The Astrophysical Journal, 530:L85–L88, 2000 February 20

THE ELUSIVE OLD POPULATION OF THE DWARF SPHEROIDAL GALAXY LEO I[1]

E. V. Held
Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy; held@pd.astro.it
and
I. Saviane, Y. Momany, and G. Carraro
Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy;
saviane@pd.astro.it, momany@pd.astro.it, carraro@pd.astro.it
Received 1999 November 27; accepted 1999 December 23; published 2000 January 27

ABSTRACT

We report the discovery of a significant old population in the dwarf spheroidal (dSph) galaxy Leo I as a result of a wide-area search with the ESO New Technology Telescope. Studies of the stellar content of Local Group dwarf galaxies have shown the presence of an old stellar population in almost all of the dwarf spheroidal galaxies. The only exception was Leo I, which alone appeared to have delayed its initial star formation episode until just a few gigayears ago. The color-magnitude diagram of Leo I now reveals an extended horizontal branch, unambiguously indicating the presence of an old, metal-poor population in the outer regions of this galaxy. Yet we find little evidence for a stellar population gradient, at least outside $R > 2'$ (0.16 kpc), since the old horizontal branch stars of Leo I are radially distributed as their more numerous intermediate-age helium-burning counterparts. The discovery of a definitely old population in the predominantly young dwarf spheroidal galaxy Leo I points to a sharply defined first epoch of star formation common to all of the Local Group dSph galaxies as well as to the halo of the Milky Way.

Subject headings: galaxies: dwarf — galaxies: evolution — galaxies: individual (Leo I) — galaxies: stellar content — Local Group

1. INTRODUCTION

Discovered nearly half a century ago by Harrington & Wilson (1978) on plates of the first Palomar Sky Survey, Leo I remains one of the most studied dwarf spheroidal (dSph) galaxies in the Local Group. This galaxy is located far from the Galaxy (about 270 kpc according to Lee et al. 1993) and has a radial velocity large enough to raise some doubts about whether it is bound to the Milky Way system (Zaritsky et al. 1989; Byrd et al. 1994). Ground-based CCD photometry of the red giant branch and main-sequence (MS) turnoff have suggested that it is dominated by a metal-poor stellar population with a young mean age, possibly the youngest among dSph galaxies (Lee et al. 1993; Demers, Irwin, & Gambu 1994). This young mean age has recently been confirmed by deep color-magnitude diagrams (CMDs) of a central field observed with the *Hubble Space Telescope* (*HST*)/WFPC2. Quantitative analysis of these data has established that most star formation activity occurred between 7 and 1 Gyr ago (Caputo et al. 1999; Gallart et al. 1999a, 1999b).

Until now, no study has been able to unambiguously detect the presence of an old stellar population. The *HST* CMDs show no evidence for the "flat" horizontal branch (HB) typical of Galactic globular clusters and other dSph galaxies. The absence of an old HB or RR Lyrae variables led to the conclusion that Leo I is *a young galaxy*, in that it started forming stars only as recently as 7 Gyr ago. This conclusion contrasts with the general evidence for dSph galaxies, most of which contain significant populations of very old stars (see Da Costa 1998; Mateo 1998).

Still, there are some hints that an old population may actually exist in Leo I. Gallart et al. (1999a) noted that old HB stars may contribute to a "bridge" of stars from the base of the red clump to the tip of the young main sequence. Caputo et al. (1999) found that the lower envelope of the subgiant branch is consistent with the presence of an old stellar population in the broad age range 10–15 Gyr. Further, a preliminary report from a study of the HB and variable stars in Leo I (Keane et al. 1993) identified a sparse bluer extension of the red clump and reported the presence of RR Lyrae variables. Also, Hodge & Wright (1978), while pointing out the large number of anomalous Cepheids in Leo I, had listed a handful of stars near the limit of their photographic photometry as "probably normal RR Lyrae variables caught at maximum."

To answer the question of whether Leo I had some star formation starting more than 10 Gyr ago, we have conducted a search for the old population in this galaxy by mapping a wide area with the New Technology Telescope in subarcsecond seeing conditions. In this Letter we report the discovery of an extended (blue-to-red) HB having morphology similar to that observed in other dSph galaxies (e.g., Sculptor and Leo II). This result implies that Leo I, along with the other dSph galaxies in the Local Group, underwent a significant early episode of star formation likely coeval to the birth of the oldest Galactic globular clusters.

2. OBSERVATIONS AND REDUCTION

Observations of Leo I were obtained on the nights of 1999 April 15–16 using the ESO Multimode Instrument (EMMI) at the ESO New Technology Telescope at La Silla, Chile. Exposures of 1200 s in *B* and 600 s in *V* were obtained as a backup program during periods of nonvisibility of the principal targets. We could observe four partially overlapping fields yielding a total field of $\sim 12' \times 12'$ in both filters. After the usual preprocessing, the frames were reduced using DAOPHOT/ALLSTAR (Stetson 1994). The photometry was calibrated using observations of Landolt (1992) standard stars, with an rms error in the transformations less than 0.03 mag. Aperture corrections were derived from all the individual

[1] Based on data collected at ESO La Silla, Chile.

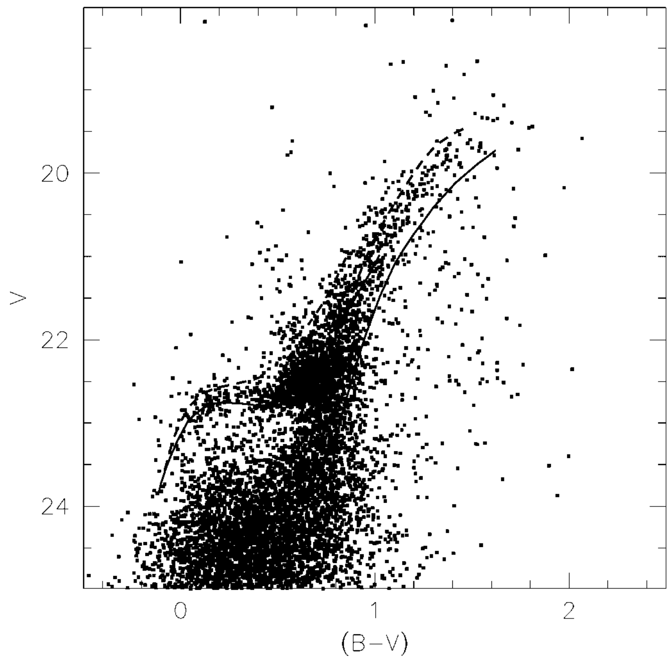

FIG. 1.—Color-magnitude diagram of the outer regions of Leo I revealing the presence of a very old stellar population. The data were selected outside a radius 4.′5 from the galaxy center. The lines are the fiducial sequences of the Galactic globular clusters NGC 5897 ([Fe/H] = −1.80; *dashed line*) and NGC 5904 (M5, [Fe/H] = −1.29; *continuous line*) offset to match the distance of Leo I (data from Ferraro, Fusi Pecci, & Buonanno 1992 and Sandquist et al. 1996). The distance and reddening to Leo I were adopted from Lee et al. (1993), while basic data for the globular clusters are from the updated Harris (1996) catalog.

frames and compared to estimate a total uncertainty of 0.05 mag in the photometric zero points.

3. RESULTS

3.1. *The Old Horizontal Branch of Leo I*

Figure 1 presents the CMD of stars in Leo I having distance from the galaxy center larger than $r = 4.'5$ (0.35 kpc). This diagram clearly reveals the presence of an extended HB comprising both red and blue stars. The RR Lyrae gap is evident at $0.2 < (B-V) < 0.4$, and the blue HB turns down near $(B-V) \simeq 0.1$. The overall HB morphology is therefore similar to that of moderately metal-rich Galactic globular clusters. In Figure 1 we have superposed the fiducial loci of the globular clusters NGC 5897 and NGC 5904, whose metallicities are [Fe/H] = −1.80 and −1.29, respectively (Harris 1996).[2] The red giant branch of Leo I appears consistent with a metal abundance intermediate between those of the clusters, i.e., $\langle$[Fe/H]$\rangle \sim -1.6$. The old HB coexists with the well-known red clump of the dominant intermediate-age population and with the more massive ($M \gtrsim 1.8\ M_{\odot}$; Caputo et al. 1999) helium-burning stars making up the yellow plume just above the red clump, sometimes referred to as "vertical red clump" ($B-V \approx 0.6$, $V \lesssim 22.4$). The mean apparent magnitude of the HB, $V \sim 22.8$, confirms the distance modulus inferred from the tip of the red giant branch (Lee et al. 1993). A full discussion of the distance to Leo I based on the mean magnitude of the old HB will be presented elsewhere.

A close-up view of the HB population in Leo I is shown in Figure 2. The top panel shows the diagram of helium-burning stars beyond $r = 2.'7$ (∼0.2 kpc). Only stars having small DAOPHOT errors (<0.05) have been plotted, resulting in a quite sharp magnitude cutoff at $V \approx 23.4$. By applying a more restrictive radial selection ($r > 5.'4$), in the middle panel we emphasize the RR Lyrae gap and the downturn of the blue HB. The HB region in the CMD of the globular cluster M5 (NGC 5904; data from Sandquist et al. 1996) is also shown for comparison (*bottom panel*).

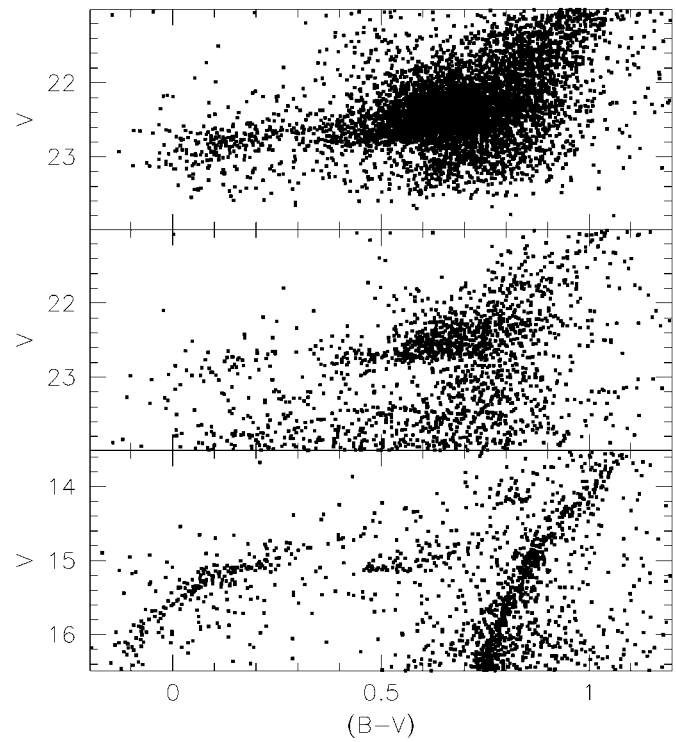

FIG. 2.—Enlarged view of helium-burning stars in Leo I. Stars in Leo I at distances from the center $r > 2.'7$ (*top panel*) and $r > 5.'4$ (*middle panel*) are compared with the CMD of the Galactic globular cluster M5 (*bottom panel*).

The CMD of the intermediate-outer region, shown in the top panel, clearly comprises helium-burning stars of different ages and masses. The old HB exhibits a complex structure, with a spread in luminosity. The oldest stars in Leo I are more clearly seen in the CMD of the outer region (*middle panel*). The morphology of the old HB of Leo I appears notably similar to that of the intermediate-metallicity globular cluster NGC 5904 (Sandquist et al. 1996). In particular, we note the following.

1. The downturn of the blue HB is similar in the two diagrams. The blue HB sequence of Leo I is truncated with respect to the more extended blue tail of M5, a difference only partially due to incompleteness (see Fig. 1).
2. A small population of stars slightly brighter than the HB, most likely stars in post-HB evolutionary stages, is quite evident in both the Leo I and M5 diagrams. The stars near the gap probably are RR Lyrae variables. The stars brighter than the HB are consistent with the post-HB isochrones of stars with initial HB masses 0.6– 0.7 $M_{\odot}$ and metallicity $Z = 0.001$ (Bertelli et al. 1994).
3. The small clump of stars ∼1 mag brighter than the HB [$B-V = 0.8$, δV(HB−AGB) $\simeq 0.95$] clearly marks the bottom of the asymptotic giant branch (AGB) of the old population.

A quantitative estimate of the HB morphology of the *old*

[2] The revised version of the Catalog of Galactic Globular Clusters is available at http://physun.physics.mcmaster.ca/Globular.html.

population in Leo I was attempted by excluding the stars on the red clump. The blue and red HB stars were counted in the intervals $-0.08 < B-V < 0.2$ and $0.4 < B-V < 0.5$ in the magnitude range $22.4 < V < 23.0$ (the bluest box was actually a trapezoid matching the downturn of the blue HB). The color range $0.2 < B-V < 0.4$ approximately corresponds to the RR Lyrae gap, and stars counted in that interval were taken as representative of variable stars. The Lee-Zinn index $I_{\rm HB} = (B-R)/(B+V+R)$ was calculated in the two radial intervals $2.'7 < r < 4.'3$ and $4.'3 < r < 8.'3$, obtaining $I_{\rm HB} = -0.09 \pm 0.07$ and -0.09 ± 0.08, respectively. The errors are formal uncertainties from Poisson statistics. Given our stringent choice of the redder box, these estimates should be properly regarded as upper limits to $I_{\rm HB}$, and experiments varying the limits of the color intervals suggest that the morphology index is in the range $-0.4 < I_{\rm HB} < 0.0$. Using the same intervals as above to define the blue and red HB, the corresponding Mironov parameter $B/(B+R)$ is 0.43 and 0.44 for the intermediate and outer regions. The HB index cannot be estimated in the inner region ($r < 2.'7$ or 0.21 kpc) due to the higher crowding and photometric errors and the contamination from young MS stars. This region approximately corresponding to a core radius (the mean half-brightness radius is 0.18 kpc; Irwin & Hatzdimitriou 1995). Note that for the intermediate and outer regions, there is no evidence of variations in the HB morphology with radius.

These results for the index $I_{\rm HB}$ indicate a uniform old HB having at least as many stars in the red as in the blue part. When the [Fe/H] versus HB-type diagram (Lee, Demarque, & Zinn 1994) is used to compare the HB morphology of Leo I with that of globular clusters in Local Group galaxies, the old HB of Leo I turns out to be significantly redder that those of old Galactic clusters of similar metallicity and similar to those of the young halo clusters (we assume that the old population in Leo I is nearly as metal-poor as NGC 5897, i.e., [Fe/H] ~ -1.8). This result provides a new (mild) example of the "second-parameter" effect in dwarf spheroidal galaxies.

3.2. *Spatial Distribution*

The surface density profile of HB stars in Leo I is shown in Figure 3, along with the surface densities of red clump and red giant branch stars. The number of old HB stars was counted in the CMD region $-0.70 < B-V < 0.51$, $22.5 < V < 23.0$, in radial annuli starting from the innermost radius $r = 2'$ (0.16 kpc). The CMD regions used for counting the red clump stars and red giants are $0.51 < B-V < 0.77$, $22.06 < V < 22.87$, and $0.83 < B-V < 1.23$, $20.30 < V < 21.37$, respectively. These density profiles have been shifted to match the profile of HB stars. The foreground contamination is negligible in all of these regions. Figure 3 shows that, outside approximately a core radius, the surface densities of old HB and red clump stars are basically consistent in Leo I, i.e., the old- and intermediate-age populations have similar spatial scale lengths.

A population change is not ruled out in the innermost region, though. By assuming a constant central surface density of $\gtrsim 16$ HB stars arcmin^{-2} (see Fig. 3), we estimate that ~80 old HB stars are expected in the WFPC2 field—a number that, if present, would easily have been detected in the *HST* CMDs.

4. DISCUSSION

Our detection of a blue HB in Leo I unambiguously indicates the existence of an underlying old stellar population in this galaxy. The observation that Leo I is not a young galaxy in the sense of having been born in the last few gigayears lends universal validity, within the Local Group, to the idea that dwarf spheroidal galaxies formed at an early epoch essentially coeval to the formation of old Galactic globular clusters.

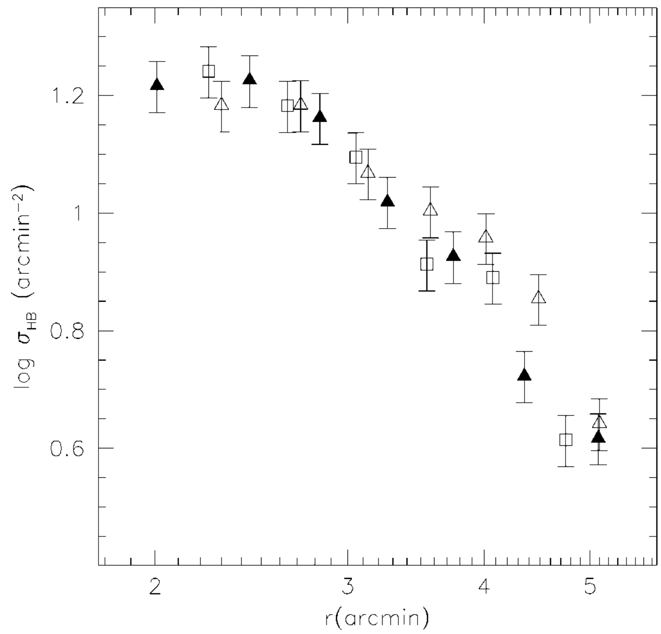

FIG. 3.—Plot of the radial surface density profiles of stars in Leo I: HB stars (*filled triangles*), intermediate-age red clump stars (*open triangles*), and red giants (*squares*). See text for details.

4.1. *The HB Morphology of Leo I*

Before expanding further on the consequences of this result, however, we briefly comment on the observed morphology of the HB in Leo I and its radial trends. The overall HB morphology is similar to the extended HBs found in other metal-poor dwarf spheroidal/elliptical galaxies, in particular Leo II (Demers & Irwin 1993), Sculptor (e.g., Kaluzny et al. 1995), Tucana (Lavery et al. 1996), and And I (Da Costa et al. 1996). To summarize our results, in Leo I we have found that (1) the HB morphology provides yet another example of the second-parameter effect, similar to that of Sculptor, Leo II, and other dSph galaxies; (2) the old and intermediate-age populations have similar scale lengths; and (3) neither the ratio of HB to red clump stars nor the HB morphology show any variations in the intermediate/outer regions.

In the context of dSph galaxies, the second-parameter effect is usually interpreted as caused by an age spread. If age is the second parameter, then the mean age of the *old population* in Leo I should be comparable to that of the young globular clusters in the Galactic halo. An age range within the old population can probably explain the observed second-parameter effect. A possible interpretation for Leo I is that the "old component" actually represents a star formation episode of finite duration, so that the extended HB reflects a mix of stars in the age interval 10–15 Gyr. However, we cannot rule out the possibility that the old HB morphology in Leo I (as well as in other dSph galaxies) is influenced by the same physical second parameter that governs the HB in globular clusters.

The absence of a radial population and HB morphology gradient in the intermediate/outer regions of Leo I reminds us of the case of the Carina dSph, where Smecker-Hane et al. (1994) also found no difference in the distribution of the red clump stars and the HB of old stars. This implies uniformity in the population mix and suggests that the size of these galaxies has not significantly changed since their initial star formation epoch. This behavior contrasts with the results for other dSph galaxies, where the intermediate-age population commonly appears to be more centrally concentrated than the oldest component. The radial gradient in the HB morphology of And I, Leo II, and Sculptor have been discussed by Da Costa et al. (1996). Two recent studies of Sculptor have shown that the red HB stars are more centrally concentrated than the dominant old population and almost vanish in the outer region (Hurley-Keller, Mateo, & Grebel 1999; Majewski et al. 1999). Majewski et al. (1999) interpret these variations in HB morphology as caused by two overlapping HBs, belonging to two distinct populations with different metallicity ([Fe/H] ~ -1.5 and ~ -2.3, respectively) and radial distribution (however, Hurley-Keller et al. 1999 find no radial gradients of the age or metallicity distribution). A clear gradient in the relative distribution of HB stars, implying a variation in the mean age and/or abundance with radius, was also found in NGC 147, Fornax, and Phoenix (Han et al. 1997; Stetson, Hesser, & Smecker-Hane 1998; Saviane, Held, & Bertelli 2000; Held, Saviane, & Momany 1999). The reason that Leo I and Carina deviate from this general scenario for the evolution of dwarf spheroidal galaxies remains to be understood.

4.2. *The Epoch of Galaxy Formation in the Local Group*

We now comment on our detection of very old stars in Leo I in the context of recent results on the old populations in the Local Group. Recent work has provided evidence for a coeval early generation of globular clusters in most galaxies throughout the Local Group. Harris et al. (1997) have shown that NGC 2419, a metal-poor cluster located in the remote Milky Way halo, has the same age, to within ∼1 Gyr, as M92. Globular clusters in the Fornax dSph also appear to have essentially the same age as Milky Way globular clusters of similar metallicity, although with a very different HB morphology (Buonanno et al. 1998). A similarly old age has been inferred for the oldest globular clusters in M33, M31, the Large Magellanic Cloud (Sarajedini et al. 1998 and references therein), and for the unique globular cluster in the WLM dwarf galaxy (Hodge et al. 1999). Therefore the earliest star formation seems to have been coeval in all parts of the Milky Way protogalaxy (Harris et al. 1997), but also across the Local Group many galaxies have experienced their first epoch of *cluster* formation at around the same time 13–15 Gyr ago (Sarajedini et al. 1998).

Our discovery of an old HB in Leo I allows us to state that a significant old component is present in *all of the Local Group dSph galaxies*. Extended HBs and/or RR Lyrae variables are known in all of the dSph/dE dwarfs the Local Group, including both the dE/dSph satellites in the M31 and Galaxy subgroups and the few dwarfs sitting (as Leo I) in isolated locations (Da Costa 1998; Mateo 1998). Circumstantial evidence for halos of old stars also exist in Local Group dwarf irregular galaxies (e.g., Minniti, Zijlstra, & Alonso 1999; Cole et al. 1999), and the presence of an old population has been confirmed in IC 1613 by detection of RR Lyrae variables (Saha et al. 1992).

Thus, the finding that the oldest globular clusters share a common early formation epoch can be extended to the stellar *field populations* in dwarf spheroidal galaxies. The old globular cluster systems and the dwarf spheroidal galaxies underwent their first star formation episode at a single common early epoch, irrespective of the environment they inhabit in the Local Group and of their subsequent star formation history. Building the early generation of stars in a narrow time interval is clearly necessary to explain the nearly simultaneous birth of stars in a variety of galaxies and Local Group environments more than 10 Gyr ago.

We are grateful to P. Stetson for making his suite of photometric programs available to us. Y. M. acknowledges support from the Italian Ministry of Foreign Affairs and the Dottorato di Ricerca program at the University of Padova.

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