1	0	0	0
20.9	0	0	0	4	3	9	15	114	47	2	1	0	0
21.1	0	1	0	2	4	13	26	140	18	0	1	0	0
21.3	0	0	0	0	1	15	50	137	18	3	0	0	0
21.5	0	0	0	1	2	27	106	169	12	1	3	0	0
21.7	1	0	1	1	9	44	191	204	8	0	0	0	0
21.9	1	1	0	5	8	80	295	206	13	0	1	0	0
22.1	2	2	3	9	20	132	513	190	10	1	2	2	0
22.3	5	4	10	12	25	152	728	232	12	8	1	0	2
22.5	3	6	9	18	34	159	634	259	33	10	3	1	0
22.7	7	19	37	53	57	156	407	169	40	9	8	6	2
22.9	7	23	39	78	101	116	241	130	36	9	12	2	2
23.1	12	30	60	123	160	169	211	121	40	19	8	5	4
23.3	12	43	99	165	212	231	219	113	33	19	14	6	1
23.5	11	38	99	163	247	257	206	141	41	14	12	7	6
23.7	1	23	94	172	258	288	213	133	57	15	11	10	7
23.9	0	4	33	135	239	245	188	125	58	28	23	6	6

and Revised Yale Isochrones (RYI) for a range of ages, respectively. The metallicities of M15 and M2 are $[\text{Fe}/\text{H}] = -2.17$ and -1.58 dex, respectively (Da Costa & Armandroff 1990). The empirical loci for the RGB of M15, M2, and the RYI were shifted according to the reddening and distance modulus of Leo I determined in this study, and are shown together with the Leo I observations in Figs. 6 and 7. The upper part of the RGB of Leo I is slightly redder than that of M15. However, the lower part of the RGB of Leo I is undoubtedly bluer than that of M15. We performed artificial star experiments in order to check whether this is a real feature or due to photometric errors. We added 2000 artificial stars with $17 < V < 22$ mag and $0.5 < (V-I) < 1.5$ mag to five VI pairs of original CCD images and followed the same procedures used to obtain the stellar photometry from the original CCD images using DOPHOT. The results from the experiments indicate that the photometric errors in magnitudes and colors are negligible in this magnitude range. And given the excellent agreement in the independent photometry obtained using the Ford and TEK CCDs, we conclude that the flatter RGB of Leo I compared with that of M15 is real.

Leo I is the first among the dSphs to exhibit a CMD showing a strong red giant clump, and it appears to be the most metal-poor stellar system yet seen with a strong red giant clump. The FWHMs of the magnitude of the stars are $\Delta V = 1.1$ mag and $\Delta I = 0.9$ mag (see Fig. 5). The corresponding absolute magnitudes are $M_V \approx 0.2$ mag and $M_I \approx -0.6$ mag. The $(V-I)$ color distribution of the red

giant clump stars with $21.1 < I < 22.0$ mag and $2.18 < V < 22.9$ mag is derived and plotted in Fig. 8. The FWHM of the color is ~ 0.3 mag. The magnitudes of RR Lyraes expected for Leo I are $M_V = 0.47$ mag and $V \approx 22.7$ mag, adopting the metallicity-luminosity relation of RR Lyraes $M_V = 0.17[\text{Fe}/\text{H}] + 0.82$ given by Lee *et al.* (1990) (see also Walker 1992, and Lee *et al.* 1993a). Therefore the mean magnitude of the red giant clump in Leo I is ~ 0.3 mag brighter than the expected magnitudes of RR Lyraes. This estimate for the difference between the magnitudes of the red giant clump and the RR Lyraes is not affected by the uncertainty in the zero point of the metallicity-luminosity relation, because we used the same metallicity-luminosity relation in deriving the distance estimate for Leo I. The expected position of RR Lyraes in Leo I is shown approximately in Fig. 6(a). There is no distinguishable HB around the expected position of RR Lyraes. Instead the stars are uniformly scattered over the area below the expected position of the HB. These stars are likely mostly MS turnoff stars of a few Gyr, as discussed in the previous section. The isochrones plotted in Fig. 7 do not reach the subgiant and RGB stages, but indicate that the red giant clump may be a few Gyr old, which is consistent with the observed position of the apparent MS population. The young age but low metallicity might explain the unprecedented behavior of the red giant clump: namely why it is so closely attached to the RGB in the CMD, why it is a few tenths of magnitude brighter than the expected HB, and why it is so spread out in luminosity. These features exhibited by Leo I have neither been seen in the CMDs of

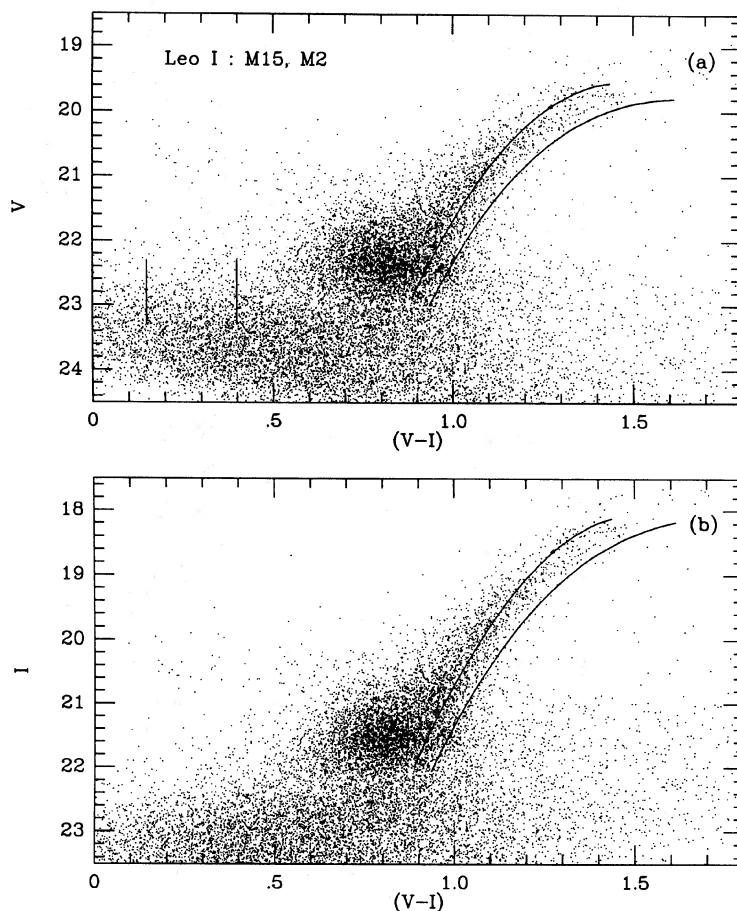


FIG. 6. CMDs for stars in Leo I in comparison with Galactic globular clusters. The solid curved lines show from left to right the loci for the giant branches of Galactic globular clusters, M15 and M2, the metallicities of which are $[\text{Fe}/\text{H}] = -2.17$ and -1.58 dex. (a) $V-(V-I)$ diagram. The expected position of RR Lyrae is marked by two parallel vertical solid lines. (b) $I-(V-I)$ diagram.

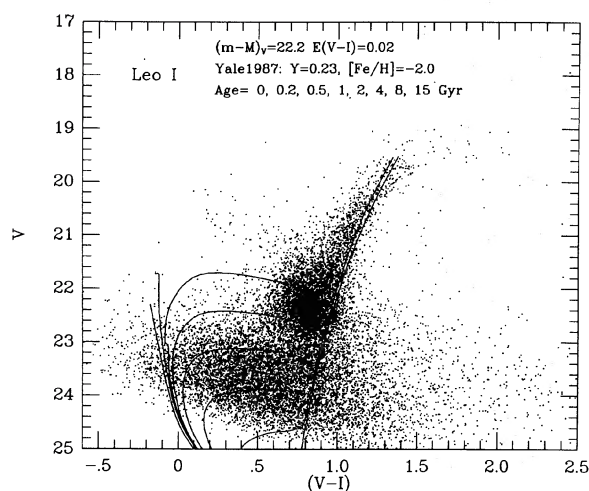
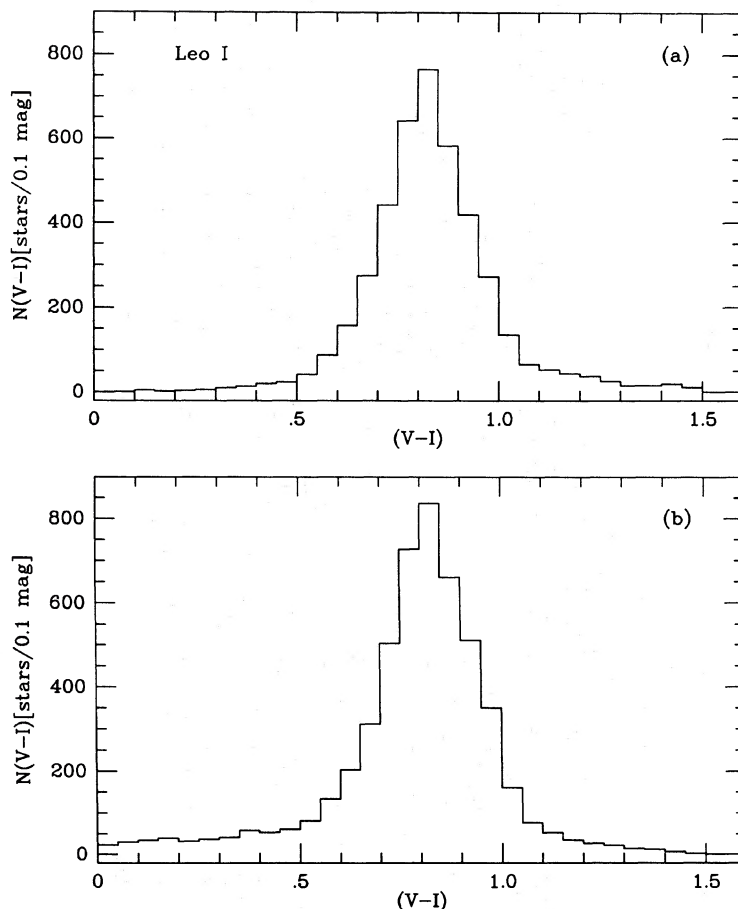


FIG. 7. $V-(V-I)$ diagram for Leo I with Revised Yale theoretical isochrones. Isochrones for $[\text{Fe}/\text{H}] = -2.0$ dex and ages of 0, 0.2, 0.5, 1, 2, 4, 8, and 15 Gyr are plotted by solid lines.

any other clusters and nearby galaxies nor been explored by stellar evolution theory. Considering the prominent red giant clump and the large concentration of MS stars, a significant fraction—perhaps most—of the stellar population in Leo I appears to be only a few Gyr old. Deeper photometry is required to verify the presence of this intermediate-age population by obtaining data of the MS for $V \gtrsim 24$ mag.

6.2 The Mass of Our Galaxy

Accurate determinations of the velocity and distance of Leo I are important for estimates of the mass of our Galaxy using timing arguments (Sandage 1986; Zaritsky *et al.* 1989; Zaritsky 1991; Fich & Tremaine 1991). Zaritsky *et al.* (1989) and Zaritsky (1991) measured velocities of six carbon stars in Leo I, obtaining 285 km s^{-1} for the heliocentric velocity and 177 km s^{-1} for the galactocentric velocity. Adopting a value of 230 kpc for the distance of Leo I, they derived a mass of our Galaxy, $1.3 \times 10^{12} M_{\odot}$ for an assumed age of the Universe of 14 Gyr. We have rederived the mass of our Galaxy following Zaritsky

FIG. 8. $(V-I)$ color distribution of red giant clump stars in Leo I.

(1991), adopting our new estimate for the distance to Leo I. For a distance of 270 kpc, we obtain a mass of our Galaxy of $1.7 \times 10^{12} M_{\odot}$, for an assumed age of the Universe of 14 Gyr.

6.3 The Metallicity and Luminosity Relation of Dwarf Galaxies

The strength of the correlation between metallicity and luminosity in dSphs and elliptical galaxies is controversial (Mould *et al.* 1983, Buonanno *et al.* 1985; Aaronson & Mould 1985; Zinn 1985; Smith 1985; Da Costa 1988; Caldwell *et al.* 1992). Caldwell *et al.* (1992) have presented the most recent collection of data for dSphs and elliptical galaxies in the Local Group (NGC 205, NGC 147, And I, and seven dSphs). They showed that the metallicity–luminosity relation for dSphs has much more scatter than originally thought, but the scatter is not significantly different than that for the classical ellipticals. In this section we reexamine this relation using the more recent data for dSphs and elliptical galaxies, as listed in Table 9.

We have added three galaxies (NGC 185, Carina, and Phoenix) into the sample used by Caldwell *et al.* (1992). The metallicity for NGC 185 is from Lee *et al.* (1992b, 1993b) using the $(V-I)$ color of the RGB. The metallic-

ity for Carina is taken from Armandroff & Da Costa (1991) and the V total luminosity and the V central surface brightness for Carina are from Mateo *et al.* (1993). The metallicity and the V total luminosity for Phoenix are from van de Rydt *et al.* (1991) using the color of the RGB. Note that Caldwell *et al.* (1992) adopted $[\text{Fe}/\text{H}] = -1.30$ dex for Leo I, following the results given by Suntzeff *et al.* (1986). Fox & Pritchett (1987) and Reid & Mould (1991), while we adopt our estimate of $[\text{Fe}/\text{H}] = -2.0 \pm 0.1$ dex.

The metallicities for all 13 dwarf galaxies are plotted against absolute V magnitude in Fig. 9(a), and against V central surface brightness $[S_V(0)]$ in Fig. 9(b). From Fig. 9 it is seen that the presence of Carina and Leo I weakens the correlation between $[\text{Fe}/\text{H}]$ and M_V [and between $[\text{Fe}/\text{H}]$ and $S_V(0)$] for dSphs ($M_V > -14$ mag), confirming the conclusion given by Caldwell *et al.* (1992). If we apply a linear regression to the sample of all 13 galaxies, we obtain $[\text{Fe}/\text{H}] = -3.23 (\pm 0.28) - 0.13 (\pm 0.02) M_V$ with a standard deviation $\sigma[\text{Fe}/\text{H}] = 0.22$ dex and a linear correlation coefficient $r = -0.86$. Similarly we obtain, for the $[\text{Fe}/\text{H}]$ and $S_V(0)$ relation, $[\text{Fe}/\text{H}] = -2.21 (\pm 1.20) - 0.16 (\pm 0.05) S_V(0)$ with a standard deviation $\sigma[\text{Fe}/\text{H}] = 0.31$ dex and a linear correlation coefficient $r = -0.71$. Leo I and Carina show the largest deviation

TABLE 9. Properties of local group dwarf galaxies.

Galaxy	[Fe/H]	M_V	S_V (mag arcsec $^{-2}$)	N(C)	$\log N(C) + M_V/2.5$
Draco	-2.1	-8.5	25.2	4	-2.80
Ursa Minor	-2.2	-8.9	25.1	1	-3.56
Carina	-1.52	-9.4	25.2	11	-2.72
Leo II	-1.90	-9.9	24.0	7	-3.11
Pheonix	-1.90	-9.9	—	—	—
Sextans	-2.05	-10.0	25.5	0	—
Sculptor	-1.80	-10.7	24.1	8	-3.38
Leo I	-2.0	-12.0	22.3	19	-3.52
Fornax	-1.40	-13.7	23.2	77	-3.59
And III	—	-10.2	25.3	6	—
And I	-1.40	-11.7	24.9	—	—
And II	—	-11.7	24.8	—	-3.30
NGC 147	-1.20	-15.1	21.6	—	—
NGC 185	-1.29	-15.4	20.9	—	—
NGC 205	-0.85	-16.3	20.2	—	—
SMC	-1.0	-16.88	—	3100	-3.26
LMC	-0.6	-18.36	—	11000	-3.30

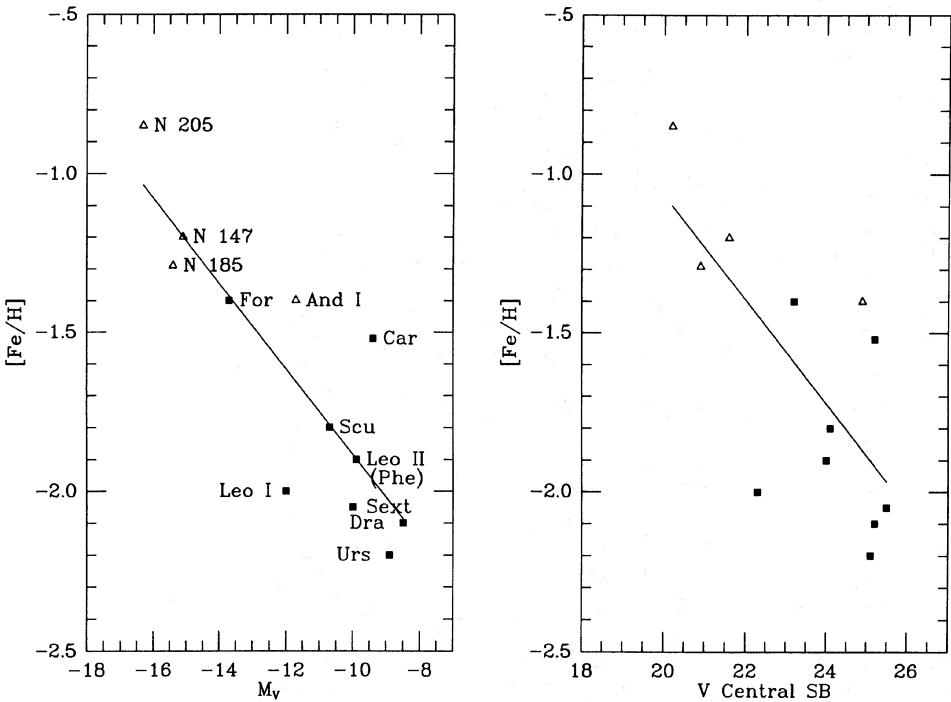


FIG. 9. Left panel: [Fe/H] vs M_V for dwarf ellipticals and spheroidals. Right panel: [Fe/H] vs V central surface brightness. Note that Leo I and Carina show a significant deviation from the main linear fit line.

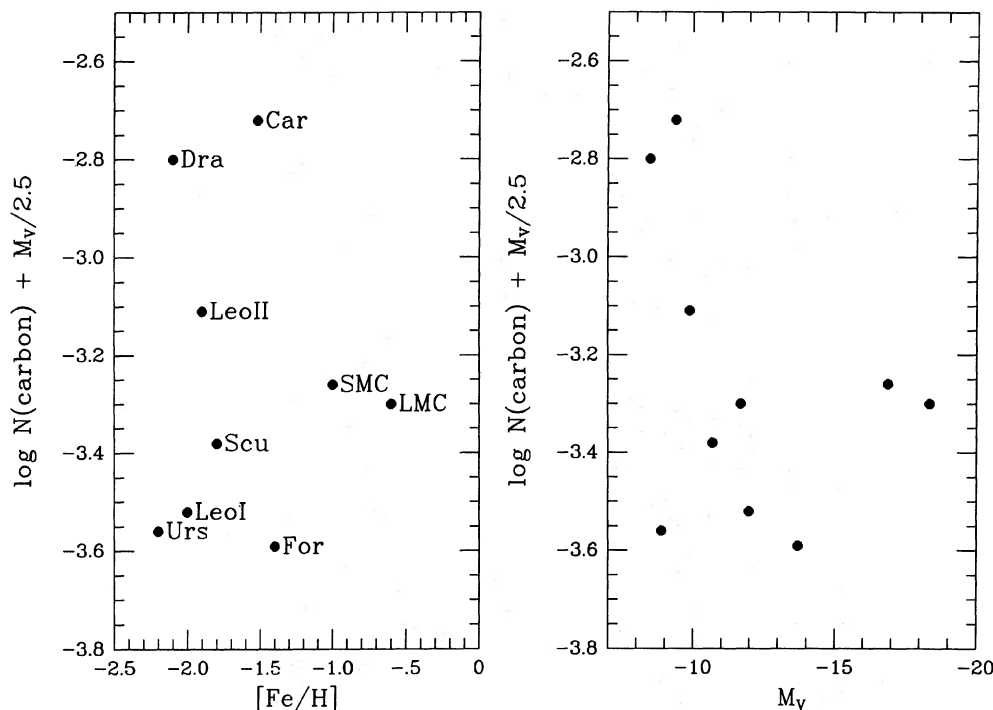


FIG. 10. Left panel: The number of carbon stars per unit V luminosity vs metallicity for dwarf galaxies in the Local Group. Right panel: The number of carbon stars per unit V luminosity vs absolute V total magnitude of parent galaxies.

from the fit line. Finally, if we limit the sample of the dSphs to those fainter than $M_V = -14$ mag (9 objects), we obtain a much smaller correlation coefficient $r = -0.60$ for the metallicity and luminosity relation.

6.4 Carbon Stars in Dwarf Galaxies

It has been suggested by Richer & Westerlund (1983), Azzopardi *et al.* (1985), and Azzopardi & Lequeux (1992) that there is some correlation between the number of carbon stars per unit luminosity and both the absolute luminosity and the metallicity of the parent galaxy (see also Aaronson 1986). Their sample consists of our Galaxy, the LMC, SMC, and eight dSphs. We examine these correlations with updated data for the metallicity and absolute V luminosity for dwarf galaxies in the Local Group, as listed in Table 9. We used the data for the carbon stars in the dSphs given by Azzopardi & Lequeux (1992). Figure 10 shows that there is little correlation between the number of carbon stars per unit luminosity and $[\text{Fe}/\text{H}]$ or M_V , in contrast to previous suggestions.

7. SUMMARY AND CONCLUSIONS

The primary results obtained in this study are summarized as follows.

(1) VI CMDs of $\sim 16,000$ stars in the $5.6' \times 5.6'$ central area of Leo I have been presented. These CMDs exhibit: (a) a well-developed RGB; (b) ~ 50 AGB above the TRGB including 15 known carbon stars; (c) no distinguishable HB although a prominent clump of red giants is

apparent at $V \approx 22.4$ mag and $(V-I) \approx 0.8$ mag; (d) ~ 50 anomalous Cepheid candidates; and (e) possible MS turn-off stars at $M_V \approx +1$ mag, which, if confirmed, would indicate the presence of a population with an age of ~ 3 Gyr.

(2) The tip of the RGB of low mass stars is found to be at $I = 18.25 \pm 0.1$ mag and $(V-I) = 1.43 \pm 0.02$ mag. From the I magnitude of the TRGB, we derive a distance modulus to Leo I of $(m-M)_0 = 22.18 \pm 0.11$ mag for an adopted extinction of $A_I = 0.04$ mag, corresponding to a distance of 270 ± 10 kpc.

(3) The mean color of the RGB at $M_I = -3.5$ mag is $(V-I)_{-3.5} = 1.29 \pm 0.02$ mag with an intrinsic dispersion of 0.08 mag. From these values we obtain a mean metallicity of $[\text{Fe}/\text{H}] = -2.0 \pm 0.1$ dex with a dispersion of ~ 0.3 dex.

(4) Applying timing arguments to the pair of Leo I and our Galaxy with our new estimate of the distance to Leo I results in a mass for our Galaxy of $M_G = 1.7 \times 10^{12} M_\odot$.

The presence of a substantial population of the MS turn-off stars with ages of ~ 3 Gyr would make Leo I the youngest amongst dSphs in the halo of the Milky Way Galaxy. While it is very difficult to detail exactly how Leo I could have formed a significant fraction of its stars as recently as ~ 3 Gyr ago, the resolution of this problem has obvious important implications for evolutionary studies of dwarf galaxies, and may provide a key in understanding the systematics of deep galaxy counts (e.g., Koo & Kron 1992).

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