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# The dwarf spheroidal galaxy DDO 44: stellar populations and distance*

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**Abstract.** We have ground-based and HST WFPC2 imaging of the nearby low surface brightness dwarf spheroidal galaxy DDO 44. For the first time DDO 44 was resolved into stars. The resulting color-magnitude diagram for about 1290 stars show the red giant branch with a tip at $I = 23.55 \pm 0.15$, which yields the distance $D_{MW} = 3.2 \pm 0.2$ Mpc consistent with membership of DDO 44 in the NGC 2403 group. The linear separation of DDO 44 from NGC 2403 is 75 kpc on the sky and $30 \pm 450$ kpc along the line of sight. The relationship between the dwarf galaxy's absolute magnitude, $M_R^o = -13.1$, the central surface brightness, $\mu_R(0) = 24.1$ mag arcsec$^{-2}$, and the mean metallicity, [Fe/H] = $-1.7$ dex follow the trend for other nearby dwarf spheroidal galaxies. One globular cluster candidate has also been identified in DDO 44.

**Key words:** galaxies: dwarf – galaxies: fundamental parameters – galaxies: individual: DDO 44 – galaxies: photometry – galaxies: abundances

## 1. Introduction

In the "Catalogue of low surface brightness galaxies" (Karachentseva & Sharina 1988) there are 1555 objects situated within the Local Supercluster volume. This sample covering the whole sky shows a striking difference in distributions of dwarf irregular (dIrr) and dwarf spheroidal (dSph) galaxies over the sky (see also Figs. 1 and 2 in Karachentseva & Vavilova 1994). About 90% of the dSphs are concentrated towards the Virgo and Fornax clusters, while the rest of them are associated with the known nearby groups of galaxies. In the groups around the Milky Way, M 31, M 81, and NGC 5128, which were studied most intensely, the dSph companions also occupy a smaller volume with $R < 300$ kpc compared to dIrr members (van den Bergh 1994, Karachentsev 1996). In contrast, the sky distribution of dIrr galaxies looks rather smooth: only about half of them are associated with groups and clusters. Based on these data, one can assume that in the space between clusters and groups, i.e., in the so-called "metagalactic field", spheroidal dwarf systems may be absent in general. Such a morphological segregation appears quite natural in an evolutionary picture where irregular dwarf systems are transformed into spheroidal ones through gas loss by external ram pressure and tidal stripping as they approach giant galaxies (Einasto et al. 1974, Lin & Faber 1983). In this respect the discovery of an isolated dSph galaxy could shed light on dwarf galaxy evolution. Da Costa (1994) and Saviane et al. (1996) have shown that the Tucana dwarf galaxy may be considered as an isolated dSph system located almost at the border of the Local Group at $\sim 0.9$ Mpc from the Milky Way.

In the present paper we study the basic properties and the environmental status of another nearby dSph galaxy, DDO 44 (van den Bergh 1959). As a large-scale photograph taken in the $B$ band (Karachentseva et al. 1985) shows, DDO 44 = UGCA 133 (Nilson 1974) = kk 61 (Karachentseva & Karachentsev 1998) has a very low surface brightness distribution without any visible knots that might be indicative of H II regions or stellar associations. With an angular dimension of $3'.0 \times 2'.0$ the galaxy's integrated apparent magnitude corresponds to $B_T = 15^{\rm m}.64$ (NASA's Extragalactic Database = NED). In the NED, DDO 44 is classified as morphological type Sm, while van den Bergh (1959) and Karachentseva & Sharina classified it as dSph. Being only 80 arcmin away from the bright Sc galaxy NGC 2403,

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** Hubble Fellow

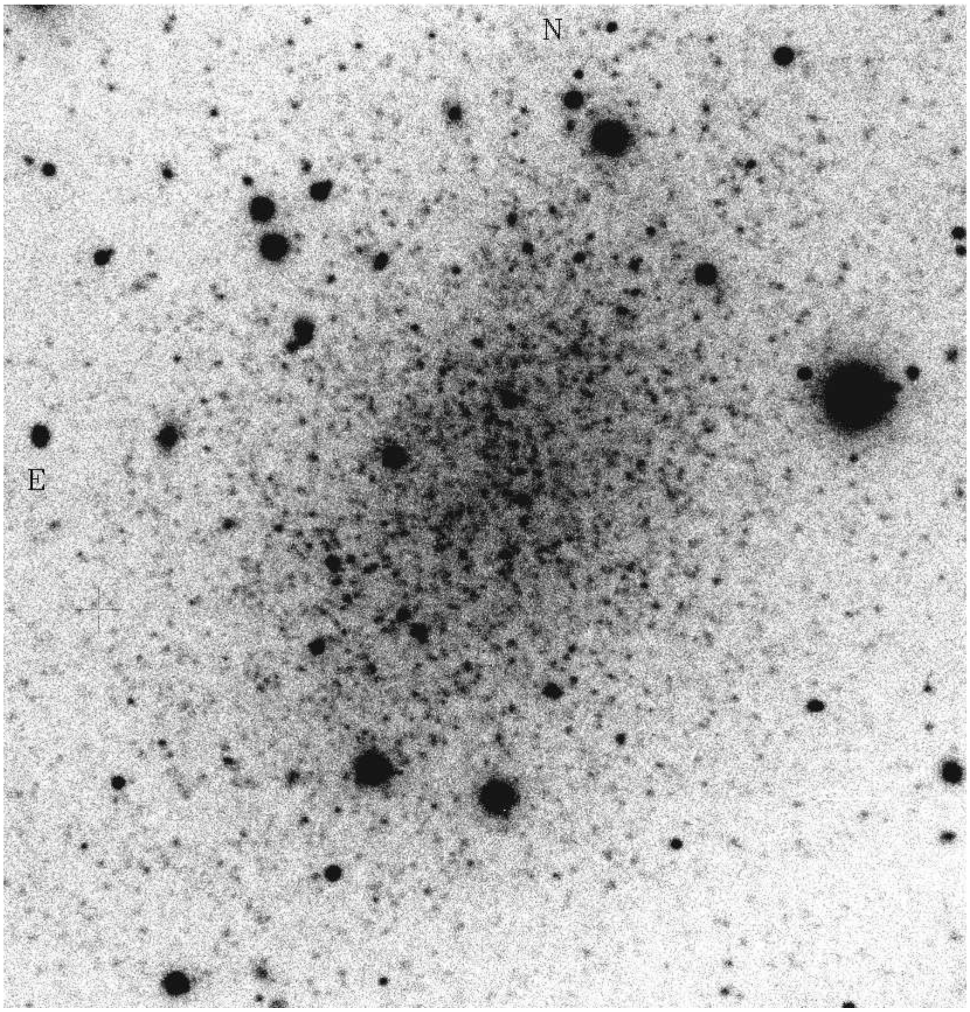


**Fig. 1.** $R$ image of DDO 44 obtained with the 6-m telescope with a seeing of $0''.9$. The field size is $170'' \times 178''$. North is up, East is left

DDO 44 seems to be a likely companion of this galaxy. Unfortunately, the radial velocity of DDO 44 is still unknown. Recent observation in the H I line yields only an upper limit for its H I flux, $S < 6$ mJy (Huchtmeier et al. 1999). Therefore a direct measurement of distance to DDO 44 can solve the question of its physical connection to NGC 2403.

## 2. Ground based observations and data reduction

DDO 44 was observed on January 19, 1999 with a CCD camera of the SAO 6-meter telescope. A CCD chip of 1024×1024 pixels provided a total field of $3'.5 \times 3'.5$ with a resolution of $0''.206$/pixel.

Two frames in the Cousins $R$ band with exposures of $2 \times 600$ s and four frames in $I$ band with exposures of $4 \times 300$ s were obtained. The seeing was FWHM = $0''.9$. The $R$ band frame of DDO 44 is shown in Fig. 1, which shows the galaxy to be resolved into a large number of faint stars. Absolute calibration and atmospheric extinction are based on observations of twenty Landolt (1992) standard stars. We have obtained the following calibrations (standard deviations of the residuals are 0.04 mag in $R$ and 0.05 mag in $I$, respectively):

$$R - r = 27^{\mathrm{m}}.38 + 0.0187 \cdot (R - I)$$
$$I - i = 26^{\mathrm{m}}.90 + 0.0513 \cdot (R - I),$$

where $r, i$ are instrumental magnitudes corrected for atmospheric extinction.

The derived images were processed with the MIDAS implementation of the DAOPHOT II program (Stetson et al. 1990). A total of about 1000 stars were measured to a limiting magnitude $I \sim 24^{\mathrm{m}}.2$. The rms uncertainty of aperture corrections is $0^{\mathrm{m}}.04$ in $R$ and $0^{\mathrm{m}}.05$ in $I$. Together with the rms errors of the $\{r, i\}$-to-$\{R, I\}$ transformation and uncertainties of the extinction corrections, $0^{\mathrm{m}}.04$ ($R$), $0^{\mathrm{m}}.05$ ($I$), these errors yield 0.07 mag zero-point rms uncertainty in the $R$ band, and 0.08 mag in the $I$ band. The final color-magnitude diagram is presented in Fig. 3. Apart from stellar photometry we also carried out aperture photometry of the galaxy in circular diaphragms, which allow to measure the integrated magnitudes in both filters.

## 3. HST WFPC2 photometry

To study the resolved stellar population of the galaxy and to measure its distance we observed DDO 44 = kk 61 with the Wide Field and Planetary Camera 2 (WFPC2) camera of the

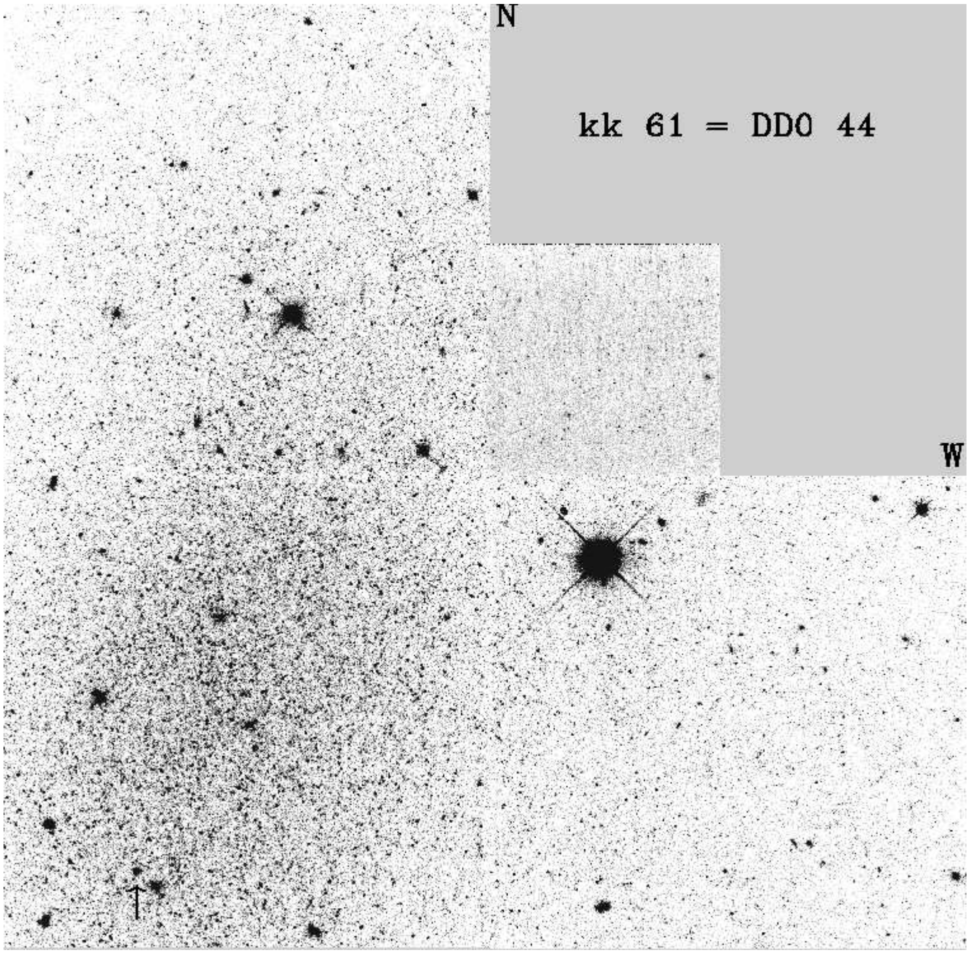


**Fig. 2.** WFPC2 image of DDO 44 made from the combination of two 600 s exposures through the F606W and F814W filters. A globular cluster candidate is indicated by the arrow in the left bottom corner.

Hubble Space Telescope (HST). The galaxy was observed on August 13, 1999 as part of a snapshot survey (program GO 8192, PI: Seitzer) to image probable nearby dwarf galaxy candidates from the list of Karachentseva & Karachentsev (1998). Exposure times were 600 s in the F606W ($V$) and the F814W ($I$) filters, respectively. Fig. 2 shows an image of DDO 44 (both filters combined). The galaxy was centered on the WF3 chip. After removing cosmic ray hits we carried out point source photometry with the DAOPHOT II package in MIDAS. A total of about 4200 stars were measured in both filters with an aperture radius of 1.5 pixels. Then we determined the aperture correction from the 1.5 pixel radius aperture to the standard $0''.5$ radius aperture size for the WFPC2 photometric system using bright uncrowded stars. Transformation of the instrumental magnitudes to the groundbased $V$, $I$ system followed the prescriptions of Holtzman et al. (1995) taking into account different relations for blue and red stars separately. Objects with goodness of fit parameters $|\mathrm{SHARP}| > 0.3$, $|\mathrm{CHI}| > 2$, and $\sigma(V) > 0.2$ mag were excluded. The final CMD in $I$, $V - I$ for 1290 stars is shown in Fig. 4.

## 4. Color-magnitude diagrams

As mentioned above, the groundbased $I$, $R - I$ color-magnitude diagram (CMD) of DDO 44 is shown in Fig. 3. The stars in the central part of the galaxy (with $r < 75''$) are indicated in the left panel, and the stars at greater angular distances are shown in the right. As is apparent from the CMD the brightest stars with $I < 21$ mag are foreground stars. The central zone of DDO 44 contains almost no stars bluer than $(R - I < 0^{\mathrm{m}}.2)$ with the possible exception of the faintest stars, whose colors may be affected by photometric errors. The error bars in the panel of Fig. 3 indicate the standard errors of magnitude and color calculated from artificial star experiments with $I = 21, 22, 23$, and 24 mag and $0 < R - I < 1$ (ADDSTAR routine).

The most remarkable feature of the CMD is a rather sharp rise in a number of stars fainter than $I = 22^{\mathrm{m}}.8$ and predominantly red colors $(R - I) > 0^{\mathrm{m}}.5$. From the groundbased image alone one would tend to identify this feature with the red giant branch (RGB), which yields a wrong distance to the galaxy.

Fig. 4 shows CMDs of DDO 44 for the central WF3 field (left panel), for the adjoining region covering the lower half of the WF2 chip and the left half of the WF4 chip in Fig. 2 (central panel in Fig. 4), and DDO 44's outer parts (the remaining halves of WF2 and WF4; right panel of Fig. 4). In the central field the number of stars rises abruptly at $I = 23^{\mathrm{m}}.5$, which we interpret as the tip of the red giant branch (TRGB). No bright blue stars with $V - I < 0^{\mathrm{m}}.7$ are present. This allows us to estimate a lower limit for the most recent star formation episode in DDO 44.

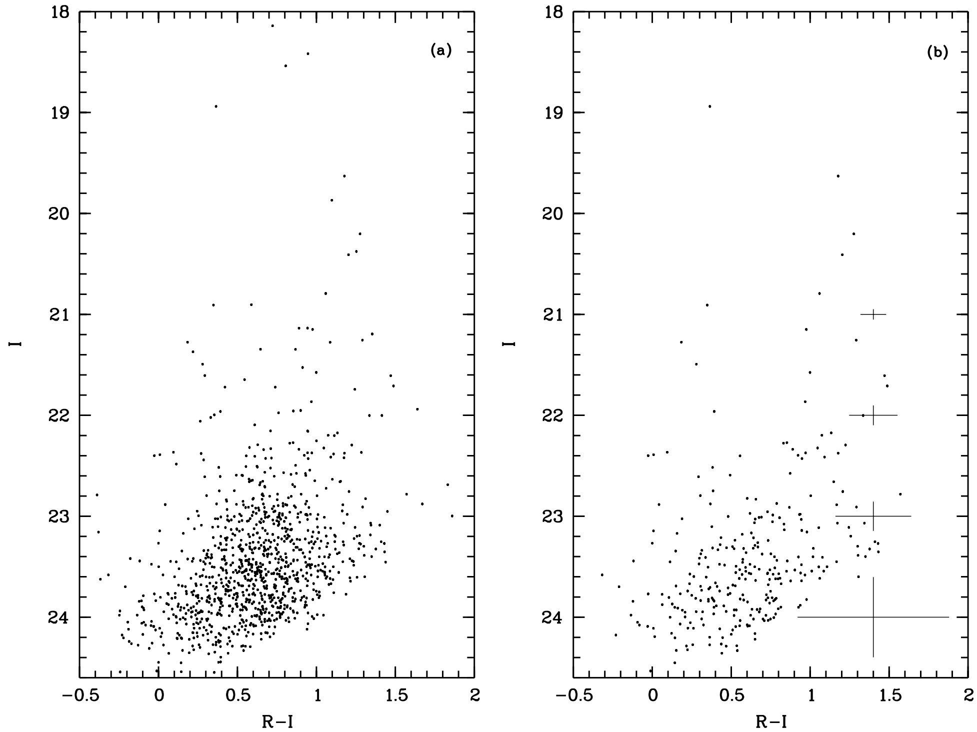


**Fig. 3a and b.** The color-magnitude diagram of resolved stars in the DDO 44 field. Stars in the inner ($R < 75''$) region of DDO 44 are shown in the left panel, while the stars in the surrounding field are presented in the right panel. Errorbars in the right panel represent the standard errors derived from photometry of artifical stars with different $I$ magnitudes and colors $R-I$ within [0,1].

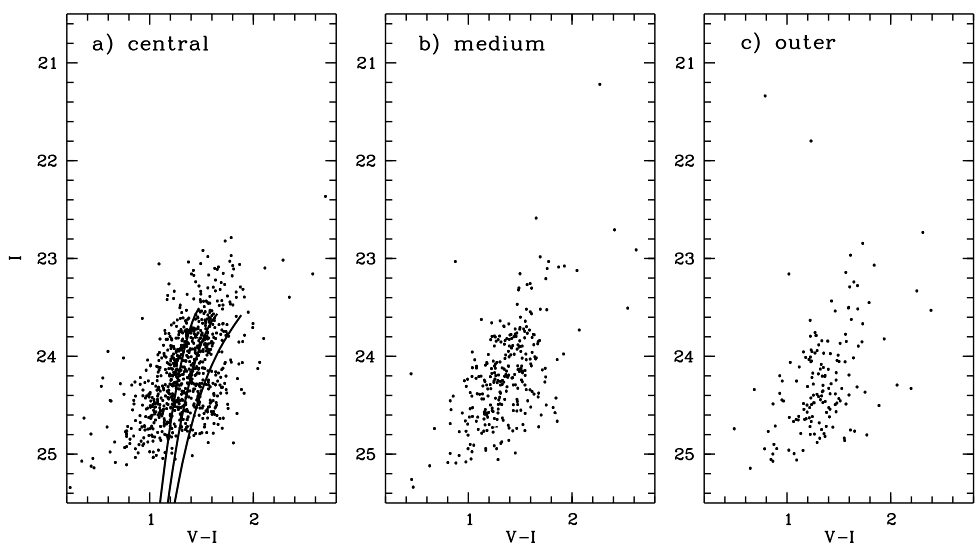


**Fig. 4a–c.** Color-magnitude diagram from WFPC2 data of DDO 44. The three panels show diagrams based on stars at the central (WF3) field, medium and outer field of equal $800 \times 800$ pixels area each. The solid lines in the left panel show the loci of the RGBs of globular clusters with different metallicities: M 15, M 2, and NGC 1851 from left to right.

Using the Bertelli et al. (1994) isochrones and adopting the DDO 44 distance and mean abundance from the next sections, the absence of bright blue stars indicates that no star formation has occurred in the galaxy for at least the last 300 Myr.

A significant number of red stars with $22.8 < I < 23.5$ is evident in the left panels of Fig. 3 and Fig. 4. These stars are probably upper asymptotic giant branch (AGB) stars. When confused with the RGB stars, the clump of AGB stars can lead to a significant underestimate of the galaxy distance in a shallow CMD. The bona-fide AGB stars are indicative of a significant intermediate-age population in DDO 44.

According to Da Costa & Armandroff (1990), the tip of RGB can be assumed to be at $M_I = -4.05$ for metal poor systems. We find the apparent magnitude of the TRGB to be $I$(TRGB) = $23\overset{\mathrm{m}}{.}55 \pm 0\overset{\mathrm{m}}{.}15$, which yields a distance modulus of $(m-M)_0 = 27\overset{\mathrm{m}}{.}52 \pm 0\overset{\mathrm{m}}{.}15$ or $D = (3.2 \pm 0.2)$ Mpc with a Galactic extinction $A_I = 0\overset{\mathrm{m}}{.}08$ from Schlegel et al. (1998). The solid lines in Fig. 4a are globular cluster fiducials from Da Costa & Armandroff, which were reddened and shifted to the galaxy distance. The fiducials cover a range of [Fe/H] values (from left to right): $-2.2$ dex (M 15), $-1.6$ dex (M 2), and $-1.2$ dex (NGC 1851).

## 5. Metal abundance

With the distance modulus of DDO 44 we can estimate the mean metallicity of DDO 44 from the mean color of the RGB

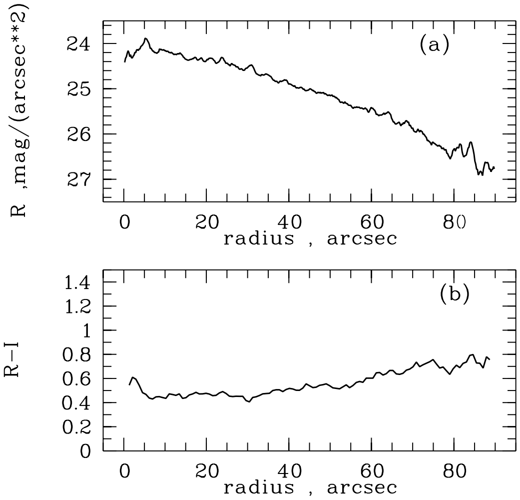


**Fig. 5a and b.** Radial distribution of surface brightness **a** and color **b** in DDO 44, averaged within circular annuli.

**Table 1.** Properties of DDO 44

| Parameter | DDO 44 |
|---|---|
| RA (1950.0) | 07 29 13.1 |
| Dec.(1950.0) | 66 59 40 |
| Galactic $l$ | 149.09 |
| Galactic $b$ | 28.96 |
| Dimension ($'$) | 3.0×2.0 |
| $B_T$ | 15.64 |
| $E(B-V)$ | 0.04 |
| Extinction: $A_B, A_I$ | 0.19, 0.08 |
| $R_T$ | 14.5±0.1 |
| $(R-I)_T$ | 0.51±0.05 |
| $\mu_R(0)$ (mag/($''$)$^2$) | 24.1±0.2 |
| $I_{TRGB}$ | 23.55±0.15 |
| $(V-I)_{0,-3.5}$ | 1.34±0.05 |
| [Fe/H] | $-1.7 \pm 0.4$ |
| $(m-M)_0$ | 27.52±0.15 |
| $D_{MW}$ (Mpc) | 3.2±0.2 |
| $M_R^o$ | $-13.1$ |
| Linear diameter (kpc) | 2.8 |
| Scale length ($''$) | $39 \pm 3$ |
| Scale length (kpc) | $0.60 \pm 0.04$ |
| Type | dSph |
| $S_N$ | 6: |
| Projected separation from NGC 2403 (kpc) | 75 |
| Radial distance to NGC 2403 (kpc) | $30 \pm 450$ |

measured at an absolute magnitude $M_I = -3.^{\rm m}5$, as recommended by Da Costa & Armandroff (1990). Based on a Gaussian fit to the color distribution of the giant stars in the range $23.^{\rm m}8 < I < 24.^{\rm m}3$ we derive a mean dereddened color of the RGB stars of $(V-I)_{0,-3.5} = 1.^{\rm m}34 \pm 0.^{\rm m}05$. Following Lee et al. (1993) this yields a mean metallicity [Fe/H] = $(-1.7 \pm 0.4)$ dex. Here the error includes also contributions from the calibration relations (0.08 mag), and a reddening uncertainty (0.03 mag).

## 6. Integrated properties of DDO 44

The radial distribution of surface brightness in the $R$ band frame (Fig. 1) averaged over azimuth is shown in the upper panel of Fig. 5. The lower panel reproduces the radial variation of the $(R-I)$ color also averaged in azimuth. In the main body of DDO 44 $(10'' < R < 70'')$ the surface brightness profile was approximated by an exponential fit with a scale length $h = 39'' \pm 3''$. The observed surface brightness is $\mu_R(0) = 24.^{\rm m}1 \pm 0.^{\rm m}2$ mag arcsec$^{-2}$. The mean galaxy color increases slightly towards the periphery of the galaxy, which may be caused by a radial age gradient in DDO 44. The galaxy's total color index, $(R-I)_T = 0.^{\rm m}51 \pm 0.^{\rm m}05$, was determined as the difference of asymptotic integral magnitudes in each band derived from curves of growth. The sky background was calculated to be $R_{\rm sky} = 20.^{\rm m}47 \pm 0.^{\rm m}01$ and $(R-I)_{\rm sky} = 1.^{\rm m}62 \pm 0.^{\rm m}01$. A summary of the basic parameters of DDO 44 is given in Table 1. The data in the first six lines are from NED, while the other listed parameters are from this paper. The symmetric shape of DDO 44, its smooth surface brightness profile, the reddish total colors $(R-I) = 0.^{\rm m}51$, $(B-R) = 1.^{\rm m}14$, and the lack of an appreciable amount of neutral hydrogen favour DDO 44 classification as a dwarf spheroidal system. The integrated absolute magnitude of DDO 44, $M_R = -13.^{\rm m}1$, and its linear diameter, 2.8 kpc, correspond to the parameters typical for spheroidal companions of the Milky Way and M31. The derived parameters of DDO 44 follow the general [Fe/H] vs. central surface brightness and [Fe/H] vs. $M_V$ relationships defined by Local Group dwarf galaxies (Caldwell et al. 1998, Grebel & Guhathakurta 1999).

## 7. Globular clusters

The two brightest dSph galaxies in the Local Group, Fornax and Sagittarius, each contain several globular clusters. In galaxies with $M_V = -13$ to $-14$ one expects to find 1–2 globulars on average (Caldwell et al. 1998). Thus one may expect about one globular cluster in DDO 44, which has $M_R = -13.1$. We searched for globular clusters in DDO 44 and found one candidate with appropriate color, $V-I = 0.^{\rm m}83$, and magnitude, $V = 22.^{\rm m}18$. Its position in the WF3 chip (Fig. 2) is indicated by the arrow. An enlargement of the HST image of this candidate is presented in Fig. 6. Note that the globular cluster candidate is not found in the center of DDO 44; i.e., DDO 44 is not a nucleated dSph. Another diffuse, but red object is situated in the right bottom corner.

The absolute magnitude of our globular cluster candidate, $M_V = -5.^{\rm m}4$, and its dereddened color, $(V-I)_0 = 0.^{\rm m}77$, are quite similar to those of the metal-poor Galactic globular cluster NGC 4147 (Peterson 1993). Fig. 7 presents the radial profile of our globular cluster candidate, along with that of a star of about the same brightness and color. From this profile the half-light radius of the cluster candidate is $0.''27$ or 4.2 pc, well within the range of 2–10 pc typical for half-light radii of Galactic globular clusters (Harris 1996).

Assuming that our candidate is indeed a globular cluster, the resulting specific frequency is $S_N \approx 6$. The specific frequency

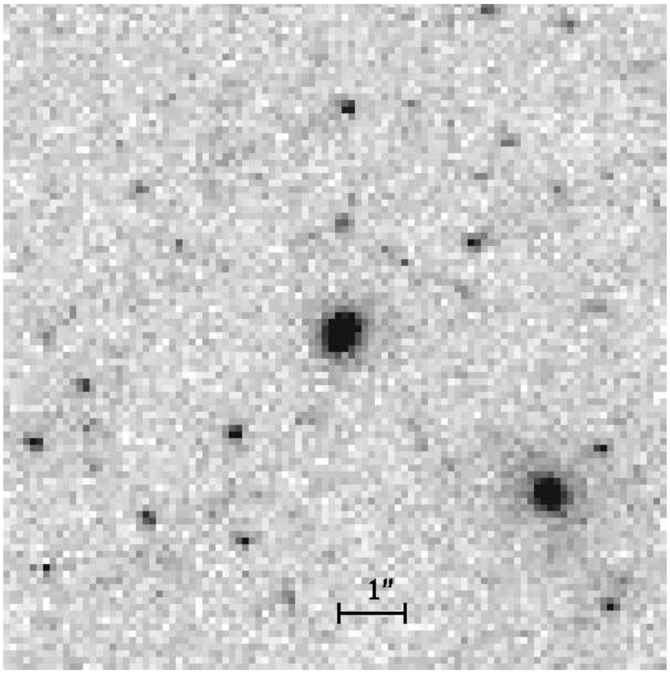


**Fig. 6.** Globular cluster candidate, shown in the F606W + F814W filters from HST.

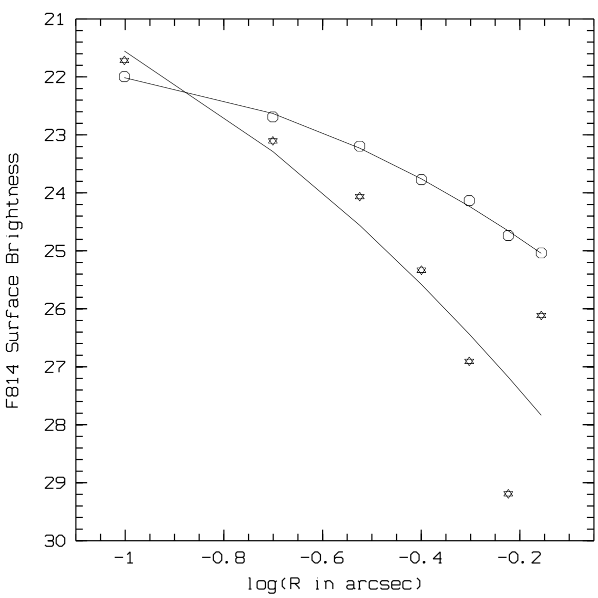


**Fig. 7.** Radial $I$ light profile of the globular cluster candidate (open circles). The diamonds show the radial profile of a star of the same magnitude.

is the number of globular clusters normalized to a galaxy with $M_V = -15$, $S_N = N_{GC} \cdot 10^{0.4(M_V+15)}$ (Harris & van den Bergh 1981), where $N_{GC}$ is the number of globular clusters and $M_V$ the absolute $V$ magnitude of the dSph. Our estimated $S_N$ is lower than that of Fornax and Sagittarius ($S_N > 10$), higher than the mean specific frequency in non-nucleated dSphs and dwarf ellipticals ($S_N = 3.1 \pm 0.5$), and similar to that of nucleated dwarf ellipticals ($S_N = 6.5 \pm 1.2$; Miller et al. 1998).

## 8. Conclusions

Based on deep $R, I$ and $V, I$ CCD images obtained with ground-based and space telescopes, we resolved the very low surface brightness dwarf galaxy DDO 44 into stars for the first time. The CMDs for ∼1290 stars show the presence of a red giant branch with $I$(TRGB) = $23\overset{\mathrm{m}}{.}55 \pm 0\overset{\mathrm{m}}{.}15$, which yields a true distance modulus of $27\overset{\mathrm{m}}{.}52 \pm 0\overset{\mathrm{m}}{.}15$. The corresponding distance of DDO 44 from the Milky Way is $D_{MW} = (3.2 \pm 0.2)$ Mpc. In projection DDO 44 lies only 80 arcmin or 75 kpc away from NGC 2403 and, taken at face value, may be its companion. The distance modulus of the spiral galaxy NGC 2403 derived from light curves of cepheids is $27\overset{\mathrm{m}}{.}5 \pm 0\overset{\mathrm{m}}{.}3$ or $D = 3.2$ Mpc (Freedman 1988). Hence, both the galaxies seem indeed to be located at a very similar distance.

The large number of bona-fide AGB stars indicates that DDO 44 may have a significant intermediate-age population. This is also observed in the more distant dSph companions of the Milky Way.

A special search for LSB dwarf galaxies (Karachentseva & Karachentsev 1998) did not reveal other dSph candidates in the extended surroundings of NGC 2403. But two well-known irregular galaxies, NGC 2366 and K 52, are separated 3.7° and 5.6° from NGC 2403, respectively. Both of them have radial velocities within 15 km s$^{-1}$ of that of NGC 2403, and their linear projected separations are 210 kpc and 310 kpc. Thus the small sample of companions of NGC 2403 seems to exibit the same effect of morphological segregation as other nearby groups.

As was noted by Karachentsev (1996), among the well-studied groups around nearby giant galaxies the number of dSph companions depends strongly on the morphological type of the main galaxy. In fact, spheroidal systems have been detected only in the vicinity of E–Sb type galaxies with massive bulges such as the Milky Way ($N_{\mathrm{sph}}$ = 9), M 31 (6), M 81 (8), and NGC 5128 (7), but not around sufficiently massive Sc galaxies like M 101, NGC 5236, M 33. This morphological relation has probably an evolutionary significance. But a presence of spheroidal dwarf companion around NGC 2403 may be the first case of disagreement with the mentioned tendency.

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