The Stellar Content of Local Group Galaxies
IAU Symposium, Vol. 192, 1999
Patricia Whitelock and Russell Cannon, eds.

Stellar Population Gradients in Phoenix and Leo I

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Abstract.
The study of gradients in the stellar populations of dwarf galaxies will give us necessary information to construct detailed models of their formation and evolution. We find clear traces of these gradients, in the sense of stars being older for larger galactocentric distances, in two interesting nearby dwarfs: Phoenix and Leo I.

1. Introduction

Most work on the star formation history (SFH) of Local Group dwarf galaxies has been typically devoted to the stellar population of their central regions. However, there is increasing evidence about the existence of galactocentric gradients in the old and intermediate-age stellar populations (e.g. Martínez-Delgado et al. 1999; Martínez-Delgado & Aparicio 1998; Han et al. 1997; Da Costa et al. 1996). In this paper we discuss the results on the stellar population gradients in two particularly interesting Local Group galaxies: Phoenix and Leo I, based on the morphology and star counts in the red-clump (RC)/horizontal-branch (HB) area and red-giant branch (RGB) in their color-magnitude diagrams (CMDs).

2. Phoenix

Figure 1 (left panels) shows the CMDs for three regions of the Phoenix dwarf galaxy at increasing galactocentric distances: region A, 0 pc $< a_h \leq 229$ pc; region B, 229 pc $< a_h \leq 457$ pc; and region C, $a_h \geq 457$ pc (see Martínez-Delgado et al. 1999). The presence of a conspicuous main-sequence in region A clearly indicates a gradient in the youngest stellar population. However, to really trace the structure of the galaxy, the intermediate-age and old populations must be investigated. We will center on these ages in the following.

The right panels of Fig. 1 show a synthetic CMD (computed for a constant star formation rate, SFR, extending from 15 Gyr ago to date) in which the observational effects of each of the corresponding regions have been simulated (see Aparicio, this book, and references therein for details on this simulation). Comparison of the right-side CMDs with the left-side ones helps to better understand the role of observational effects in the morphology of the latter.

https://doi.org/10.1017/S0074180900204300 Published online by Cambridge University Press

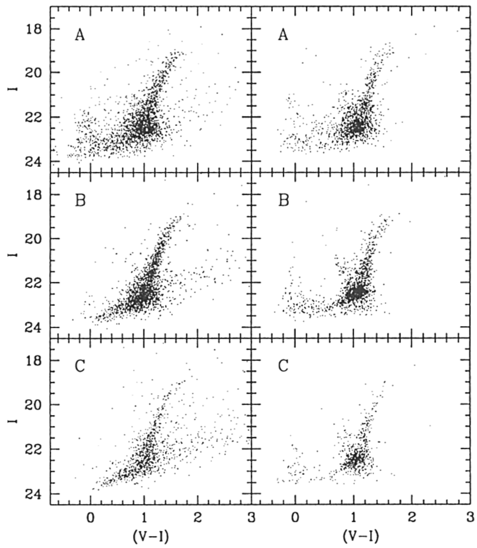

Figure 1. Observed (left) and model (right) CMDs for the three selected regions of the Phoenix dwarf galaxy.

2.1. Gradient in the RC Morphology

The RC of Helium burning stars is a powerful indicator for the intermediate-age population. Interestingly, a spatial gradient is found in the number of stars populating the RC of Phoenix. To quantify it we compare the observed ratios of RGB to RC stars across the galaxy ($N_{\rm RGB}/N_{\rm RC}$) with those for the model CMDs shown in Fig. 1 ($N^{\rm s}_{\rm RGB}/N^{\rm s}_{\rm RC}$). The result is that while the raw $N_{\rm RGB}/N_{\rm RC}$ ratio increases, the synthetic $N^{\rm s}_{\rm RGB}/N^{\rm s}_{\rm RC}$ decreases with galactocentric radius.

This gradient in the RC morphology is compatible with two different scenarios: a) the presence of a substantial intermediate-age population in the central region of Phoenix, which would be less prominent in the outer regions of the galaxy; b) a variation of the metallicity of the old population with galactocentric radius, in which the more metal rich old stars are concentrated in the inner regions of the galaxy hence moving He-burning stars from the HB into the RC. However, scenario b) would produce a change in the position and/or width of the RGB which is not observed in our CMD, therefore supporting scenario a).

Table 1. Gradients in the RC and HB of Phoenix dwarf galaxy

	$N_{\rm RGB}/N_{\rm RC}$	$N^{\rm s}_{\rm RGB}/N^{\rm s}_{\rm RC}$	$N_{\rm HB}/N_{\rm RGB}$	$N^{\rm s}_{\rm HB}/N^{\rm s}_{\rm RGB}$
region A	0.32 ± 0.03	0.35 ± 0.03	0.40 ± 0.06	0.11 ± 0.03
region B	0.41 ± 0.03	0.25 ± 0.02	0.28 ± 0.04	0.20 ± 0.03
region C	0.46 ± 0.06	0.22 ± 0.01	0.44 ± 0.08	0.18 ± 0.02

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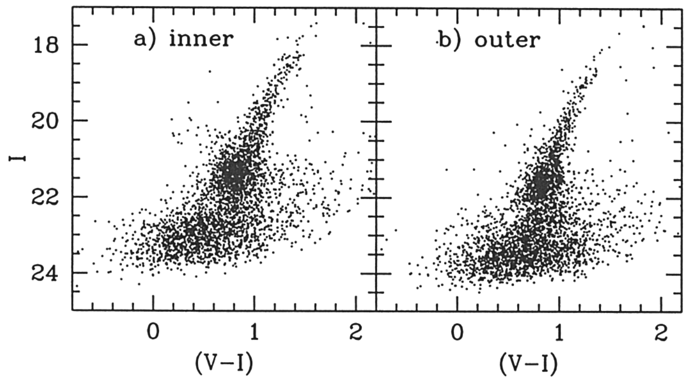

Figure 2. CMD for the central ("inner") and an "outer" region of Leo I dSph galaxy. Both CMDs have the same number of stars.

2.2. Gradient in the HB Morphology

The CMDs of the different regions of Phoenix plotted in Fig. 1 display a clear variation of the HB morphology from the center to the external parts of the galaxy. While the presence of a blue HB in the CMD of the region C is strong evidence that an old population exists in the outer part of the galaxy, the gradient in the morphology could at least partially be an artifact of observational effects, since the HB is near the limit of our photometry.

To analyze quantitatively this issue, we have obtained the ratio of the HB to RGB stars for the three CMDs, in a way similar to that used to study the RC morphology. The results are listed in Table 1. $N^s_{\rm HB}/N^s_{\rm RGB}$ is similar for regions B and C, but $N_{\rm HB}/N_{\rm RGB}$ is significantly larger for region B. Since the color of the RGB remains almost unchanged from regions B and C, the difference in $N_{\rm HB}/N_{\rm RGB}$ might be the result of the outer region of the galaxy being probably older.

3. Leo I

We have used the deep photometry published by Lee et al. (1993) to investigate the existence of stellar population gradients in Leo I. Figure 2 shows the CMD for two selected regions in this galaxy: a) inner, elliptical region of semiaxes 60 and 35 pc; b) region outside an ellipse of semiaxes 118 and 92 pc and reaching up to about 180 pc from the center of the galaxy. The CMD of the inner region shows a wider RGB, a rounder RC and a number of stars bluer and brighter than the RC, which indicate the presence of relatively recent star formation ($\sim$ few hundred Myr) in the center of the galaxy. The CMD of the outer region, however, shows a RC less populated in its blue bright quadrant (where the *younger* intermediate-age stars would be), and less (if any) stars bluer and brighter than the RC.

We computed for Leo I the ratio of the number of stars in a section of the RGB ($N_{\rm RGB}$) and in the upper and lower halves of the RC ($N_{\rm RC,up}$, $N_{\rm RC,dn}$), which respectively represent the *younger* intermediate-age stars and *older* inter-

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mediate-age *plus* old stars respectively. Since we are ~ 2 mag above the limit of the photometry, we neglect incompleteness effects.

Results are listed in Table 2. The ratio $N_{\rm RGB}/N_{\rm RC,up}$ increases slightly towards the outer part, while the opposite trend is observed for $N_{\rm RGB}/N_{\rm RC,dn}$. As in the case of Phoenix this could indicate a population older on average in the outer part of the galaxy. In Gallart et al. (1999b) we conclude that the width of the Leo I RGB in the center of the galaxy is caused mainly (if not completely) by the stellar age range. This, together with the characteristics of the CMD and the ratios listed in Table 2, suggests to us the conclusion that the narrower RGB in the outer part may be due to star formation that stopped earlier there.

Table 2. Gradients in the RC of Leo I dSph

	$N_{\rm RGB}/N_{\rm RC,up}$	$N_{\rm RGB}/N_{\rm RC,dn}$
Inner	0.69 ± 0.07	1.0 ± 0.11
Outer	0.83 ± 0.11	0.49 ± 0.06

4. Conclusion

The time is ripe to address the study of spatial gradients in the stellar populations of dwarf galaxies, which will give us necessary information to construct detailed models of their formation and evolution. A full characterization of these gradients requires photometry reaching the oldest main sequence turnoffs, which will allow us to retrieve the SFH in different regions of these galaxies with similar detail as the SFH we have obtained for an inner Leo I field using HST data (Gallart et al. 1999b). This can be done using ground based observations for the nearest dSph galaxies and HST data for the remaining members of the Local Group (since it will be possible to reach the oldest MS turnoffs for even the more distant objects with the Advanced Camera).

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Discussion

Lee: When I was working with the Leo I data (Lee et al. 1993, A.J.) I recognized there are differences in the CMDs of inner region and outer region. At that time I thought the differences in the (RGB + RGC) might be mostly due to the crowding difference. So crowding effects should be taken into account for studying the differences in Leo I. However, there is an obvious difference between the two regions, which is the presence of a small group of bright yellow stars in the left side of the red giant clump. I suggested before that they may be mostly anomalous Cepheids.