THE FULL-FLEDGED DWARF IRREGULAR GALAXY LEO A
VLADAS VANSEVIČIUS,1,2, 3 NOBUO ARIMOTO,2 TAKASHI HASEGAWA,4 CHISATO IKUTA,2 PASCALE JABLONKA,5 DONATAS NARBITIS,3 KOUI OHTA,5 RIMA STONKUTĖ,3 NAOYUKI TAMURA,7 VALDAS VANSEVIČIUS,3 AND YOSHIHIKO YAMADA2, 8
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ABSTRACT
We have studied Leo A, an isolated and extremely gas-rich dwarf irregular galaxy of very low stellar mass and metallicity. Ages of the stellar populations in Leo A range from ~10 Myr to ~10 Gyr. Here we report the discovery of an old stellar halo and a sharp stellar edge. We also find that the distribution of stars extends beyond the gaseous envelope of the galaxy. Therefore, by its structure as well as stellar and gaseous content, Leo A is found to resemble massive disk galaxies. This implies that galaxies of very low stellar mass are also able to develop complex structures, challenging contemporary understanding of galaxy evolution.
Subject headings: galaxies: dwarf — galaxies: individual (Leo A) — galaxies: irregular — galaxies: stellar content

1. INTRODUCTION
Understanding galaxy formation and evolution on the Hubble timescale is one of astronomy’s greatest challenges. The importance of dwarf irregular galaxies (DIGs), and particularly stellar populations in their outskirts, for study of the galaxy buildup and star formation processes is well recognized and has been widely discussed recently (see, e.g., Hodge 2003). DIGs are excellent targets to study galaxy evolution, as their long relaxation times keep traces of interactions, merging events, or starbursts at least for a few billion years. Many studies (Minniti & Zijlstra 1996; Aparicio et al. 2000; Held et al. 2001; Drozdovsky et al. 2003) were devoted to search for the outer stellar edges and extended old stellar populations in DIGs. While the radial reddening of the stellar populations distributed in the disklike structures was reported, the prominent edges were never revealed (Hodge 2003).

For our study we selected the nearby DIG Leo A (Fig. 1). Leo A is one of the most isolated galaxies in the Local Group (van den Bergh 1999). It is extremely gas rich (Young & Lo 1996) and possesses very low stellar mass (Mateo 1998) and metallicity (Skillman et al. 1989; van Zee et al. 1999). On the basis of Hubble Space Telescope (HST) photometric observations in the central part of the galaxy, a young age was deduced (Tolstoy et al. 1998). This conclusion challenged further investigations. Deep HST photometry was performed in the adjacent field, and the signatures of an old stellar population were identified (Schulte-Ladbeck et al. 2002). The final proof of the old stellar population in Leo A was brought by the discovery of the RR Lyr variables (Dolphin et al. 2002). In addition, it was noted that the red giant branch (RGB) stars are distributed more widely than the blue stars (Dolphin et al. 2002). The gaseous content of the galaxy was investigated in detail (Young & Lo 1996), and a symmetrical H I envelope, twice more extended than the Leo A stellar distribution, was discovered. A very small lopsidedness measured in the red continuum and in the He I emission (Heller et al. 2000) suggests that Leo A has not experienced any strong event of merger or interaction for at least a few billion years and that it is a good target for study of quiescent galaxy evolution.

2. OBSERVATIONS AND DATA REDUCTIONS
Taking into account the angular size of Leo A (the Holmberg’s dimension is ~7’’ × 4’’; Mateo 1998), the Subaru Telescope equipped with the Prime Focus Camera (Suprime-Cam; Miyazaki et al. 2002) is an ideal instrument to study the stellar content at the galaxy’s very outskirts (Fig. 1). The single-shot Suprime-Cam mosaic (5 × 2 CCD chips) covers a field of 34’ × 27’’ (pixel size 0’’2 × 0’’2), and a magnitude of $V \sim 25$ mag is reached in 60 s. We acquired images in three broadband filters: $B$ (5 × 600 s), $V$ (5 × 360 s), and $I$ (30 × 240 s) during two photometric nights (seeing less than 0’’8) on 2001 November 20–21. Standard reduction procedures were performed with a software package (Yagi et al. 2002) dedicated to the Suprime-Cam data. We employed six central CCD frames of the mosaic and performed crowded-field stellar photometry by applying DAOPHOT (Stetson 1987) implemented in the IRAF software package (Tody 1993) on five individual exposures in each photometric band. In order to use HST data for the central part of the galaxy consistently, we transformed the instrumental magnitudes to the HST photometric system, F439W, F555W, and F814W (for further abbreviation we use $B$, $V$, and $I$) by referring to the HST photometric data archive (J. Holtzman et al. 2004, in preparation). A transformation accuracy of ~0.01 mag in the $V$ and $I$ bands and of ~0.02 mag in the $B$ band was achieved. A complete data set with detailed descriptions of the applied reduction and photometry procedures will be published elsewhere (T. Hasegawa et al. 2004, in preparation).9

9 Photometric data available upon request: vladas@astro.lt.
In order to trace the entire extent of the old stellar populations in Leo A we employed the RGB stars. The following RGB star selection criteria have been applied: (1) location of stars in the color-magnitude diagram, $I$ versus $(V - I)$, within the zone marked in Figure 2; (2) high photometric accuracy, $\sigma_I < 0.06$ mag and $\sigma_V < 0.08$ mag; (3) good fit with the stellar point-spread function (DAOPHOT parameters: $\chi^2 < 1.5$; |sharpness| < 0.4); and (4) photometric criterion devoted to wipe out the objects with nonstellar spectra, $(B - V) - (V - I)$, in the range of $-0.40$ to $+1.10$. The main parameters deduced for the RGB star distribution are as follows: center at R.A. = 09$^\mathrm{h}$59$^\mathrm{m}$24.0$^\mathrm{s}$, decl. = 30$^\circ$44$'$47" (J2000.0); ellipticity (ratio of semimajor to semimajor axis) $b/a = 0.60 \pm 0.03$ coincident with $b/a$ of the H I envelope (Young & Lo 1996); and position angle of the major axis P.A. = 114$^\circ$ $\pm$ 5$. For a detailed examination we selected the field located inside the ellipse ($b/a = 0.60$) of $a = 12$' centered at the derived position (stellar content is shown in Fig. 2a), which is large enough to comfortably accommodate Leo A inside. We detected 1394 RGB stars distributed symmetrically and smoothly within this field. The average accuracies for the RGB star sample are (1) coordinate matching among the $B$, $V$, and $I$ bands, 0.06; and (2) photometry, $\sigma_I = 0.019$ (4.6), $\sigma_V = 0.015$ (4.7), and $\sigma_I = 0.010$ (4.7) (the average number of detections in each band is given in parentheses).

The radial profile (RP) of the RGB star surface number density (arcmin$^{-2}$; Fig. 3) was constructed by integrating within elliptical ($b/a = 0.60$) rings of width, $\Delta a = 0.5$ (at the Leo A distance, 800 kpc, 1' corresponds to 230 pc). We performed RP robustness tests by varying $b/a = (0.55, 0.60, 0.65)$, P.A. = (104$^\circ$, 114$^\circ$, 124$^\circ$), and $\Delta a = 0.2$–1.0, as well as a magnitude cut at the faint limit, $I = (22.5, 23.0, 23.5)$, and found no significant change in the RP’s form. Five distinct RP zones are noticeable (Fig. 3): (1) a crowded central part, $a = 0.0$–2.0 (completeness at $I = 23$ mag varies with radius from 80% to 90%); (2) an old exponential disk extending far beyond the previously estimated size of the galaxy (Mateo 1998), $a = 2.0$–5.5 (for representative stellar content, see Fig. 2b); scale length (SL) $1.03 \pm 0.03$; (3) the discovered stellar component in DIGs, which we call “halo,” $a = 5.5$–7.5 (for stellar content, see Fig. 2c), SL $1.84 \pm 0.09$; (4) a sharp cutoff of the RGB star distribution coincident with the observed edge (Young & Lo 1996) and predicted cutoff of the H I envelope (Sternberg et al. 2002), $a = 7.5$–8.0; and (5) a sky background zone where we derived a number density of contaminants to the RGB stars, $a = 8.0$–12.0 (for representative stellar content, see Fig. 2d). In order to show the entire extent of the discovered structures in Leo A, we overplotted some characteristic size ellipses ($b/a = 0.60$) on the Suprime-Cam V-band image (Fig. 1). It is worth noting that the suspected Leo A RR Lyr variable C1-V01 (Dolphin et al. 2002) is located just outside the ellipse marking the galaxy size, confirming the old age and large extent of the discovered stellar halo.

4. DISCUSSION AND CONCLUSION

In the cold dark matter cosmology scenarios, galaxies are assumed to build up and develop their internal structure via hierarchical merging of the primordial density fluctuations into larger systems. Therefore, our discovery of the stellar populations possessing distinct spatial distributions in the undisturbed very low mass DIG Leo A, which is unlikely built via merging, suggests an alternative way of galaxy structure for-
Fig. 2.—Color-magnitude diagrams of the stellar-like objects in Leo A. The objects are shown (a) in the elliptical (blu = 0.6) area, $a < 12'$ containing Leo A and its surroundings, the number of objects plotted, $N = 12,604$; (b) in the representative old disk area, $3.0 < a < 5.0$, $N = 2462$; (c) in the discovered halo area, $5.5 < a < 7.5$, $N = 974$; and (d) in the background area, $9.0 < a < 10.5$, $N = 780$. The RGB stars employed for the structure analysis of Leo A were selected from the zone marked by lines: magnitude ranges from the RGB tip mag down to mag; the inclined lines are given by the equations $I = 20.4$ mag down to $I = 23.0$ mag; the inclined lines are given by the equations $I = 31 - 7(V - I)$ and $I = 28 - 6(V - I)$. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 3.—Radial profile of the RGB star surface number density in Leo A. The lines fitted to the old disk, $2.0 < a < 5.5$, and the halo, $5.5 < a < 7.5$, radial profiles, and the background, $8.0 < a < 12.0$ are shown. The Holmberg’s radius ($a = 3.5$) and the observed size of the $\text{H} \alpha$ envelope (Young & Lo 1996) ($a = 7.5$) are indicated with arrows. [See the electronic edition of the Journal for a color version of this figure.]
these Leo A features imply that the main disk properties of DIGs and of massive galaxies (van der Kruit 2001) are rather similar.

We conclude that the young and old Leo A disks, together with the discovered old halo and sharp stellar edge, closely resemble basic structures found in the large full-fledged disk galaxies. This suggests complex formation histories even in very low stellar mass galaxies such as Leo A and challenges contemporary understanding of galaxy evolution.

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