

Faint dwarf spheroidals in the Fornax Cluster

A flat luminosity function

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Received 4 November 2002/ Accepted 1 December 2002

Abstract. We have discovered ≈ 70 very faint dwarf galaxies in the Fornax Cluster. These dSphs candidates follow the same magnitude-surface brightness relation as their counterparts in the Local Group, and even extend it to fainter limits. The faintest dSph candidate in our sample has an absolute magnitude of $M_V \approx -8.8$ mag and a central surface brightness of $\mu_V \approx 27$ mag/arcsec². There exists a tight color-magnitude relation for the early-type galaxies in Fornax that extends from the giant to the dwarf regime. The faint-end slope of the luminosity function of the early-type dwarfs is flat ($\alpha \approx -1.1 \pm 0.1$), contrary to the results obtained by Kambas et al. (2000).

Key words. galaxies: clusters: individual: Fornax cluster – galaxies: dwarf – galaxies: fundamental parameters – galaxies: luminosity function

1. Introduction

Little is known about the very faint end of the galaxy luminosity function (LF) – the realm of the dwarf spheroidal (dSph) galaxies. The current CDM models of galaxy and structure formation (e.g. Moore et al. 1998) suggest that dwarf galaxies were very abundant in the early universe and represented the building-blocks of larger galaxies. Especially in galaxy clusters, large numbers of dwarf galaxies should have been formed. Different models result in a steep slope at the faint end of the LF: $-1.4 \leq d \log N / d \log L \leq -2.0$ (e.g. Kauffmann et al. 1994).

Most of our knowledge about the dwarf spheroidals comes from studies of Local Group examples (e.g. Mateo 1998). Some authors do not distinguish them from the somewhat brighter dwarf ellipticals (dEs), but here we follow the definition given by Grebel (2001) who characterizes them as diffuse, low surface brightness dwarfs with $M_V < -14$ mag and $\mu_V > 22$ mag arcsec⁻². Although primarily old stellar populations, dSphs are not the simple systems they were once thought to be – many show evidence of star formation in multiple bursts and traces of molecular gas (e.g. Grebel 1997). Such gross differences are very likely due to the effects of the environment these galaxies exist in, and thus are efficient tracers of evolutionary processes in galaxies. A large-scale study of these systems in nearby clusters would be essential for the understanding of the “global” picture of galaxy evolution.

The faint end of the luminosity function of the Local Group is quite flat compared with CDM model predictions. A Schechter function fit gives a faint-end slope of $\alpha = -1.1 \pm 0.1$ (Pritchet & van den Bergh 1999). Several CCD studies of galaxy clusters show rising numbers of low-luminosity dEs down to about $M_V \approx -11$ mag with very different faint-end slopes in the range $-1.1 > \alpha > -2.2$ (e.g. de Propris et al. 1995; López-Cruz et al. 1997). However, it is not known whether the galaxy luminosity function in clusters continues to $M_V = -9$, as it does in the Local Group. In fact, the latest discoveries of previously unknown dSphs (e.g. Armandroff et al. 1999) raises the question of how complete is the Local Group sample. Is there a true cutoff or one imposed solely by small number statistics? The detection of a lower-L cutoff would add strong constraints to galactic formation models.

The most complete investigation of the Fornax dwarf galaxies was done by Ferguson (1989) as well as by Davies et al. (1988). As shown by Hilker et al. (1999a) and Drinkwater et al. (2001) the morphological classification of Fornax members by Ferguson (1989) is very reliable and very few dEs were missed within the survey limits.

The luminosity function of the Fornax dwarf galaxies was studied by Ferguson & Sandage (1988). The faint end slope of the dE/dS0 LF, fitted by a Schechter (1976) function up to $M_V \approx -13$, is quite flat ($\alpha = -1.08 \pm 0.10$). However, in a recent study, Kambas et al. (2000) report the discovery of a very large number of low surface brightness dwarfs in Fornax, resulting in a steep faint-end slope of the LF ($\alpha \approx -2.0$) down to $M_B \approx -12$ mag.

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2. Observations and data analysis

The observations were performed in an observing run in December 1999 with the 100-inch du Pont telescope at Las Campanas, Chile. The Wide-Field CCD images a 25' diameter field, with a scale of about 0.774"/pixel. 14 fields in the central region of the Fornax cluster and one additional background field have been observed through the Johnson *VI* filters. All nights were photometric throughout, and the seeing was in the range 1".5–2".0.

The CCD frames were processed with standard IRAF routines, instrumental aperture magnitudes were derived using SExtractor2.1 (Bertin & Arnouts 1996). Surface brightness profiles of all galaxies were measured with the ellipse fitting routines under the STSDAS package of IRAF.

In order to optimize the detection of faint resolved sources by the software routines, all CCD fields were first inspected carefully by eye, independently by the authors MH and SM, to search for low surface brightness objects with sizes of Local Group dSphs (core radii of 150–400 pc, corresponding to core diameter of 3" to 9" in Fornax distance). This search resulted in the detection of about 70 previously uncatalogued dSph candidates.

The detection-sensitive parameters of SExtractor2.1 were then optimized such that most objects of the by-eye-catalog were detected by the program. Further visual inspection of the SExtractor detections within the same parameter space as the visual detections, added about 10% more dSph candidates to the by-eye-catalog. About 10% of the obvious by-eye detections could still not be found by the routine. These sources were kept in the catalog, but not considered for the determination of the LF.

For the study of the faint end of the LF, the number counts of dSph candidates have to be completeness corrected. Therefore, we randomly distributed 2000 simulated dSphs (in 100 runs) in each of the 14 CCD fields. The magnitudes and central surface brightnesses were chosen such that they extended well beyond the observed parameter space at the faint limits. The optimized detection parameters were used to recover the artificial galaxies. The same selection criteria as for the discovered dSphs were applied to derive the completeness values as a function of magnitude and central surface brightness (see Fig. 2). For the number counts of the LF the completeness in each CCD field has been corrected individually to account for the differing number densities.

Further details of the observations and data analysis will be given in Hilker et al. (2003, in prep.).

3. Dwarf spheroidal candidates in Fornax

Since the faintest Local Group dSphs appear just resolved when projected to the Fornax distance (1" corresponds to about 92 pc at 19 Mpc; Ferrarese et al. 2000), the first selection criterion for dSphs in Fornax was a measured *FWHM* larger than 5". Furthermore the color range was restricted to within $\pm 2\sigma$ of the color-magnitude relation (see Fig. 1). Finally, probable dSphs candidates should be located within $\pm 2\sigma$ of the magnitude-surface brightness relation (Fig. 2).

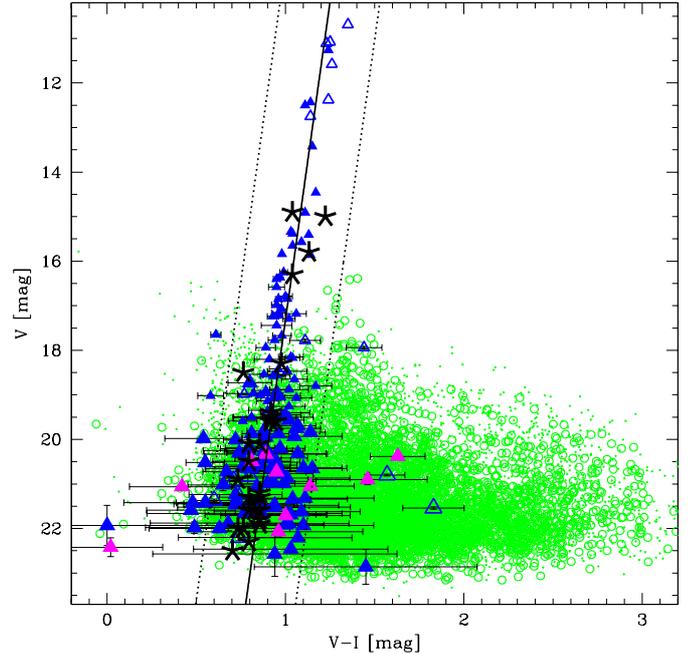


Fig. 1. CMD of all extended (circles) and point sources (dots) in our Fornax field also in comparison with Local group dSphs. The formerly known Fornax members are marked as small triangles. The larger triangles are newly discovered dSphs. Light grey triangles are dwarfs that have been detected only by eye. Open symbols mark galaxies that lie outside 2σ of the magnitude-surface brightness relation. The solid line is a fit to the color-magnitude relation of dEs between $0.3 < (V - I) < 1.4$. Dotted lines are the 2σ deviations from the fit. Asterisks are the Local Group dSphs (data from Grebel et al. 2002) projected to the Fornax distance.

The photometric parameters of the dwarf galaxies have been derived from the analysis of their surface brightness profiles: the total magnitude by a curve of growth analysis, the color within an aperture of 8" diameter, and the central surface brightness from an exponential fit to the outer part of the profile.

3.1. The color-magnitude relation

In Fig. 1 the color magnitude diagram (CMD) of all objects is shown. The newly discovered dSphs are highlighted by large triangles. Except for some outliers, they follow a well defined color-magnitude sequence in the sense that the fainter galaxies are bluer. A linear fit to the data yields: $(V - I) = -0.035 \cdot V + 1.61$ with a rms of 0.14.

The color-magnitude relation of early-type galaxies is well known from other clusters (e.g. Coma cluster, Secker et al. 1997). It is likely explained by a strong metallicity-luminosity relation (see Poggianti et al. 2001). Here we show for the first time that this relation extends all the way down to the regime of dSphs. For the Local Group dSphs, there do not exist homogeneous $(V - I)$ colors. However, assuming that they are single stellar populations and then transforming their average iron abundances $[\text{Fe}/\text{H}]$ (Grebel et al. 2002) to $(V - I)$ colors using Eq. (4) given in Kissler-Patig et al. (1998), they follow surprisingly well the same color-magnitude relation (Fig. 1).

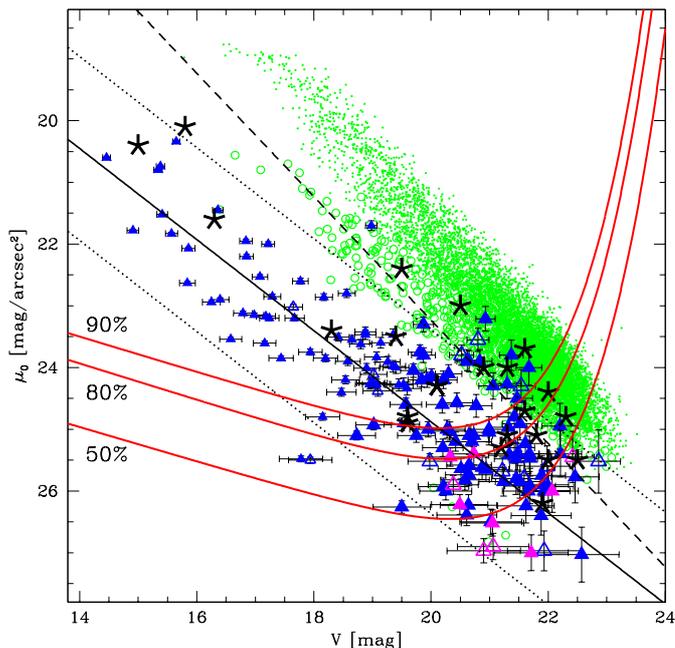


Fig. 2. Magnitude-surface brightness diagram in our Fornax field and the Local Group dEs and dSphs. The central surface brightness derived from an exponential fit is plotted. Symbols are as in Fig. 1, except that open triangles here mark galaxies that lie outside 2σ of the color-magnitude relation. The dashed line indicates a scale length of $2''.5$ for an exponential profile. The solid and dotted lines are the fit to the magnitude-surface brightness relation and its 2σ deviations. The solid curves show the completeness limits of 90, 80 and 50%.

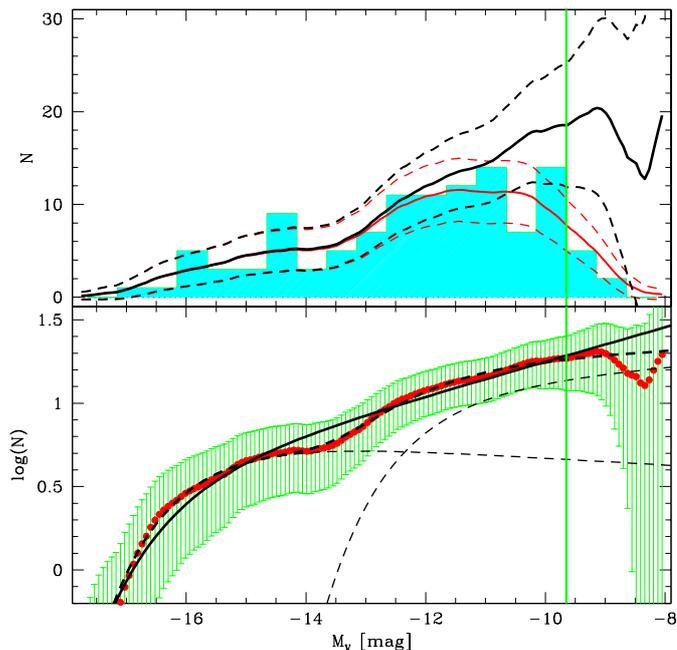


Fig. 3. Luminosity function of dEs and dSphs in Fornax. The 50% completeness limit is indicated by a vertical line. Upper panel: the shaded histogram are the uncorrected number counts. The thin line gives a binning independent representation of the counts (Epanechnikov kernel of 0.5 mag width). The thick line are the completeness corrected counts, with the 1σ uncertainty limits (dashed). Lower panel: completeness corrected number counts in logarithmic representation. The best fitting single Schechter function (solid curve) and sum of two Schechter functions (dashed curves) are shown.

3.2. The magnitude-surface brightness relation

Dwarf ellipticals are known to follow a $r_{\text{eff}}-M_V$ relation distinct to that of giant ellipticals (e.g. Bender et al. 1992). Also, they follow a tight $M_V-\mu_V$ relation in the sense that central surface brightness increases with increasing luminosity (Ferguson & Sandage 1988). The validity of this relation has been a subject of lively debate. A number of authors have argued against the existence of a magnitude-surface brightness relation for dEs (i.e. Irwin et al. 1990) and questioned the cluster membership assignment to dEs based on morphology. However, Drinkwater et al. (2001) confirm the surface brightness-magnitude relation for Fornax dwarfs, based on their spectroscopic survey.

Our data shows that the magnitude-surface brightness relation continues even to fainter magnitudes. As one can see in Fig. 2, the sequence of Fornax cluster dSphs matches well the location of Local Group dSphs in this plot (data from Grebel et al. 2002). Note that some more compact dSphs still might be hidden in the barely resolved objects.

4. The faint end of the luminosity function

In Fig. 3, the luminosity distribution of the dEs and dSphs in Fornax is shown. When fitting a Schechter (1976) function to the counts with a completeness larger than 50% the faint-end slope is $\alpha = -1.11 \pm 0.10$. This agrees with the result

by Ferguson & Sandage (1988), although their faintest dwarfs were 2.5 mag brighter than ours.

There seems to be a dip in the luminosity distribution at about $M_V = -14$ mag. Although this might be due to small number counts (the amplitude of the dip is about equal to the Poisson error of the number density at the corresponding magnitude), it is interesting to note that this is near the luminosity where the separation of dEs and dSphs is defined (e.g. Grebel 2001). A sum of two Schechter functions does better fit the data (see lower panel in Fig. 3) but does not change the faint-end slope.

4.1. Comparison with Kambas' results

Recently, Kambas et al. (2000) reported the discovery of a very large number (>3400) of very low surface brightness (VLSB) galaxies which are concentrated towards the center of the Fornax cluster. The resulting faint-end slope is very steep: $\alpha \approx -2$. Thus, although having a comparable limiting magnitude, Kambas' results are in large disagreement with ours. The data sets and selection criteria of both studies are quite different. Kambas et al. took R band images on a CCD chip with a scale of $2''.3$ per pixel, thus having a 3 times lower resolution than we do. The VLSB candidates were selected by lower limits in the scale length and surface brightness derived from the isophotal magnitude and area measured by SExtractor.

No curve-of-growth analysis or surface brightness profile fitting was performed to cross-check the SExtractor results.

To find the reason for this discrepancy, Kambas kindly provided us with his data. In the overlapping region of both data sets, all VLSBs (in total 473) were also detected by us. According to Kambas et al., only 110 of them are background objects. However, by comparison with our data we found that at least 300 of the 473 objects are clear non-members of the Fornax clusters. About 90 objects are clear point sources even at our 3 times higher resolution. More than 250 objects have a $(V - I)$ color redder than 1.4 mag, and thus are background galaxies (which could not be detected with only one filter at hand). Many other VLSB candidates are either clearly multiple or are located in the halo of brighter galaxies or close to saturated stars.

We therefore suggest that most of Kambas' VLSB dwarf candidates are not dwarf galaxies in Fornax. And we conclude that SExtractor values that characterize the sizes of objects do not provide reliable selection criteria close to the resolution limit and close to the magnitude and surface brightness limit.

5. Summary and conclusions

A deep wide field survey of the central 2.4 square degrees of the Fornax cluster has revealed a large population of previously undetected low surface brightness dwarf galaxies whose brightness profiles could be measured. It is found that they resemble the Local Group dwarf spheroidals. In particular, they follow the same magnitude-surface brightness relation. Also they follow a quite tight color-magnitude relation which can be explained by a metallicity effect, in the sense that fainter dwarf galaxies are more metal-poor than brighter ones.

Our study has therefore shown for the first time that the counterparts of the Local Group dwarf spheroidals do exist in cluster environments. The faint end slope of their luminosity function is flat ($\alpha = -1.1 \pm 0.1$) in comparison to the expected initial slope of small halos in current CDM simulations of galaxy clusters. If theory is right, this might point to the destruction of a large number of dwarfs during the evolution of a cluster. One might suggest that the debris of these dwarfs have partly built up the huge cD halo around the central galaxy (e.g. Hilker et al. 1999b).

A dip in the luminosity function at the transition between dwarf ellipticals and dwarf spheroidals (at $M_V \simeq -14$ mag) might point to two distinct families of galaxies. Although their photometric properties are very similar, dEs and dSphs might have experienced different evolutionary histories, i.e. that dSphs evolved from dwarf irregulars that have consumed their gas or have lost it by ram pressure stripping (Grebel 2001).

Our study has also shown that the combination of deep multi-color photometry in a wide field with a sufficient resolution is crucial in order to unambiguously identify dwarf spheroidal candidates in nearby clusters. In upcoming studies one should push the limits to even fainter magnitudes and surface brightnesses, since we have still not seen a mass cutoff of the smallest galactic systems.

Acknowledgements. We gratefully thank A. Kambas for providing us with his data. LI and SM acknowledge support from "Proyecto FONDAF 15010003". SM was supported by DAAD PhD grant Kennziffer D/01/35298. MH thanks du Pont staff for support.

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