STELLAR POPULATIONS AND THE LOCAL GROUP MEMBERSHIP OF THE DWARF GALAXY DDO 210

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ABSTRACT

We present deep $BV$ CCD photometry of the stars in the dwarf galaxy DDO 210. The color-magnitude diagrams of DDO 210 show a well-defined red giant branch (RGB) and a blue plume. The tip of the RGB is found to be at $I_{\text{TRGB}} = 20.95 \pm 0.10$ mag. From this, the distance to DDO 210 is estimated to be $d = 950 \pm 50$ kpc. The corresponding distance of DDO 210 to the center of the Local Group is 870 kpc, showing that it is a member of the Local Group. The mean metallicity of the RGB stars is estimated to be $[\text{Fe/H}] = -1.9 \pm 0.1$ dex. Integrated magnitudes of DDO 210 within the Holmberg radius ($r_{H} = 110'' = 505$ pc) are derived to be $M_{B} = -10.6 \pm 0.1$ and $M_{V} = -10.9 \pm 0.1$ mag. $B$ and $V$ surface brightness profiles of DDO 210 are approximately consistent with an exponential law with scale lengths $r_{s}(B) = 161$ and $r_{s}(V) = 175$ pc. The brightest blue and red stars in DDO 210 (BSG and RSG) are found to be among the faintest in the nearby galaxies with young stellar populations: $\langle M_{V}(3) \rangle_{\text{BSG}} = -3.47 \pm 0.11$ and $\langle M_{V}(3) \rangle_{\text{RSG}} = -4.75 \pm 0.13$ mag. An enhancement of the star formation rate in the recent past (several hundred Myr) is observed in the central region of DDO 210. The opposite trend is observed in the outer region of the galaxy, suggesting a possible two-component structure of the disk/halo kind found in spiral galaxies. The real nature of this two-component structure must, however, be confirmed with more detailed observations.

Key words: distance scale — galaxies: individual (DDO 210) — galaxies: irregular — galaxies: photometry — galaxies: stellar content — Galaxy: evolution

1. INTRODUCTION

DDO 210 is a faint dwarf galaxy in Aquarius discovered by van den Bergh (1959). It was resolved in ground-based photographic images, so that it was sometimes considered to be located nearby and to be a member of the Local Group (Fisher & Tully 1975, 1979; Yahil, Tammann, & Sandage 1977). It has been known to be a dwarf irregular galaxy. Lo, Sargent, & Young (1993) obtained an H I mass of $3 \times 10^{6} M_{\odot}$ and a total virial mass of $1.4 \times 10^{7} M_{\odot}$ in DDO 210, calculated assuming a distance of 1.0 Mpc. Taylor, Kobulnicky, & Skillman (1998) gave an upper limit for the CO emission of $I_{CO} < 0.11$ K km s$^{-1}$.

The distance to DDO 210 has never been measured reliably and is not yet well known. From the proximity of DDO 210 in the sky and in velocity to NGC 6822, Fisher & Tully (1979) assumed that both galaxies were at the same distance (0.7 Mpc). On the other hand, from $BV$ CCD photometry of bright stars in DDO 210, Greggio et al. (1993) suggested that this galaxy may be located as far away as 4 Mpc, placing it beyond the edge of the Local Group. Van den Bergh (1994) estimated the distance to be 0.8 Mpc from simple comparison of the DDO 210 and the Leo I color-magnitude diagrams (CMDs).

In this paper, we present a study of stellar populations in DDO 210 and the Local Group membership of this galaxy based on deep ground-based $BV$ CCD photometry. A brief progress report of this study was given in Lee (1999), which is superseded by this paper. This paper is composed as follows: Section 2 describes the observations and data reduction; § 3 investigates the morphological structure of DDO 210. Section 4 presents the CMDs of the galaxy; § 5 estimates the distance to DDO 210 and concludes on the Local Group membership of DDO 210. Section 6 presents the surface photometry of DDO 210, § 7 investigates the property of the brightest blue and red stars in DDO 210, and § 8 discusses the star formation history (SFH). Finally, § 9 summarizes the primary results.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations and Data Reduction

$BV$ CCD images of DDO 210 were obtained during three different observing runs at the Palomar 1.5 m telescope, the University of Hawaii (UH) 2.2 m telescope, and the NOT 2.5 m telescope of Roque de los Muchachos obser-
TABLE 1
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| Telescope       | $T_{\text{exp}}$ (s) | Air Mass | FWHM (arcsec) | UT (Start)       | Filters |
|-----------------|----------------------|----------|---------------|------------------|---------|
| Palomar 1.5 m   |                      |          |               |                  |         |
| 1200            | 1.56                 | 1.2      | 1992 Aug 23:52| $B$              |         |
| 900             | 1.65                 | 1.0      | 1992 Aug 23:12| $V$              |         |
| 600             | 1.45                 | 0.9      | 1992 Aug 23:25| $I$              |         |
| UH 2.2 m        |                      |          |               |                  |         |
| 1000            | 1.33                 | 1.2      | 1994 Oct 9:32 | $B$              |         |
| 3 × 900         | 1.20                 | 1.0      | 1994 Oct 9:05 | $V$              |         |
| 3 × 600         | 1.25                 | 0.9      | 1994 Oct 9:50 | $I$              |         |
| NOT 2.5 m       |                      |          |               |                  |         |
| 3 × 900         | 1.21                 | 0.8      | 1997 Jul 27:36| $V$              |         |
| 4 × 600         | 1.26                 | 0.9      | 1997 Jul 27:10| $I$              |         |

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**Fig. 1.—** Gray-scale map of the $V$-band CCD image of DDO 210. North is at the top and east is to the left. The size of the field is 7.5 $\times$ 7.5. Rectangular regions labeled as C, I, and F represent, respectively, the central, intermediate, and control-field regions. The square labeled F2 in the lower middle area represents the field covered by the Roque de los Muchachos observations.
TABLE 2

| ID  | X   | Y   | V   | B−V | V−I |
|-----|-----|-----|-----|-----|-----|
| 1782| 526.3| 789.4| 16.85| 0.61| 0.83|
| 1029| 405.3| 641.8| 17.09| 0.88| 1.06|
| 1755| 358.8| 778.7| 17.19| 0.50| 0.87|
| 1149| 300.1| 661.4| 17.48| 0.64| 0.84|
| 1571| 538.4| 726.6| 17.88| 0.55| 0.38|
| 1423| 461.5| 704.5| 18.12| 0.86| 1.02|
| 1763| 598.6| 783.2| 18.35| 0.90| 1.35|
| 1253| 668.7| 690.4| 18.83| 0.90| 1.35|
| 855| 611.0| 590.1| 19.32| 0.59| 0.73|
| 918| 668.2| 622.5| 19.72| 0.64| 0.91|
| 1243| 323.0| 675.7| 19.73| 1.50| 2.23|
| 1780| 287.7| 788.0| 19.84| 0.42| 0.77|
| 1468| 490.5| 708.8| 20.14| 1.13| 1.74|
| 1805| 303.0| 801.4| 20.29| 0.57| 0.94|
| 1071| 685.8| 647.1| 20.32| 1.25| 2.14|
| 926| 425.1| 625.0| 20.40| 1.01| 1.64|
| 1444| 231.0| 706.2| 20.40| 0.27| 0.73|
| 1830| 255.9| 815.9| 20.88| 0.70| 1.28|
| 1423| 366.1| 733.0| 20.77| 0.32| 0.89|
| 1253| 368.7| 722.3| 20.77| 1.30| 2.13|
| 1407| 462.0| 702.5| 20.93| 1.14| 1.35|
| 1829| 118.1| 814.4| 20.96| 1.29| 2.24|
| 1362| 317.2| 694.8| 21.01| 0.18| 0.22|
| 1656| 487.9| 745.8| 21.05| −0.17| 0.04|
| 1710| 468.5| 761.3| 21.05| 0.23| 0.63|
| 1189| 668.9| 667.5| 21.20| 1.03| 0.85|
| 1548| 441.5| 722.1| 21.24| 0.57| 0.61|
| 799| 176.6| 558.5| 21.30| 1.07| 1.67|
| 910| 675.6| 620.1| 21.39| 1.12| 1.71|
| 1477| 461.5| 709.6| 21.40| 0.41| 0.72|
| 1506| 470.3| 714.7| 21.44| 0.91| 1.15|
| 820| 291.7| 571.0| 21.45| 1.01| 1.48|
| 1303| 464.4| 713.9| 21.48| −0.15| 0.19|
| 1632| 515.3| 739.2| 21.50| 0.12| 0.62|
| 1517| 523.8| 717.2| 21.54| −0.14| 0.34|
| 1713| 321.5| 761.6| 21.59| 0.77| 1.38|
| 1524| 560.7| 718.2| 21.69| −0.14| −0.10|
| 1339| 563.5| 690.8| 21.72| 0.92| 0.49|
| 1339| 410.0| 690.5| 21.90| 1.13| 1.62|
| 1353| 452.4| 693.3| 21.95| 0.07| 1.28|
| 1831| 424.8| 815.9| 21.96| 1.02| 1.51|
| 1344| 420.6| 691.7| 21.99| 0.56| 0.61|

The Roque de los Muchachos VI photometry is the deepest, so we have preferably used it for the analysis of the stellar populations in DDO 210. The Hawaii BVI data were used for the analysis of the bright stellar populations. The total number of stars that were measured in V and at least one other color with ALLSTAR σ values less than 0.25 is ~1800. Table 2 lists BVI photometry of the measured bright stars with V < 22 mag inside the boundary of the I region. X and Y coordinates increase to the east and south, respectively.

2.2. Comparison with Previous Photometry

Previous BVI photometry of stars in DDO 210 was given by Marconi et al. (1990), Greggio et al. (1993, hereafter G93), and Hopp & Schulte-Ladbeck (1995, hereafter HP95). The photometry by Marconi et al. (1990) was based on a wrong calibration and was corrected in G93. We have compared our photometry with these previous ones. The results of the comparison are ΔV (this study minus G93) = +0.01 ± 0.09, Δ(B−V) (this study minus G93) = +0.05 ± 0.15 for 30 common stars with V < 22 mag, and ΔV (this study minus HP95) = −0.04 ± 0.10, Δ(B−V) (this study minus HP95) = +0.05 ± 0.11 for 35 common stars with V < 22 mag. These results show a reasonable agreement in V and B−V among the three photometry sets.

3. MORPHOLOGICAL STRUCTURE

Figure 1 shows that, morphologically, DDO 210 seems to have two components: the central component, represented by the C region (2.32 × 0.87), and the extended component, represented by the I region (4.85 × 2.13). From now on, by the I region we will refer only to the outer part of this region, i.e., excluding the C region. Both are elongated in the east-west direction but do not have common centers, the central component lying more eastward than the extended one. A color map created by combining BVI images shows that the stars in the central component are mostly very blue, while the stars in the outer region are mostly yellow to red. We have estimated the ellipticity and the position angle of the extended component to be roughly e = 0.5 and P.A. = 173°, respectively. In summary, DDO 210 is an elongated dwarf galaxy with a likely young stellar component close but out of its center. This confirms the common tendency of dwarf galaxies to show off-center star-forming regions.

4. COLOR-MAGNITUDE DIAGRAMS

We display V(B−V) and I(V−I) diagrams of the measured stars in the C, I, and F regions in Figures 2 and 3. Note that the area of the C region in the field is the same as that of the F region, so that we can estimate the contamination due to foreground stars by comparing the diagrams of each region.

Several distinguishable features of the stars in DDO 210 are seen in Figures 2 and 3. First, there is a blue plume of...
bright stars with $B - V < 0.4$ in the C + I region. Comparison of the C + I and F regions in Figure 2 shows that these bright blue stars are mostly members of DDO 210. The brightest end of the blue plume extends up to $V \approx 21.0$ mag and $B - V \approx -0.2$. These stars are young and are mostly located in the C region.

Second, there are several bright red stars with $20 < V < 21$ mag and $1.0 < B - V < 1.5$ in the C and I regions in Figure 2. They might be young, red supergiants in DDO 210. However, the fact that a large number of stars is found in the F region with $V < 22$ mag (for every color); the fact that they are more numerous in the I than in the C region, as should be expected from the bigger field size; and, more important, the fact that the blue population (which must be expected as a counterpart of the bright, red one) in the I region is less numerous than in the C region drives the conclusion that many of the bright, red stars in the I region are in the foreground.

Third, Figure 3 shows that there is a strong concentration of red stars fainter than $I \approx 21$ mag and redder than $V - I \approx 0.8$ mag in the C and I regions. This feature corresponds to the red giant branch (RGB) and asymptotic giant branch (AGB) locii, populated by old and intermediate-age stars of DDO 210. The tip of the RGB (TRGB) is seen at $V - I \approx 1.4$.

5. DISTANCE AND METALLICITY

We estimate the distance to DDO 210 using the $I$ magnitude of the TRGB, as described in Da Costa & Armandroff (1990) and Lee, Freedman, & Madore (1993). The $I$ magnitude of the TRGB is estimated using the $I(IV-I)$ diagram in Figure 3 and the luminosity function of red stars in the range defined by $(V-I, I) = (0.5, 23.5), (1.2, 23.5), and (1.8, 19)$. Figure 4 shows the $I$-band luminosity function of the measured red stars in the C + I region. We also plot the luminosity functions of stars of the same color range in the F and the F2 regions in Figure 4. This figure shows that while some stars in DDO 210 can be still populating the F2 region, the F region is very likely free of them. In any case, for the purposes of this section, the contribution due to foreground stars is negligible for the bright part of the luminosity function of the C + I region. The luminosity function shows a sudden increase at $I = 20.95 \pm 0.10$ mag. This corresponds to the TRGB seen in the CMD in Figure 3. We will adopt this value as the $I$ magnitude of the TRGB.

The mean color of the TRGB is estimated to be $V-I = 1.44 \pm 0.04$. The bolometric magnitude of the TRGB is then calculated from $M_{\text{bol}} = -0.19[\text{Fe/H}] - 3.81$. Adopting a mean metallicity of $[\text{Fe/H}] = -1.86 \pm 0.12$ dex as estimated below, we obtain a value for the bolometric magnitude of $M_{\text{bol}} = -3.46$ mag. From the equation $BC_I = 0.881 - 0.243(V-I)_{\text{TRGB}}$, the bolometric correction at $I$ for the TRGB is estimated to be $BC_I = 0.54$ mag. The intrinsic $I$ magnitude of the TRGB is then $M_I = M_{\text{bol}} - BC_I = -4.00$ mag.

We adopt in this study the foreground reddening value $E(B-V) = 0.03$ mag for DDO 210 from Burstein & Heiles.
F and F2 regions, respectively. The solid and dotted lines represent the luminosity functions of the region. The solid and dotted lines represent the luminosity functions of the (1982) and Ratnatunga & Bahcall (1985), corresponding to Schlegel, Finkbeiner, & Davis (1998), E(B – V) = 0.05. Finally, the distance modulus of DDO 210 is obtained: (m – M)I = 24.89 ± 0.11 mag, corresponding to a distance of 950 ± 50 kpc.

The metallicity of an old stellar population can be estimated from the color of the RGB. DDO 210 has a composite stellar population also containing young stars, but an estimate of the metallicity using that approach is still quite useful, as no previous determinations exist. We have estimated the mean metallicity using the V – I color of the RGB stars to be 0.5 mag fainter than the TRGB, (V – I)TRGB = 0.12 dex. This value is similar to those of M15, M2, and NGC 1851, the metallicities of which are [Fe/H] = –2.17, –1.58, and –1.29 dex, respectively. The mean errors for the magnitudes and colors are illustrated by the error bars at the right.

Although the uncertainty is obviously large.” If DDO 210 was at the distance of 4 Mpc, the absolute magnitude of the bright tip of the RGB would be M_I ≈ −7 mag. This is unrealistic, because the V-band absolute magnitude of the TRGB is known to be almost constant at M_I ≈ −4.0 mag for various types of resolved galaxies with old red giant populations (Lee et al. 1993).

With the distance estimate obtained as above, we can tell whether DDO 210 is a member of the Local Group or not. Assuming that the center of the Local Group is, from our Galaxy, at a distance of 250 kpc (de Vaucouleurs et al. 1991, hereafter RC3), and the velocity with respect to the center of the Local Group is derived to be −137 ± 5 km s^{-1} (de Vaucouleurs et al. 1991), and the velocity with respect to the center of the Local Group is derived to be −137 ± 5 km s^{-1}. From these values we conclude that DDO 210 is definitely a member of the Local Group. DDO 210 does not belong to either the Milky Way subgroup or the M31 subgroup.

6. Surface photometry

The low surface brightness of DDO 210 and the presence of several bright foreground stars in the field make it difficult to reliably derive the surface photometry of the galaxy. We have proceeded to take the surface photometry as follows: First, we removed several bright stars that are considered to be obvious foreground stars both from the DDO 210 and the F-region images using IMEDIT in IRAF. The mean intensity of the F region was used for background-sky estimation. Then we performed aperture photometry of DDO 210 using elliptical annular apertures with the ellipticity and position angle determined in § 3. The results are
listed in Table 3 and displayed in Figure 6. In Table 3, \( r \) represents a mean radius of the major axis of an ellipse, and \( r_{\text{out}} \) presents the outer radius of an elliptical aperture. Surface brightnesses are given in terms of \( \text{mag arcsec}^{-2} \).

Figure 6 shows that the surface brightness profiles of DDO 210 follow approximately the exponential disk law. The scale lengths of DDO 210 are determined from these profiles to be \( r_{\text{in}}(B) = 35'' / 161 \text{ pc} \) and \( r_{\text{in}}(V) = 38'' / 175 \text{ pc}. \) The steep increase of the brightness in the center is due to a bright star located close to the center of the galaxy. The magnitude and color of this star (ID 1407) are \( B = 20.87 \pm 0.10 \) and \( V = 1.14 \pm 0.10 \). With this color, it could be a main-sequence star in the halo of the Milky Way, 5 kpc from the Sun or 7.5 kpc from the Galactic center. It is also possible, however, that it is a yellow supergiant in DDO 210. The color profile of DDO 210 in Figure 6 shows that the colors are almost constant around \( B - V \approx 0.25 \) within \( r \approx 50'' \) (except for the central region), and get redder beyond \( r \approx 50'' \). This shows that blue stellar populations are located mostly within \( r \approx 50'' \).

The Holmberg radius corresponding to \( \mu_B = 26.5 \text{ mag arcsec}^{-2} \) is approximately \( r_{\text{H}} = 110'' = 505 \text{ pc} \). The integrated magnitudes of DDO 210 within this radius are \( B = 14.37 \pm 0.03, V = 14.06 \pm 0.03, \) and \( I = 13.03 \pm 0.04 \) mag. The RC3 lists, as total magnitudes of DDO 210, \( B = 14.00 \pm 0.52 \) and \( V = 13.88 \pm 0.52 \) mag. These magnitudes are similar to ours, but the errors in our photometry are much smaller. The corresponding absolute magnitudes are \( M_B = -10.6 \pm 0.1, M_V = -10.9 \pm 0.1, \) and \( M_I = -11.9 \pm 0.1 \) mag. This result shows that DDO 210 is the faintest among the known dwarf irregular galaxies in the Local Group (Mateo 1998).

7. THE BRIGHTEST BLUE AND RED STARS IN DDO 210

Little is known about the nature of the brightest stars in DDO 210. In the study of M supergiants in Local Group irregular galaxies Elias & Frogel (1985) stated, “[C]ertainly DDO 210 does not have a population of red supergiants comparable to that in Sextans A, which implies that it either is more distant or has no red supergiants.” Because it turns out that DDO 210 is closer than Sextans A (this study; Mateo 1998), the only possibility is that there may be no red supergiants in DDO 210. Our photometry allows us to investigate the nature of the brightest stars in DDO 210.

We have determined the mean colors and magnitudes of the brightest stars. In the \( V - (B - V) \) diagram of the C+I region of DDO 210 shown in Figure 2, it is obvious which stars are the three brightest blue stars in DDO 210 (1556, 1503, and 1517), but it is not obvious which stars are the three brightest red stars, because of contamination due to some foreground stars. We chose, as the three brightest red

| \( R_{\text{eff}} \) (arcsec) | \( \mu_B \) (mag) | \( \mu_V \) (mag) | \( \mu_I \) (mag) | \( R_{\text{out}} \) (arcsec) | \( B \) (mag) | \( V \) (mag) | \( I \) (mag) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 6.2             | 22.74 ± 0.43    | 22.31 ± 0.53    | 21.26 ± 0.68    | 8.8             | 17.54           | 17.08           | 16.02           |
| 13.9            | 23.74 ± 0.19    | 23.50 ± 0.23    | 22.55 ± 0.44    | 17.6            | 16.69           | 16.34           | 15.32           |
| 22.4            | 23.78 ± 0.31    | 23.59 ± 0.25    | 22.89 ± 0.23    | 26.4            | 16.01           | 15.73           | 14.83           |
| 31.1            | 24.16 ± 0.26    | 23.96 ± 0.22    | 23.17 ± 0.17    | 35.2            | 15.59           | 15.34           | 14.47           |
| 39.8            | 24.25 ± 0.27    | 24.06 ± 0.24    | 23.22 ± 0.18    | 44.0            | 15.23           | 15.00           | 14.14           |
| 48.6            | 24.40 ± 0.34    | 24.21 ± 0.31    | 23.30 ± 0.37    | 52.8            | 14.95           | 14.73           | 13.83           |
| 57.4            | 24.77 ± 0.33    | 24.55 ± 0.29    | 23.62 ± 0.32    | 61.6            | 14.75           | 14.53           | 13.63           |
| 66.1            | 25.01 ± 0.16    | 24.67 ± 0.19    | 23.38 ± 0.41    | 70.4            | 14.61           | 14.37           | 13.40           |
| 74.9            | 25.55 ± 0.24    | 25.20 ± 0.28    | 24.04 ± 0.58    | 79.2            | 14.52           | 14.27           | 13.29           |
| 83.7            | 25.82 ± 0.28    | 25.47 ± 0.38    | 24.11 ± 0.53    | 88.0            | 14.44           | 14.19           | 13.20           |
| 92.5            | 25.92 ± 0.33    | 25.43 ± 0.40    | 23.77 ± 0.60    | 96.8            | 14.38           | 14.11           | 13.09           |
| 101.3           | 26.34 ± 0.40    | 26.03 ± 0.53    | 24.82 ± 1.03    | 105.6           | 14.33           | 14.06           | 13.03           |
| 110.1           | 26.49 ± 0.38    | 26.23 ± 0.60    | 24.29 ± 0.60    | 114.4           | 14.29           | 14.02           | 12.99           |
| 118.9           | 26.27 ± 0.49    | 25.81 ± 0.48    | 24.26 ± 0.51    | 123.2           | 14.23           | 13.97           | 12.92           |
| 127.7           | 26.46 ± 0.59    | 26.03 ± 0.48    | 24.52 ± 0.62    | 132.0           | 14.19           | 13.92           | 12.86           |
stars, three among the ones with $20 < V < 21$ and $1.0 < B-V < 1.5$ (1468, 1071, and 926). The mean magnitudes and colors of these three brightest blue and red stars (hereafter, BSG and RSG) in DDO 210 are derived to be, respectively, $\langle V(3) \rangle_{\text{BSG}} = 21.51 \pm 0.11$ mag and $\langle B-V(3) \rangle_{\text{BSG}} = -0.15 \pm 0.03$ and $\langle V(3) \rangle_{\text{RSG}} = 20.23 \pm 0.13$ mag and $\langle B-V(3) \rangle_{\text{RSG}} = 1.13 \pm 0.12$. The corresponding absolute magnitudes and colors are $\langle M_V(3) \rangle_{\text{BSG}} = -3.47$ mag, $\langle B-V(3) \rangle_{0,\text{BSG}} = -0.18$, $\langle M_V(3) \rangle_{\text{RSG}} = -4.75$ mag, and $\langle B-V(3) \rangle_{0,\text{RSG}} = 1.10$, respectively. If some of the chosen brightest red stars are foreground stars, the mean magnitudes of the brightest red stars in DDO 210 will be fainter.

We have compared the magnitudes and colors of the brightest stars in DDO 210 with those of other galaxies with young stellar populations in Figure 7. The data for other galaxies are from Lyo & Lee (1997). Figure 7 shows that both the brightest blue and red stars in DDO 210 are the faintest among the sample galaxies. This result is consistent with the fact that DDO 210 is the faintest among the known dwarf irregular galaxies in the Local Group. Figure 7 also shows that the brightest red stars are the least red among the sample galaxies. This can be interpreted in the sense that the brightest red stars in DDO 210 may be more metal-poor than those in brighter galaxies.

8. THE STAR FORMATION HISTORY OF DDO 210

From a qualitative point of view, the presence of a conspicuous RGB-AGB structure implies star formation at intermediate to old ages in DDO 210. Moreover, the age of the youngest population in DDO 210 can be estimated from comparison of the CMD with theoretical isochrones. Figure 8 displays the $V-(B-V)$ CMD of DDO 210 together with three isochrones for metallicities $Z = 0.0004$ and ages 30, 100, and 300 Myr from the Padua library (see Bertelli et al. 1994 and references therein). It shows that star formation as recent as some 30 Myr ago has taken place in the galaxy.

The star formation history (SFH) can be derived quantitatively in detail from deep CMDs as shown by Gallart et al. (1999). The CMD of DDO 210 is not deep enough for such a derivation, but it can still be used to sketch the SFH. For this purpose, stars with $-4 < M_V < -2.5$ have been counted in the CMD of the C, I, and F2 regions and divided into two groups: bluer and redder than $(V-I)_0 = 0.5$. After normalizing to the same area, the counts of the F2 region have been subtracted from those of the C and I regions to correct for foreground contamination. The relatively strong foreground contamination of the DDO 210 field prevents us from using the stars over the TRGB for the calculation of the SFH. On the other hand, the maximum magnitude used ($M_I = -2.5$ mag) and the fact that we pursue only a rough estimate of the star formation rate (SFR) allow us to neglect crowding effects.

Following a method similar to that described in Aparicio, Gallart, & Bertelli (1997c) and Aparicio, Tikonov, & Karachentsev (1999), a synthetic CMD has been calculated with 100,000 stars brighter than $M_I = -1.5$ mag, a constant SFR, and random metallicities in the interval $0.0001 < Z < 0.0003$, which corresponds to the interval of [Fe/H] found from the RGB of DDO 210. The synthetic stars have been divided into two age intervals: younger and older than 1 Gyr, and the same boxes as for the observational CMDs have been defined in each of the resulting synthetic CMDs. The resulting SFRs for 15–1 and 1–0 Gyr ago are given in Table 4 and shown in Figure 9 for the central (C) and the outer (I) regions of DDO 210. These values are also given after surface normalization (right-hand ordinate axis of Fig. 9). The areas used for those normalizations have been $2.18$ arcmin$^2$ or $1.67 \times 10^3$ pc$^2$ for the C region and $8.11$ arcmin$^2$ or $6.21 \times 10^3$ pc$^2$ for the I region.

DDO 210 shows an SFH behavior in its central region similar to what has been found in other dIrr galaxies, like NGC 6822 (Gallart et al. 1996), Pegasus (Aparicio et al. 1997b), Antlia (Aparicio et al. 1997a), and DDO 187 (Aparicio et al. 1999). Overall, it consists of an enhancement of the SFR for the recent past of the history of the galaxy with respect to the value averaged for its entire life. This can be interpreted as the result of a fluctuating SFR (see Aparicio et al. 1999). It is also interesting to note that this recent strength of the SFR does not affect the entire galaxy but only the central part. For the outer I region, the SFR...
TABLE 4

| Rate                          | DDO 210 Center | DDO 210 Outer |
|------------------------------|---------------|--------------|
| $\psi_{1.5-1} \left(10^{-4} \, M_\odot \, yr^{-1}\right)$ | 0.44          | 0.29          |
| $\psi_{1.0-0} \left(10^{-4} \, M_\odot \, yr^{-1}\right)$ | 1.14          | 0.09          |
| $\psi_{1.5-1/4} \left(10^{-10} \, M_\odot \, yr^{-1} \, pc^{-2}\right)$ | 2.66          | 0.47          |
| $\psi_{1.0-0/4} \left(10^{-10} \, M_\odot \, yr^{-1} \, pc^{-2}\right)$ | 6.87          | 0.15          |

Fig. 9.—Star formation history of DDO 210. The bottom part of the right-hand ordinate axis scale refers to the surface normalized $\psi(t)$ of the external region of the galaxy. The upper part of the same scale refers to the central region. The values of $\psi(t)$ for the two age intervals plotted (15–1 and 1–0 Gyr ago) must be considered as the averages for those intervals. The error bars correspond to Poissonian statistics on the star counts. The dashed lines show the intervals of time over which the averages have been done but are not intended to give accurate information about the detailed shape of the star formation history.

decreased for recent epochs. This behavior is common to other dIrr’s: WLM (Minniti & Zijlstra 1996), Antlia (Aparicio et al. 1997a), Phoenix (Martinez-Delgado, Gallart, & Aparicio 1999), and DDO 187 (Aparicio et al. 1999) and may suggest a two-component disk-halo structure of the kind seen in larger spiral galaxies. However, more detailed data are needed to firmly state such conclusion.

9. SUMMARY AND CONCLUSION

We have presented a study of the stellar populations and the Local Group membership of the dwarf galaxy DDO 210 based on deep $BV I$ CCD photometry. The primary results obtained in this study are summarized as follows:

1. $BV I$ CMDs of ~1800 stars in the $7.5 \times 7.5$ area of DDO 210 have been presented. These CMDs exhibit a well-defined RGB and a blue plume.

2. The TRGB is found to be at $I = 20.95 \pm 0.10$ mag and $V - I = 1.44 \pm 0.04$ mag. From this, a distance modulus of $(m - M)_0 = 24.89 \pm 0.11$ mag is derived, corresponding to a distance of $950 \pm 50$ kpc. The distance to the barycenter of the Local Group is derived to be 870 kpc. From this result and the systemic velocity of DDO 210 we conclude that DDO 210 is definitely a member of the Local Group.

3. The mean color of the RGB at $M_I = -3.5$ mag is $V - I = 1.34 \pm 0.04$ mag. From this value we obtain a mean metallicity of the RGB: $[\text{Fe/H}] = -1.86 \pm 0.12$ dex.

4. $B$ and $V$ surface brightness profiles of DDO 210 follow roughly the exponential disk law with scale lengths of $r(B) = 35' = 161$ and $r(V) = 38' = 175$ pc. The Holmberg radius corresponding to $\mu_B = 26.5$ mag arcsec$^{-2}$ is $r_H = 110' = 505$ pc. The integrated magnitudes up to this radius are $M_B = -10.6$, $M_V = -10.9$, and $M_I = -11.9$ mag.

5. The magnitudes of the brightest blue and red stars in DDO 210 are derived: $<M_B(3)_{BSG} = -3.47 \pm 0.11$ and $<M_B(3)_{TRGB} = -4.75 \pm 0.13$ mag. The brightest blue and red stars in DDO 210 are found to be among the faintest in nearby galaxies with young stellar populations.

6. The SFRs of the central and extended regions of DDO 210 have been calculated. The central region shows an enhancement of the star formation activity in recent epochs, in agreement with what has been observed in other dwarf irregular galaxies. In the extended region of DDO 210, the SFR has been lower in the recent past than the value averaged for the entire life of the galaxy, indicating a possible two-component structure for the galaxy, which must, however, be confirmed with more detailed data.

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