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Deep CCD photometry of the dwarf spheroidal galaxy Leo I

Serge Demers,[1]★ M. J. Irwin[2]★ and Isabelle Gambu[3]

[1] *Département de Physique and Observatoire du Mont Mégantic, Université de Montréal, Montréal H3C 3J7, Canada*
[2] *Royal Greenwich Observatory, Madingley Road, Cambridge CB3 0EZ*
[3] *Département de Physique, Université de Montréal, Montréal H3C 3J7, Canada*

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ABSTRACT

We present *B*, *V* photometry of Leo I obtained with the Lick 2048 × 2048 CCD installed at the prime focus of the CFHT. The colour–magnitude diagram to $V = 22.2$ shows a wide giant branch and a red clump indicative of the presence of an intermediate-age population. Our observations do not detect any 'blue' horizontal branch. The apparent magnitudes of the red clump and of the carbon stars lead to a distance estimate of 205 ± 25 kpc for Leo I. We deduce, from the mean colour and the width of the giant branch, a value of [Fe/H] = − 1.6 and an upper limit in abundance dispersion of 0.25 dex. *V* magnitudes and $B - V$ colours of the known carbon stars are given, and two additional carbon star candidates are identified. The Hodge & Wright variables are located, and a short list of magnitudes and colours is presented.

Key words: Hertzsprung–Russell (HR) diagram – galaxies: individual: Leo I – Local Group – galaxies: photometry – galaxies: stellar content.

1 INTRODUCTION

The dwarf spheroidal galaxies Leo I and Leo II were discovered by Harrington & Wilson (1950) during the course of the original Palomar sky survey. At apparent distances of ~ 200 kpc, they were catalogued as the most distant satellites of the Milky Way. Because of the difficulty of working with objects at these distances, very few studies of their stellar populations have been published. Indeed, Leo I is actually more seriously handicapped than Leo II for study, because it is located only 20 arcmin north of the very bright 1st-magnitude foreground star Regulus, and also because it is a more densely populated galaxy. This peculiar position conspired to make the earlier photographic investigations extremely difficult. However, with the advent of CCD arrays, the reflected light of Regulus became much easier to handle, and this has led to a revival of interest in this object.

However, in spite of this, there is still little published work on Leo I. A variable star survey was carried out by Hodge & Wright (1978), who showed that Leo I contains an unusual number of anomalous Cepheids, implying the presence of a substantial intermediate-age population. Their observations barely reach the RR Lyrae variables. Colour–magnitude diagrams (CMDs) of Leo I have been published by Fox & Pritchet (1987), Reid & Mould (1991) and more recently by Lee et al. (1993). Somewhat conflicting results concerning the distance and range of abundances of Leo I emerge from these investigations.

Our original goal for this project was to produce a CMD reaching the horizontal branch, in order to establish more securely the distance of Leo I. Without the knowledge of the authors, Lee et al. (1993) had already achieved this aim with more appropriate data than we were able to collect during our two nights of observations.

Given the uncertainties surrounding the distance to Leo I and its pivotal role in determining the mass of our Galaxy, to which it is probably bound (e.g. Zaritsky et al. 1989), we feel that independent estimates of its distance, metallicity and star formation history are vitally important. Furthermore, our data were taken in the *B* and *V* passbands (cf. *V* and *I* of Lee et al. 1993), and the CCD frame covers a larger area than that of Lee et al. (1993). We also obtained data for Leo II (Demers & Irwin 1993, hereafter DI93) concurrently with Leo I, and were therefore able to use the Leo II data to help interpret the properties of Leo I.

Details of the observations and data reduction are given in the next section; in Section 3, we present luminosity functions and CMDs for Leo I, and investigate the properties of the known carbon and variable stars in this galaxy. In Sections 4 and 5, we present a discussion of the distance to Leo I and the age/metallicity properties of Leo I.

2 OBSERVATIONS

The photometric data presented here were obtained at the prime focus of the Canada–France–Hawaii 3.6-m telescope

★Visiting Observers, Canada–France–Hawaii Telescope, operated by the National Research Council of Canada, le Centre National de la Recherche Scientifique de France and the University of Hawaii.

(CFHT), using FOCAM during two consecutive nights in 1992 March. The observing conditions for both nights were excellent, with seeing averaging 0.7 arcsec and photometric conditions prevailing throughout. The Ford 2048 × 2048 thick, front-illuminated, blue coated CCD chip was used as the detector. In this configuration, the pixel size is 0.206 arcsec, thus providing a field of view on the sky of 7 × 7 arcmin^2. Standard CFHT *B* and *V* filters were used, corresponding to Johnson *B* and *V*. Sky flats were obtained from the twilight sky on both nights, and proved to be more than adequate in mapping the CCD pixel sensitivity variations to better than 1 per cent.

The data analysis was done at the Université de Montréal, using IRAF version 2.10 and the DAOPHOT package within it. Standard procedures for trimming, bias-correcting, flat-fielding, etc., were performed before using DAOPHOT. Since we used a thick CCD in the blue and visual part of the spectrum, no corrections for atmospheric fringing effects were necessary. The journal of the Leo I observations discussed in this paper is presented in Table 1. By co-adding the relevant frames, total effective integration times of ~7800 s in *B* and ~3800 s in *V* were obtained. The relative proportion of *B* to *V* exposure times was chosen to enable a similar depth to be reached in each passband. The quantum efficiency of the chip is 5 per cent at 400 μm, and 45 per cent at 600 μm. This explains the somewhat shallower limiting magnitudes ($V \sim 23$; $B \sim 23$) than we had originally hoped to obtain.

The exposure times of the first night may appear unusual. They were caused by a minor problem in the CCD control software, which meant that the true exposure time was some fixed fraction of the selected exposure time. This was noted and rectified during the next day, so that exposure times on the second night were as expected. Because the error was deterministic, it was straightforward to derive the correct exposure times for the first night and take full advantage of the photometric conditions.

2.1 Standard stars

Each night, we observed three or four fields of standard stars at several air-masses ranging from 1.0 to 1.5. They were selected from the new list of Landolt (1992). We had close to 40 reference stars, chosen to provide a $B-V$ range from −0.15 to 2.2, each night. Details of the analysis and data reduction, as well as the coefficients used, can be found in DI93.

Table 1. Journal of observations.

Julian date 2 448 000.0+	filter	exposure (sec)	FWHM ″	airmass
707.795	B	998	0.9	1.502
707.810	B	998	0.9	1.029
707.825	V	499	0.8	1.047
707.835	V	499	0.8	1.010
707.918	V	499	0.8	1.127
707.928	V	499	0.8	1.165
707.943	B	998	0.9	1.231
708.758	V	600	0.7	1.143
708.769	V	600	0.8	1.108
708.772	B	1200	0.9	1.073
708.782	B	1200	0.9	1.039
708.950	B	1200	1.2	1.294
708.967	B	1200	1.3	1.414
708.981	V	600	1.1	1.537

3 RESULTS

3.1 Luminosity function and colour–magnitude diagram

The *B*- and *V*-band luminosity functions (LFs) for Leo I are shown in Fig. 1 and, for comparison, the *B*- and *V*-band LFs for Leo II are also given. Completeness corrections, shown as dashed histograms for the *V*-band functions, were calculated by placing additional stars of known magnitude in the data frames and seeing what proportion were recovered using DAOPHOT. We give, in Table 2, the percentages of stars recovered as a function of the apparent *V* and *B* magnitudes for Leo I. As is immediately obvious, the LFs for the two galaxies are dissimilar. The reasons for the dissimilarity are readily apparent on examination of the respective CMDs. The expected number of foreground stars in our 7 × 7 arcmin^2 field is quite negligible. Ratnatunga & Bahcall (1985) estimated that in the direction of Leo I there is 0.8 star per square arcmin in the visual magnitude interval 19 to 23.

The *B*, *V* colour–magnitude diagram from Leo I is presented in Fig. 2, which can be compared with the Leo II CMD in DI93. For Leo I, we have included all 4200 stars for which both *B* and *V* magnitudes are available. The sample of stars was limited to stars with colour errors smaller than 0.10; the errors on the instrumental magnitudes were computed by DAOPHOT. The error bars, on Fig. 2, take into account the zero-point errors of the magnitude and colour, which are respectively 0.02 and 0.03 mag. Stars identified in the first pass by DAOFIND were removed, and the field was searched for fainter stars. Over 1000 fainter stars could be added to the diagram, but they do not bring more information to the CMD and just produce a huge scatter at the faint magnitudes. We have limited, as in the case of Leo II, our photometry to stars found in the first execution of DAOFIND.

Unlike Leo II, the Leo I CDM shows no evidence of a ‘blue’ horizontal branch, suggesting that it does not have a predominant old stellar population. This result is not surprising in the light of the recent results of Lee et al. (1993), who have shown that Leo I has no obvious horizontal branch and claim that its distance, derived by locating the tip of the red giant branch, is 270 ± 30 kpc, corresponding to a true modulus of $(m-M)_0 = 22.17 \pm 0.15$.

We interpret the excess of stars apparent in the *V*-band LF at $V \sim 22$ as a red giant clump similar to the one found in the intermediate-age population components of the Magellanic Clouds and the Fornax dwarf spheroidal (Demers, Irwin & Kunkel, in preparation). The appearance of this clump, combined with the lack of a significant horizontal branch in the Lee et al. (1993) data, suggests that the dominant stellar population in Leo I is only a few billion years old. The stars at around $V = 20.5$, $B-V = 0.25$ are representatives of the large anomalous Cepheid population of Leo I, and we discuss them in Section 3.3

From the *V*-band LF for all stars, corrected for incompleteness, we derive a mean apparent magnitude for the red giant clump of $V = 22.30 \pm 0.05$, which compares well

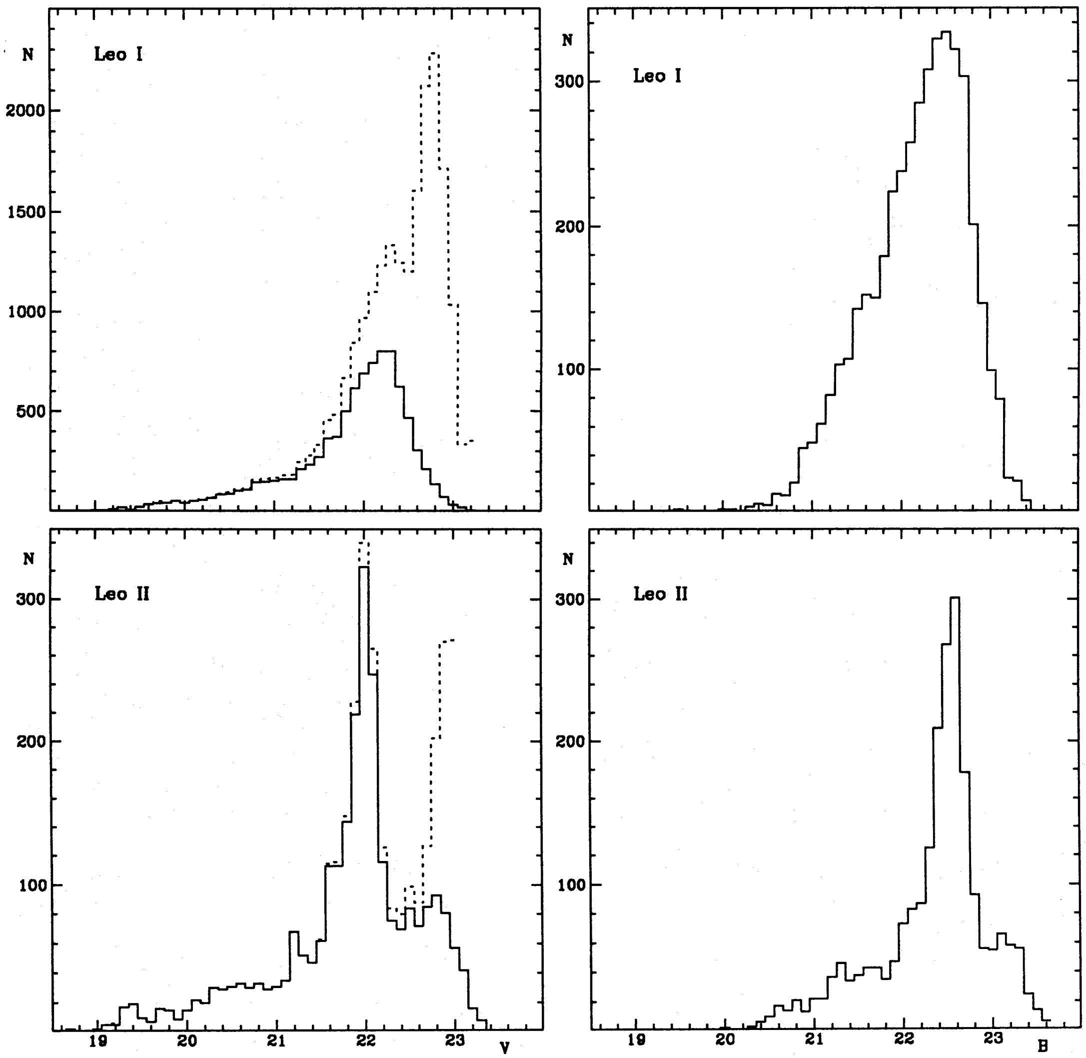

Figure 1. Comparison between the differential luminosity functions of Leo I and Leo II. The distributions, corrected for completeness, are shown by dashed lines.

Table 2. Percentage of stars recovered in Leo I.

mag.	V	B
20.0	99%	100%
20.5	95	96
21.0	90	95
21.2	87	92
21.4	83	90
21.6	80	87
21.8	75	82
22.0	71	79
22.2	65	75
22.4	50	68
22.5	39	61
22.6	19	54
22.8	6	13
23.0	3	2

with the value found by Lee et al. (1993). Likewise, our estimate of the magnitude of the tip of the red giant branch from the *B*, *V* CMD of $V = 19.6$ also agrees very well with the result of Lee et al. (1993). However, if the properties of the red giant clump are similar to those of Fornax and also to the intermediate-age Magellanic Cloud population, then the distance of Leo I must be significantly closer than that postulated by Lee et al. (1993) (see Section 4).

Another significant feature in the CMD is the unusually wide giant branch, indicative of a considerable abundance variation, and reminiscent of the giant branch of Fornax; see, for example, Sagar, Hawkins & Cannon (1990) or Mateo et al. (1991).

3.2 The giant branch structure

We are fortunate in having obtained the data on Leo II and Leo I during the same observing run at the CFHT, in essen-

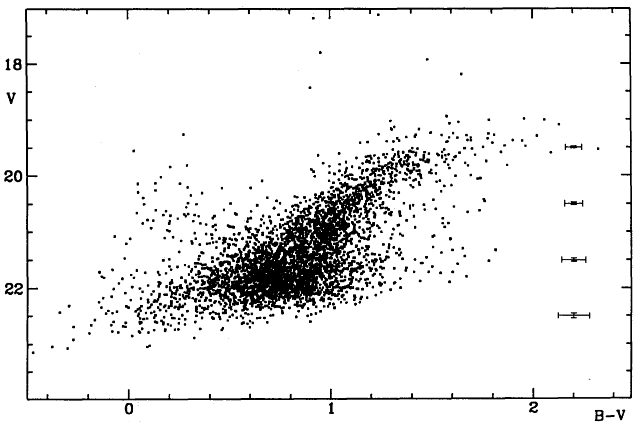

Figure 2. The colour–magnitude diagram of Leo I.

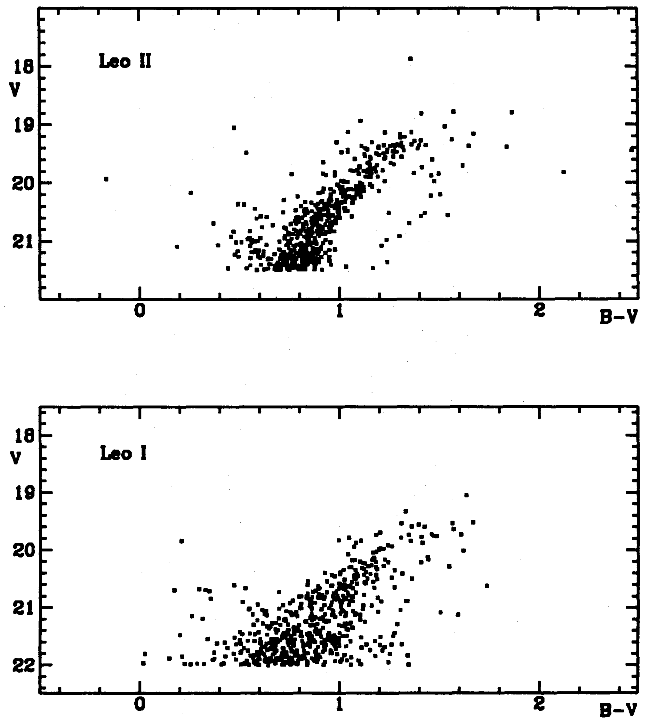

Figure 3. Comparison of the first 2.5 mag of the giant branches of Leo II and Leo I. One-sixth of the stars of Leo I were plotted to make the number of stars nearly equal in the two CMDs.

tially identical observing conditions. It is thus relatively straightforward to compare directly the widths of the giant branches from the two CMDs. At a given magnitude level, the half-width, at halfway to the maximum, of the colour distribution of the giant branch of Leo II is ~0.06. This can be almost entirely accounted for by the measuring errors (cf. fig. 1 of DI93). Fig. 3 shows the first ~2.5 mag of the giant branches of Leo II and Leo I. To facilitate comparison between the galaxies, the number of points on each giant branch has been equalized by using a random selection of only one out of six of the Leo I data points. Two differences are immediately apparent: the giant branch of Leo I is much wider and consequently not as well-defined as that of Leo II, and there are a significant number of blue stars ($B-V<0.5$) present in Leo I which are not present in Leo II. It is interesting to note that these blue stars are not present in the CMD of Fornax (Demers, Irwin & Kunkel, in preparation).

The unusual appearance of the giant branch of Leo I cannot be explained by the more crowded stellar images (we counted more than 9000 stars in the V frame), or the poor PSF fits. Again, the data of Leo I can be compared with those of Leo II. Fig. 4 displays, for stars with $V<21.5$, two parameters computed by DAOPHOT: χ defines the goodness-of-fit of the PSF, and σ_V corresponds to the error on the magnitude computed by DAOPHOT. To display σ_V, we have added the error due to the uncertainty of the zero-point of the transformation equations. Needless to say, not only do the data of Leo I compare very well with those of Leo II; they are actually better! The individual CCD frames of Leo I were better matched than those of Leo II. As an additional check, we produced CMDs for small uncrowded areas of the Leo I field. The appearance of the giant branch was not modified. We can therefore conclude that the crowded central part is not responsible for the dispersion of the giant branch.

3.3 The carbon stars of Leo I

The most comprehensive carbon star survey of Leo I is the GRISM survey carried out by Azzopardi, Lequeux & Westerlund (1985, 1986). They identified 20 carbon stars, most of which are located on our CCD field. We present, in Table 3, the magnitudes and $B-V$ colours of these carbon stars. We also add two extremely red giants which may also be carbon stars. These stars can be identified, using their x and y coordinates, from inspection of Fig. 5. Our candidate No. 1 is outside of the field of Azzopardi et al. Unfortunately, carbon stars show an intrinsic range of absolute visual magnitudes, making their usefulness as distance indicators of elliptical or spheroidal galaxies questionable. However, in spite of that caveat, they can provide a rough estimate of the distance (see Section 4.4).

Magnitudes and colours of a few carbon stars of Leo I have been published by Fox & Pritchet (1987). The match between their V magnitudes and $B-V$ colours and ours is rather poor. Their V magnitudes are fainter than ours by $\Delta V=0.6\pm0.2$, while their $B-V$ colours are, on the average, slightly bluer than ours, with $\Delta(B-V)=0.04\pm0.52$. We have no reason to suspect the zero-point of our magnitude scale. Indeed, our data compare well with the observations of Lee et al. (1993). For example, we note that the magnitude of the tip of the giant branch of Leo I is at $V=19.6$, and that the mean V magnitude of the red clump stars is at $V=22.3$, identical values to those found by Lee et al. (1993).

3.4 The known variables of Leo I

Hodge & Wright (1978) have identified 23 variables in Leo I. Most of these variables are anomalous Cepheids; they are brighter than the RR Lyrae stars and have periods longer than one day. We have located, on our CCD frames, 15 of the Hodge & Wright (1978) variables. In Table 4, we present the magnitudes and colours of the variables obtained from the combined V and B frames. These magnitudes and colours

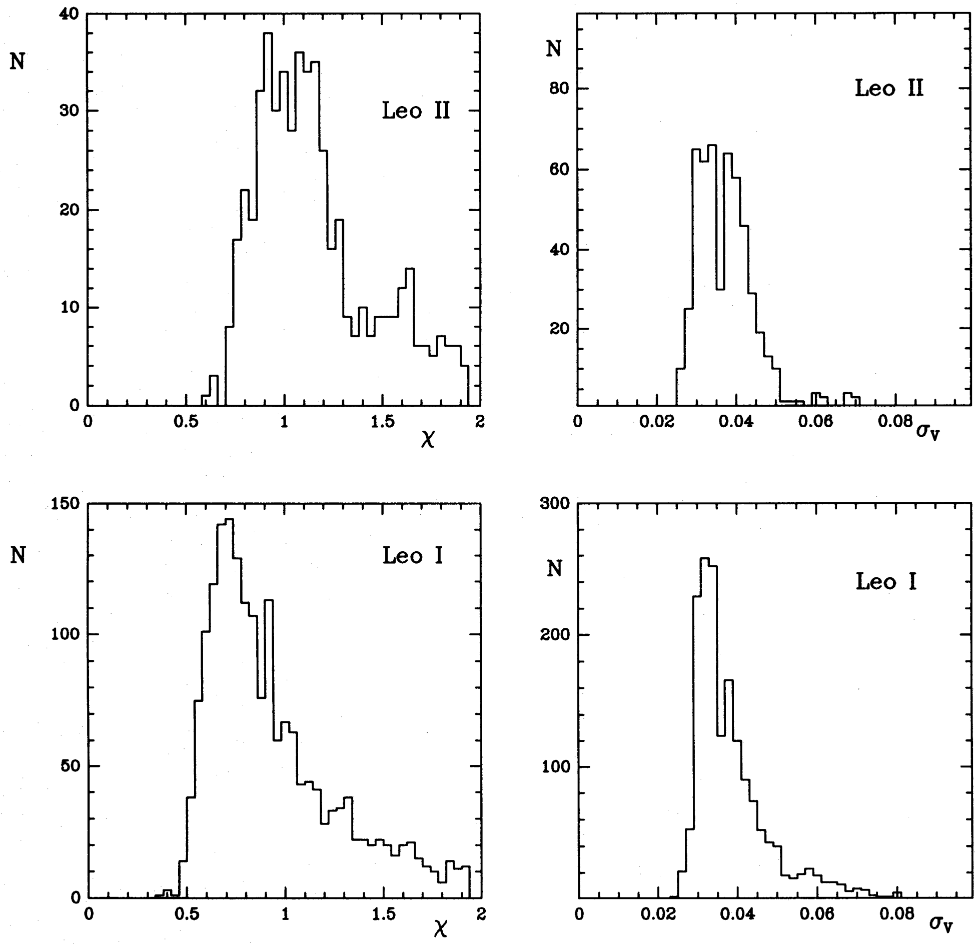

Figure 4. Distribution of two image parameters calculated by DAOPHOT. This comparison shows that the magnitudes of Leo I are determined with better accuracy than those of Leo II.

Table 3. Magnitudes and colours of carbon stars.

name	x	y	V	B–V	comments
ALW 1	751	1539	19.59	1.84	
ALW 2	733	1370	18.98	1.95	
ALW 3	879	1408	19.70	2.65	
ALW 4					outside our field
ALW 5	844	1108	19.53	2.32	
ALW 6					outside our field
ALW 7	910	777	19.09	2.13	
ALW 8	1024	1029	19.33	1.33	
ALW 9	1331	1463	19.64	1.37	
ALW 10	1272	1249	19.47	1.86	
ALW 11	1128	597	19.51	1.40	
ALW 12	1344	909	19.66	1.62	
ALW 13	1119	323	19.48	1.96	
ALW 14	1535	1290	19.00	2.05	
ALW 15	1654	794	19.29	2.02	
ALW 16	1462	112	19.59	2.09	
ALW 17					outside our field
ALW 18	1685	1170	19.92	1.40	
ALW 19	292	766	19.37	1.90	
ALW 20	390	724	19.34	2.66	
new 1	1026	701	19.82	1.87	spectral type unknown
new 2	1800	1121	19.38	1.94	spectral type unknown

should correspond roughly to the average values of the star. We have, unfortunately, too few data points to confirm the variability of these stars. For the sake of completeness, we also include, in Table 4, the four V magnitudes obtained by combining frames obtained consecutively. These four data points could be combined with a more exhaustive set of observations of the variables. As noted by Reid & Mould (1991), variable 22 is reddish and variable 9 is also red. Few of these stars are blue enough to be RR Lyrae variables.

We particularly note, on our CMD, a region of stars at $B-V=0.0$–0.4 with apparent magnitudes between $V=20$ and 21.5. Comparison of the scatter, of the few observations, for the red and blue stars at this magnitude level does not indicate that the blue stars are more variable than the red ones. A similar exercise was carried out for fainter stars in the $V=21.5$ to 22.5 interval. Again there is no suggestion that the observations of blue stars have a larger scatter than those of the red ones.

4 THE AGE AND DISTANCE OF LEO I

Leo I, being located at a high galactic latitude ($b=49°$), should suffer little interstellar extinction. A colour excess of

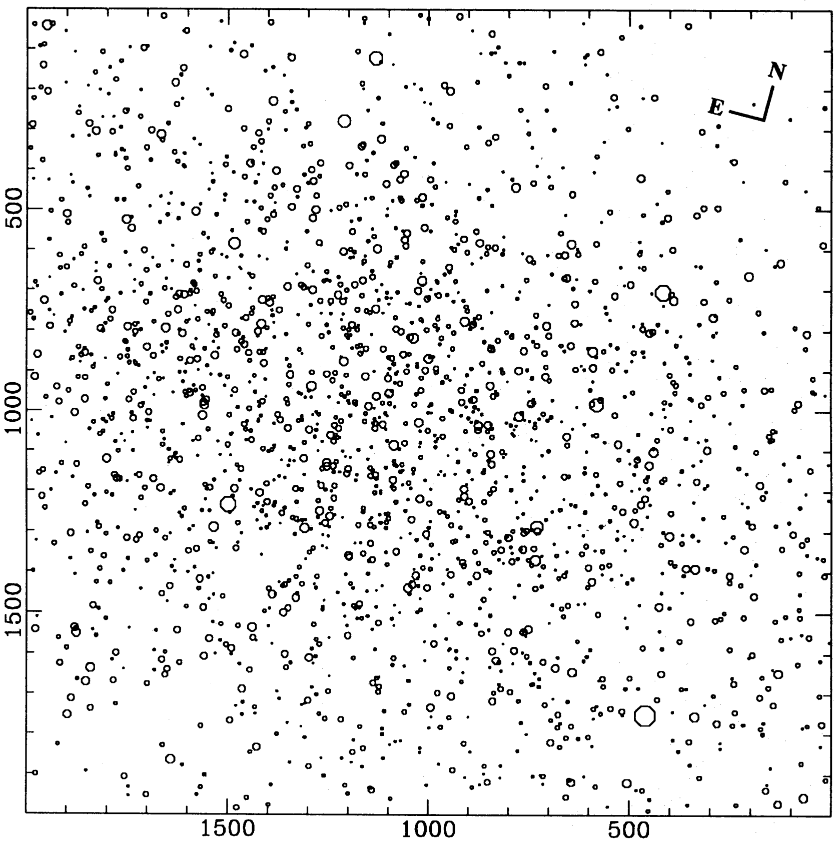

Figure 5. Map of the bright stars of Leo I; the field is 7 × 7 arcmin^2.

Table 4. Photometry of the variables of Hodge & Wright.

no.	V	$B-V$	707.830 V	707.925 V	708.763 V	708.981* V
2	20.63	0.60	20.79	20.93	20.44	20.96
3			20.98	20.73	21.17	
6	20.70	0.92	20.84	20.73	20.80	20.75
7	21.23	0.83	21.40	21.35	22.39	
8	19.81	0.29	19.68	19.66	20.07	20.07
9	20.34	1.27	20.45	20.40	20.43	20.38
10	20.71	0.34	20.46	20.47	21.39	
13	21.83	0.89	22.09	22.02	22.10	
16	20.76	0.59	21.22	21.22		20.88
17	20.21	0.46	20.14	19.77	20.53	20.51
18	20.88	0.89	21.04	20.97		20.29
20	21.92	0.83	22.14	21.98		
21	20.33	1.03	20.46	20.40	20.43	20.25
22	19.82	1.24	19.95	19.86	19.91	19.87
23	21.19	0.40	21.34	21.38	21.35	

*JD + 2 448 000.0.

$E(B-V)=0.02$ is estimated from the maps of Burstein & Heiles (1982). However, their latest compilation of the reddening of galaxies (Burstein & Heiles 1984) gives a much larger value, namely $E(B-V)=0.09$. Webbink (1985), in his compilation of properties of globular clusters and spheroidals, adopted a colour excess of $E(B-V)=0.02$ for Leo I. This value was based on the Burstein & Heiles (1982) data, and we shall adopt it for the purpose of our discussion.

4.1 The age of the main stellar population of Leo I

From the revised Yale isochrones (Green, Demarque & King 1987), for a stellar population with $Z=0.0004$ (close to [Fe/H] = −1.8) and a helium abundance parameter, Y, in the range 0.2 to 0.3, well-populated red giant branches appear at 3–7 Gyr. For Local Group galaxies, Y tends to the lower end of this range, suggesting a lower age limit of around 3 Gyr for the bulk of the stellar population of Leo I. Development of a giant branch after, say, 1 Gyr is only possible if the abundance is much higher, [Fe/H] = −0.4. Estimates of the abundance of Leo I (see Section 5) range from [Fe/H] of −1 to −2. It is therefore unlikely that the age of the red giant stars is much less than about 3 Gyr.

Corroboration for this limit comes from the presence of subgiant stars in the V, I CMD of Lee et al. (1993). Theoretical predictions for the lifetime of stars in the shell H-burning phase are that no subgiant stars should be present for ages less than about 3 Gyr. The absence of significant numbers of blue horizontal branch stars and the presence of a relatively high proportion of AGB carbon stars suggest an upper age limit of ~7 Gyr for the dominant stellar component. There is no sign of a significant old stellar population component similar to that found in Leo II, Ursa Minor, Draco, Sextans or Sculptor. Both Fornax and Carina (Mighell 1990; Demers, Irwin & Kunkel, in preparation) have strong intermediate-age components, though there is also unambiguous evidence for an old population of 'blue' horizontal branch stars in both Carina and Fornax.

Hatzidimitriou (1991) introduced an alternative age estimator for objects with dominant red horizontal branch/red giant clump populations, based on the relative location of the clump and giant branch on a CMD. This indicator, d_{B-R}, is defined as the colour difference between the median colour of the horizontal branch or clump stars and the red giant branch at the level of the clump. This difference is independent of the distance and is also insensitive to the adopted metallicity value. Unfortunately, the width of the giant branch and the proximity of the red clump to the limiting magnitude of our CMD make it rather difficult to measure this quantity with any accuracy, but we can use it to define an upper limit.

The median colour of the red giant clump is $B-V=0.70\pm0.03$, while the extrapolated colour of the red giant branch at the red clump magnitude is unambiguously <0.8 leading to a limit on $d_{B-R}<0.15$. This corresponds to an upper age limit of ~ 5 Gyr for the bulk of the stellar population.

The unusual giant branch morphology of Leo I, particularly the width of its giant branch, plus uncertainties in distance and metallicity estimates, preclude serious isochrone fitting attempts. Consequently, for the remainder of this paper, we tentatively adopt an age of 5 Gyr for the bulk of the stellar population, with a likely error of ± 2 Gyr.

4.2 Previous distance estimates

Because of its proximity to Regulus, as explained in the Introduction, optical studies of Leo I have been difficult to achieve. Hodge (1966) estimated the distance modulus of Leo I to be 21.8 ± 0.6 mag or 220 ± 50 kpc, from the apparent magnitude of its brightest stars. This confirmed Baade's (1963) impression that Leo I was at the same distance as Leo II. The data of Fox & Pritchet (1987) and those of Reid & Mould (1991) are consistent with this distance estimate. Furthermore, using the above distance, the bolometric magnitudes of the known Leo I carbon stars match fairly well those found in the other dwarf galaxies (Azzopardi & Lequeux 1991).

More recently, Lee et al. (1993) estimated the distance of Leo I from the apparent I magnitude of the tip of its giant branch. They deduced a true modulus of $(m-M)_0=22.17\pm0.15$, which pushes this dwarf spheroidal much further away than previously believed. Neither in their data or ours is there clear evidence of either any RR Lyrae stars or any obvious 'blue' horizontal branch in the CMD, which would have enabled an unambiguous determination of the distance. However, the presence of a strong red giant clump in Leo I, indicative of a dominant intermediate-age stellar component, provides an alternative means for estimating the distance. Other measures of distance can be obtained by comparing the giant branch morphology of Leo I to suitable comparison giant branches such as those of Fornax, Leo II or globular clusters of similar metallicity, whilst the magnitudes of the carbon stars, also at the tip of the giant branch, give yet another estimator. These alternatives are discussed in the following subsections. The main difficulty with most of these estimators is that the distance deduced depends rather closely on the adopted metallicity, with $[Fe/H]=-1.5$ producing a short distance modulus ~ 21.7 and $[Fe/H]=-2.0$ favouring a long distance modulus ~ 22.2.

4.3 Using the red giant clump as a distance indicator

The clump of stars observed at the base of the giant branch in the CMDs of Galactic clusters (e.g. Cannon 1970) and in the intermediate-age stellar population of the Magellanic Clouds can be identified with the core helium-burning phase of stellar evolution. Both theoretical evolutionary tracks for such stars (e.g. Seidel, Demarque & Weinberg 1987) and empirical results (e.g. Mateo & Hodge 1985) suggest that the luminosity of clump stars can be used as a distance indicator for stellar populations older than 1 Gyr. According to Seidel et al. (1987), for a given metallicity and helium abundance, the total difference in mean clump luminosity for ages between 1 and 10 Gyr is ~ 0.1 mag. The difference in clump luminosity for a change in [Fe/H] between -0.3 and -1.3 is also ~ 0.1 to 0.2 mag. Empirical support for this comes from fig. 7 of Mateo & Hodge (1985). Furthermore, for clump stars older than 1 Gyr, there is also a marked dependence of the colour/temperature of the clump stars on metallicity. This is well illustrated in Mateo & Hodge (1985).

This result is supported in other cluster/stellar populations. Other Local Group galaxies with similar red giant clumps include the Fornax dwarf spheroidal and the intermediate-age field and cluster components of the Magellanic Clouds. Our own unpublished CTIO 4-m photographic plate data of Fornax show a strong red giant clump and a much smaller component population of 'bluer' horizontal branch stars at the same magnitude. The horizontal branch of the Fornax globular cluster 1 is also at the same magnitude, $V=21.36$ (Demers, Kunkel & Grondin 1990). Likewise, the intermediate-age component populations of the Magellanic Clouds have a strong red giant clump at a magnitude similar to the older component horizontal branch stars (e.g. Hardy & Durand 1984; Hardy et al. 1984). The age spread and metallicity of these systems are similar to the range of metallicities found for Leo I. If we take the M_V of the red giant clump in Leo I to be ~ 0.6, then its distance modulus, corrected for absorption, would be 21.7 ± 0.2, corresponding to a distance of 220 ± 20 kpc.

4.4 Distance from carbon star magnitudes

The mean magnitude of the carbon stars identified in our Leo I sample is $V=19.40$, with a standard deviation about the mean of ±0.32. We compare this mean value with the mean of two samples of carbon stars, in the Large Magellanic Cloud and in Fornax. Richer (1981) published magnitudes and colours of some 60 carbon stars in the bar of the LMC for which the mean $V=16.6\pm0.7$. Adopting, for the LMC, a true modulus of 18.57 (Welch et al. 1987) and a uniform colour excess of $E(B-V)=0.06$ (van den Bergh 1975), we obtain $M_v=-2.15$. Lundgren (1990) has obtained the V magnitudes of nearly 20 carbon stars in Fornax, with a mean $V=18.65\pm0.6$. A modulus of 20.76 for Fornax (Demers et al. 1990) also leads to $M_v=-2.11$, a value essentially identical to the mean in the LMC. If one adopts this absolute magnitude for the carbon stars in Leo I, then its modulus is 21.5 ± 0.3, a significantly smaller distance than that obtained by Lee et al. (1993).

As we noted earlier, the distance estimates for Leo I using the giant branch morphology polarize into two camps: a metallicity of $[Fe/H]=-1.5$ favours a distance modulus

~21.7, which is also supported by the carbon star distance and the red clump distance; whilst the adoption of a metallicity of [Fe/H] = −2.0 gives a larger distance modulus ~22.2, which is supported by the magnitude of the tip of the GB.

Adopting [Fe/H] = −1.5 for the metallicity of Leo I, and combining all the distance estimates based on this value using a weighted average, we obtain an apparent distance modulus to Leo I of 21.62 ± 0.25. Table 5 summarizes these results. With the adopted colour excess, this corresponds to a distance of 205 ± 25 kpc.

5 THE METALLICITY OF LEO I

5.1 The abundance of Leo I

The abundance of Leo I has been determined by Suntzeff et al. (1986) from spectroscopy of two of its giants. They found [Fe/H] = −1.50 ± 0.25, a value quite reasonable for the second most massive dwarf spheroidal. Reid & Mould (1991) proposed an even higher value, [Fe/H] = −1.0 ± 0.3, based on isochrone fitting to an *R*, *I* colour–magnitude diagram, while Fox & Pritchet (1987) estimated [Fe/H] = −1.4, using a *B*, *V* colour–magnitude diagram and isochrone fitting. On the other hand, Lee et al. (1993) determined, from the $V-I$ colour of the tip of the giant branch, a much lower abundance, namely [Fe/H] = −2.1 ± 0.1.

As noted earlier, estimates of the abundance based on CMDs are rather sensitive to the adopted distance. We can illustrate this by using the technique of Sagar et al. (1990) to determine the mean abundance of the giants of Leo I. Their equation (1) links the mean $B-V$ colour of the red giant branch of globular clusters at $M_v = -1.4$ with the [Fe/H] abundance. The observed giant branch colour of $B-V = 1.15$ at $M_v = -1.4$ (assuming an apparent distance modulus of 21.62) yields an abundance of [Fe/H] = −1.6 ± 0.4. This abundance is higher than the recent estimate of Lee et al. (1993), who quoted a mean metallicity of [Fe/H] = −2.1 ± 0.1. However, if we now adopt the large distance, namely 22.2, Sagar's method yields [Fe/H] = −1.93, a value similar to that found by Lee et al. (1993). Likewise, globular clusters of low metallicity could be fitted to the giant branch of Leo I, resulting in distances similar to that found by Lee et al. (1993).

5.2 Dispersion of abundance

We evaluate the dispersion of abundances among the giants of Leo I from the width of its observed giant branch. We assume that the width of the giant branch of Leo II, observed by us on the same nights (DI93), represents simply the scatter due to the photometric errors. Thus subtraction of the $B-V$ width of Leo II (in quadrature) from the width of Leo I will yield the excess due to the range of abundances. This statement is true only if the age dispersion within Leo I is small. Inspection of the Revised Yale isochrones shows that the giant branch, at a given magnitude level, is shifted by $\Delta(B-V) = 0.05$ when the age changes from 3 to 13 Gyr. We define $\sigma^2 = \sigma^2_{\rm Leo\,I} - \sigma^2_{\rm Leo\,II}$, where σ is taken to be half the FWHM of the distribution of colours read in a narrow magnitude interval. This gives $\sigma = 0.12 \pm 0.03$. From this value one should subtract the effect of the age dispersion, leading to an upper limit, using Sagar et al.'s (1990) equation, of a [Fe/H] dispersion of 0.25 dex. Furthermore, no colour gradient of the Leo I giants is seen as a function of the distances along its major axis. We used here an ellipticity of $\varepsilon = 0.21$ to define the ellipses, a value quoted by Irwin & Hatzidimitriou (1993).

Table 5. Distance estimates for Leo I.

method:	$(m-M)_v$	uncertainty
median V of the red clump	21.70	±0.20
M_v of carbon stars	21.5	±0.3
weighted average	21.62	±0.25
I of tip of GB (Lee et al.)	22.17	±0.15

6 SUMMARY

The CFHT *B*, *V* CCD photometry of Leo I shows a strong red giant clump and a wide giant branch. The red clump together with the known carbon stars is indicative of a dominant intermediate-age population (age ~5 Gyr) and reminiscent of the giant branch population of the Fornax dwarf spheroidal. Leo I is, after Fornax, the brightest spheroidal surrounding the Galaxy. One would expect Leo I to have a metallicity [Fe/H] ~ −1.5 if it follows the general trend of [Fe/H] versus M_v; see Caldwell et al. (1992) for a recent compilation. However, given the mounting evidence for a dispersion in this mean relation, this is hardly a conclusive argument, and clearly further high-resolution spectroscopy of giant stars is required to make a more reliable abundance determination. With the currently available data we feel that the 'best' estimate for the metallicity of Leo I is [Fe/H] = −1.5 ± 0.25, and correspondingly the shorter distance scale $(m-M)_0 = 21.6 \pm 0.2$ is appropriate.

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