A STELLAR POPULATION GRADIENT IN VII Zw 403: IMPLICATIONS FOR THE FORMATION OF BLUE COMPACT DWARF GALAXIES

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ABSTRACT

We present evidence for the existence of an old stellar halo in the blue compact dwarf galaxy VII Zw 403. VII Zw 403 is the first blue compact dwarf galaxy for which a clear spatial segregation of the resolved stellar content into a core-halo structure is detected. Multicolor Hubble Space Telescope WFPC2 (HST/WFPC2) observations indicate that active star formation occurs in the central region, but is strikingly absent at large radii. Instead, a globular-cluster–like red giant branch suggests the presence of an old (>10 Gyr) and metal-poor ([Fe/H] = −1.92) stellar population in the halo. While the vast majority of blue compact dwarf galaxies have been recognized to possess halos of red color in ground-based surface photometry, our observations of VII Zw 403 establish for the first time a direct correspondence between an old red color and the presence of old, red giant stars. If the halos of blue compact dwarf galaxies are all home to such ancient stellar populations, then the fossil record conflicts with delayed-formation scenarios for dwarfs.

Subject headings: galaxies: compact — galaxies: dwarf — galaxies: evolution — galaxies: halos — galaxies: individual (UGC 6456) — galaxies: stellar content

1. INTRODUCTION

The stellar content and evolutionary history of blue compact dwarf (BCD) galaxies have been a puzzle for some time. The low metal abundances derived from the H II regions of BCDs (between about Z⊙/3 and Z⊙/50; Thuan et al. 1994), combined with their high rates of star formation and large H I masses (Thuan & Martin 1981), have raised the question of whether BCDs are truly young galaxies that formed their first stars recently, or old galaxies that occasionally light up with bright, compact, starburst regions (Searle & Sargent 1972; Searle, Sargent, & Bagualo 1973; Izotov & Thuan 1999). In their original definition of a “young” galaxy, Searle & Sargent (1972) specified this as a galaxy that formed most of its stars in recent times. In subsequent years, the argument over BCD ages has evolved into a more polarized one, because it is important to understand whether or not there might exist any local galaxies that are only now forming their very first generation of stars from pristine gas. Such BCDs that are making all of their stars in the ongoing starburst could be considered to be local examples of primeval galaxies (Thuan & Izotov 1998), and they would be fundamentally different from old galaxies, which began forming their first stars over 10 Gyr ago at high redshifts.

Several lines of evidence support the old-galaxy hypothesis. Thuan (1983) found indications for the presence of evolved stars from the integrated, near-IR colors of BCDs. Fanelli, O’Connell, & Thuan (1988) used UV spectra to show that the star formation rates of BCDs are discontinuous. A deep CCD imaging survey by Loose & Thuan (1986) first revealed that the bright, compact star-forming regions of BCDs are embedded in much fainter, redder halos, with elliptical outer isophotes. Nearly all galaxies in their sample (>95%) show such an underlying low surface brightness component. Subsequent CCD surveys have confirmed this result (e.g., Kunth, Maurogordato, & Vigroux 1988; Papaderos et al. 1996; Telles, Melnick, & Terlevich 1997; Meurer 1999). Evolutionary synthesis models (e.g., Krüger et al. 1991) and chemodynamical models (e.g., Riechsch & Hensler 1998) favor the old-galaxy view as well.

Hubble Space Telescope (HST) observations of several extremely metal poor BCDs recently led Thuan, Izotov, & Lipovetsky (1997) and Thuan & Izotov (1998) to propose that primeval BCDs may yet be found locally. Their argument is based in part on the blue colors observed for the unresolved underlying disks. This is seen in I Zw 18 (Z⊙/50) by Hunter & Thronson (1995), in SBS 0335−052 (Z⊙/41) and SBS 0335−052W (around Z⊙/50) by Thuan et al. (1997), Papaderos et al. (1998), and Lipovetsky et al. (1999), and in SBS 1415+437 (Z⊙/21) by Thuan et al. (1999). Based on abundance measurements, Izotov &
Thuan (1999) suggest that in fact all galaxies with \( Z \leq Z_{\odot}/20 \) are young, with ages not exceeding 40 Myr, while those with \( Z \leq Z_{\odot}/5 \) are no older than \( \approx 1-2 \) Gyr. In the definition of Izotov & Thuan, then, a "young" galaxy is a galaxy that has not experienced any star-forming events prior to the current one (which might have enriched its gas beyond that observed). By most accounts, even galaxies with ages of less than 2 Gyr would be considered to be relatively young galaxies, since their formation redshift would not have been coeval with that of the large or other dwarf galaxies.

The controversy over the age of BCDs reflects our current knowledge of galaxy formation and evolution. Did dwarf galaxies form from primordial density fluctuations at \( z \gg 5 \) (Ikeuchi & Norman 1987)? Are the dwarfs observed today the leftover building blocks of large galaxies (White & Rees 1978; Dekel & Silk 1986)? Is the formation of dwarfs delayed until \( z \approx 1 \), when the UV background cooled sufficiently for gas to collapse within small dark matter halos and form stars (Blanchard, Valls-Gabaud, & Mamon 1992; Babul & Rees 1992)? Are dwarfs rapidly evolving for \( z < 1 \), in which case they could account for the rapid evolution in the galaxy luminosity function necessary to explain the faint blue excess (Broadhurst, Ellis, & Shanks 1988; Babul & Ferguson 1996; Spaans & Norman 1997; Ferguson & Babul 1998; Guzmán et al. 1998)? Where are the local isolated \( \text{H} \text{I} \) clouds still awaiting their first generation of stars (Briggs 1997)?

Resolved stellar populations are the fossil record of a galaxy's star formation history (SFH). They can also be used to provide a definition of a galaxy's age. Here we consider as "young" a galaxy that contains only "young" stars, i.e., stars with ages less than 100 Myr. Intermediate-age stars signal that a galaxy is at least of intermediate age; we consider this to be the case when stars that are older than a few hundred Myr are detected. Since the time resolution of color-magnitude diagrams (CMDs) of distant galaxies decreases rapidly if the stellar ages exceed 1 Gyr, a detection of stars with ages of about 1 Gyr is often considered sufficient to show the presence of old stars. We, however, prefer to consider all stars with ages of up to 10 Gyr as intermediate-age stars, and reserve the term "old" for stars of the kind that inhabit Galactic globular clusters and have ages greater than 10 Gyr. An "old" galaxy is therefore one that has formed at least some stars more than 10 Gyr ago.

The dwarf galaxies in the Local Group exhibit an astounding variety of SFHs, yet all contain old stars (Mateo 1998) in the above sense. However, there are no BCDs known in the Local Group. VII Zw 403 is hence a key object. It is so close that \( HST \) observations can resolve it into individual stars (Schulte-Ladbeck, Crone, & Hopp 1998, hereafter SCH98; Lynds et al. 1998); thus, it has become possible for the first time to derive the distance of a BCD using a stellar distance indicator (rather than just a recession velocity). This is crucial for the interpretation of the stellar content.

Recent determinations of the present-day metallicity of the ionized gas in VII Zw 403 (or rather, its O/H ratio), were published by Martin (1997) and Izotov, Thuan, & Lipovetsky (1997). Martin finds log \((\text{O}/\text{H}) = -4.42 \pm 0.06\), and Izotov et al. give \(-4.31 \pm 0.01\). Both groups employ the metallicity scale for which the Sun has log \((\text{O}/\text{H}) = -3.07\). We note that Izotov & Thuan (1999) also use this solar value. On this scale, the metallicity of VII Zw 403 is between 1/22 and 1/17 of solar.

Despite its low metallicity (\( \approx Z_{\odot}/20 \)), SCH98 argued that VII Zw 403 is not a young galaxy, based on the detection of a red giant branch (RGB) with a well-defined tip and a red asymptotic giant branch (AGB). VII Zw 403 also exhibits extended outer isophotes (Loose & Thuan 1986; Hopp & Schulte-Ladbeck 1995) with a red color that is consistent with an old, metal-poor population (Schulte-Ladbeck & Hopp 1998). The spectrum of the background sheet displays absorption lines that indicate an evolved population underlying the recent starburst (Hopp et al. 1998).

In this paper, we provide further arguments that the existence of an early epoch of star formation can be surmised from the morphology of VII Zw 403. We demonstrate that in radial bins outward from its starburst center, the contribution to the CMD by young stars decreases, while the red tangle that contains the old and metal-poor RGB (Aparicio & Gallart 1994) becomes a narrow feature. For radii larger than about 1 kpc, the young stars are absent and the stellar content is well described by a globular-cluster–like stellar population. We argue that this resolved old stellar population supports earlier suggestions that the faint halos of BCDs harbor old stars.

2. OBSERVATIONS AND REDUCTIONS

\( HST \) WFPC2 observations of VII Zw 403 were obtained in the continuum (F336W, F555W, and F814W filters, approximately the Johnson-Cousins \( U, V, \) and \( I \) bands) and in the \( H \alpha \) emission line (F656N filter). The relevant exposures are listed in Table 1 of SCH98.

As described in SCH98, we reran the pipeline with improved calibration files, removed cosmic rays, corrected for charge transfer efficiency (CTE), and corrected for geometric distortion. We conducted photometry on \( H \alpha \)-subtracted images. We used DAOPHOT to perform PSF photometry on each of the four WFPC2 chips. We calibrated the photometry using the most up-to-date SYNPHOT tables. After determining the positions of each point source, we merged the object catalogs of the four chips into a single file of positions and instrumental magnitudes in the Vega magnitude system. The accuracy of these coordinates relative to the guide star system is about 0.5.

In Figures 1a and 1b, we provide the errors for the point-source measurements in the continuum filters, as well as the results of our completeness tests. DAOPHOT/ALLSTAR residuals in F555W and F814W filters on all chips can be summarized by stating that they reach 0.1 mag at magnitudes of about 26 and 25.5, respectively. We checked the completeness of our photometry for each chip by adding a distribution of false stars consistent with the magnitude distribution of the real stars. The percentage of recovered stars indicates that completeness is about 50% at \( m_{F555W} = 26 \), \( m_{F814W} = 25 \). (Fig. 4 of SCH98 indicates there are "holes" in the distribution of red stars on the PC due to incompleteness effects; this presumably also produces a less well populated red tangle in the first two panels of Fig. 3 below.)

The foreground Galactic reddening for VII Zw 403 is \( E(B-V) = 0.025 \) (Burstein & Heiles 1984); we correct for the corresponding extinction using the tables provided in Holtzman et al. (1995; see their Tables 12a and 12b). A small and patchy internal reddening \( E(B-V) < 0.16 \)
cannot be ruled out (Lynds et al. 1998), but is not central to the arguments presented below (the location of the blue plume in the CMD is consistent with no or low internal reddening for the majority of the young stars detected, and the old stars in “Baade’s red sheet” are measured throughout the halo, where we find no evidence for internal extinction).

Final colors are transformed $U$, $V$, and $I$ magnitudes using the color terms given in Holtzman et al. (1995; see their Table 7).

3. RESULTS

Figure 2 is a position plot of all stars detected in both $V$ and $I$ (5459 objects). We used the distribution of sources detected in both $U$ and $V$ to locate the center of star formation in VII Zw 403 (R.A. = 172:002, decl. = 78:994, J2000). We then cast concentric circles about this location. In Figure 3, we display the $[(V-I)_0, I_0]$ CMDs observed within each of six radial bins marked in Figure 2. The CMDs of the first and sixth bins are also superimposed with
stellar evolutionary tracks. These tracks use the stellar atmospheres of F. Castelli (see, e.g., Bessell, Castelli, & Plez 1998) for a metallicity of $Z_{\odot}/30$, which were folded with the HST filter/system response and kindly made available to us by L. Origlia. Stellar evolution is based on the Fagotto et al. (1994) isochrones for $Z = 0.0004$ ($Z_{\odot}/50$). These models were chosen because they most closely represent a "compromise" metallicity for the stellar populations that we observe (i.e., without trying to model the enrichment history in detail as well, on which we comment below). As is always the case, the comparison of theoretical tracks (or synthetic CMDs) with data depends on the accuracy with which we can ascertain either one and thus map one onto the other. We will consider as safe conclusions that do not depend on the choice of a particular model. For instance, a well-populated RGB is usually only observed if a stellar population with an age upward of about 1 Gyr is present, irrespective of the stellar metallicities adopted (see also Sweigart, Greggio, & Renzini 1990). We will point out, where appropriate, when inferences are based on what we consider to be more uncertain model results. The location of the tracks on the observed CMDs employs the distance modulus derived below.

The changes in stellar content with position are quite striking. The center displays a CMD that has a dominant blue plume of main-sequence (MS) stars and blue supergiants (BSG) or blue-loop (BL) stars, a prominent red supergiant (RSG) plume, a few very red AGB stars, and a weak red tangle. In the second bin, this red tangle and the region of intermediate-mass BL stars are much more populated. We note that $H_\alpha$ emission is detected only in the first and second bins. By the third bin, both the blue plume and the RSG plume have weakened, whereas the red tangle is strong. By the fourth bin, most stellar indicators of young ages have disappeared. Our detection limit of $V_0 \approx 28$ is low enough to show that MS stars younger than about 200 Myr are absent. The few remaining BL stars, which suggest ages of a few hundred Myr, are still present in this bin. In the fifth and sixth bins, we see the outer regions of the galaxy. Here, the red tangle has become a narrow band. There are seven objects that are red and brighter than $I_0 \approx 23$. A likely explanation is that these are Galactic foreground stars. The number of Galactic foreground stars within the WFPC2 images is expected to be very small (Méndez & Guzmán 1998); since the fifth and sixth bins cover the largest area, they may contain a few. The CMDs of the fifth and sixth

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**Fig. 2.** Positional plot of all stars detected in $V$ and $I$. Circles drawn about the center have radii of 0:002, 0:005, 0:01, 0:0125, 0:0175, and 0:025, and are used to show the radial change of stellar content in Fig. 3. The green circles show the old vs. young demarcation of Fig. 4. The blue lines mark the quadrant used for the stellar density profile in Fig. 5.
bins suggest that only intermediate-age and old AGB and RGB stars are found in the outer regions of VII Zw 403.

In SCH98 we used the tip-of-the-red-giant-branch (TRGB) method to obtain the distance to VII Zw 403. Using the red tangle in the star-forming region, we estimated a metallicity [Fe/H] of \(-1.2\), resulting in $M_I = -4.10$ for the TRGB and a distance modulus of 28.4 mag (with a total random error of 0.09 and a dominant systematic error of 0.18). This corresponds to a distance of 4.8 Mpc. We now rederive the distance using the CMD of the outer bins only. The new $I_{TRGB}$, $24.25 \pm 0.05$, is not significantly different from our old value. Following Lee, Freedman, & Madore (1993), we can estimate [Fe/H] from the $V - I$ color either just below the TRGB at $M_I = -3.5$, or, even better, at $M_I = -3.0$. We have done both and find a consistent $(V - I)_0$ color of 1.28, with an rms error of 0.03 (for $M_I = -3.5$) and a dispersion of 0.21. This translates into a mean metallicity of $\langle [\text{Fe/H}] \rangle = -1.92 \pm 0.04$ (or $Z = 0.00024$, or $Z_\odot/83$), with a spread or metallicity range (corrected for measurement error) of $\pm 0.7$. We now find the TRGB at $M_I = -3.98$, or $m - M = 28.23$, or a distance of about 4.4 Mpc, in excellent agreement with the value of 4.5 Mpc derived by Lynds et al. (1998).

At this distance, 1" corresponds to about 21.5 pc. The Holmberg diameter of VII Zw 403 was measured by Schulte-Ladbeck & Hopp (1998) as $2a_H = 146''$, which translates into a physical diameter of 3.1 kpc. Figure 3 shows that the young stars are contained within the inner

Fig. 3.—CMDs for each of the circular bins marked in Fig. 2, with the radii translated from angular scale to physical scale. Padua tracks with $Z = 0.0004$ for stellar masses of 1, 4, and 15 $M_\odot$ are overlaid in green.
few hundred pc, and are absent beyond a radius of 1 kpc. Not surprisingly, this agrees with the “typical” size of a BCD (Thuan & Martin 1981).

In Figure 2 we colored in green the two radii that clearly separate the young and old stellar components of VII Zw 403. In Figure 4 we display the CMDs inside the inner (386 pc) and outside the outer (1352 pc) radius in blue and red, respectively. This illustrates the change in width of the red tangle due to a diminishing contribution by intermediate-mass stars. We mark the position of the TRGB, and provide an absolute-magnitude scale. We also overlay the empirical globular-cluster ridge lines of da Costa & Armandroff (1990), which indicate that the halo population of VII Zw 403 is similar to the population of Galactic globular clusters, the prototypes of Population II.

Figure 4 shows that AGB stars, which populate a strip from \([(V-I)_0, M_I] \approx [1, -4] \to [3.5, -6.5]\) are found at both small and large radii. The strip may contain stars as old as 10 Gyr and \(Z = 0.0004 (Z_\odot/50)\) at its bright, blue end. The extent of the AGB to the red requires \(1/5 > Z_\odot > 1/20\); here the average location of stars is well described by the 4 Gyr isochrones (Bertelli et al. 1994). Note that theoretical models of the AGB phase are very uncertain. This is because (1) their atmospheres contain difficult-to-model molecules, and (2) mass loss is an important but ill-known parameter that determines their evolution. If the AGB models can be believed, then VII Zw 403 has had an interesting chemical history.

Schulte-Ladbeck & Hopp (1998) showed that their surface brightness profiles of VII Zw 403 could be fitted with an exponential law, with scale lengths of 25'7 in \(B\) and 25'2 in \(R\). In Figure 5, we display the \(I\)-band surface density of resolved stars versus radius, derived from star counts in the complete quadrant marked in Figure 2 by blue lines. An exponential law describes well the distribution of the resolved stars outside of the innermost region, where there is incompleteness. The scale length for all stars in \(I\) is 25'6 (or about 550 pc), in excellent agreement with our ground-based results. For the red stars (0.6 < \(V-I\) < 1.5) only, the scale length is 31'8 (or about 680 pc).

Fig. 4.—CMD showing stars located in the core (blue) and those found in the halo (red). The dashed green line marks the TRGB and is the basis for the absolute-magnitude scale. The solid green lines show the empirical globular cluster ridge lines of da Costa & Armandroff (1990) for \([\text{Fe/H}] = -2.17, -1.91, -1.58, -1.54, -1.29, \text{and} -0.71 \ (\text{left to right})\). Error bars are given for the mean \((V-I)\) color of the RGB. The slanted shape of the red tangle is due to increasing errors and incompleteness toward fainter magnitudes.
As a consequence of our observation that the CMD of the halo of VII Zw 403 is very reminiscent of that of a dwarf Spheroidal galaxy (dSph), and in connection with the interesting question of the exact nature of the faint blue galaxies, we compare the scale length of VII Zw 403 to that of dSphs. We find that the scale length is about 1.5 times larger than those of the largest Local Group dSphs, such as NGC 147, NGC 185, NGC 205, or Fornax (Mateo 1998).

We may ask how typical this scale length is for BCDs in general. One note of caution: other BCDs do not have direct distance determinations, and the recession velocities in the literature are scaled with (different values of) $H_0$, resulting in fairly unreliable scale lengths. Nevertheless, the distance errors might average out over a large sample of scale lengths. We compared the scale length of VII Zw 403 to values derived for the BCD-dominated samples of Bothun et al. (1989) and Telles et al. (1997). In both papers, deep CCD exposures to relatively large angular diameters were used for detailed surface photometry, and exponential scale lengths were derived. The central starburst contribution was ignored in the determination. Bothun et al. used $r$-band data, while Telles et al. used $V$-band observations. We transformed both data sets to the same distance scale, with $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In the Bothun et al. sample, 24% of the objects have scale lengths of 0.7 kpc and smaller. Telles et al. found 38% of their objects in this regime. Surface photometry of 93 galaxies from the emission-line galaxy sample of Popescu, Hopp, & Elsässer (1997) was performed by Vennik, Hopp, & Popescu (1999). Again, this sample is dominated by BCDs, but contains a few galaxies of other types. The scale lengths are derived from $R$ images, and 44% of the galaxies show scale lengths of 0.7 kpc and smaller. Papaderos et al. (1996) studied a sample of 14 galaxies in much more detail than the other authors. Here, the derived $R$-band scale lengths range from 0.17 to 2.3 kpc. Despite the various and different selection effects of the four samples from the literature, we conclude from this comparison that the scale length found for the underlying galaxy in VII Zw 403 is fairly typical for BCDs.

4. DISCUSSION

Several pieces of evidence now suggest that VII Zw 403 has an old stellar halo, and this has implications for the formation of BCDs.

While it has previously been assumed that red colors at large radii point to the presence of evolved stellar background sheets in BCDs, the RSG, AGB, and RGB stars actually overlap over a wide range in effective temperatures and hence colors (cf. Fig. 6). Therefore, a red background sheet cannot be considered evidence of an old, underlying
host galaxy unless it can be proved that the stellar population that dominates the integrated color of a BCD is an old one. This has now been accomplished with the detection of red giants in the halo of VII Zw 403.

However, owing to the well-known age-metallicity degeneracy, comparatively young (≈ 1 Gyr) and metal-rich RGB stars can populate the same region of a CMD as old (10–15 Gyr) and metal-poor RGB stars, based on optical broadband colors. We interpret the color dispersion of the RGB with a variation in chemical abundance; however, age dispersion (and/or differential reddening) can also broaden the RGB (e.g., Bertelli et al. 1994). In the case of VII Zw 403, we argue that the well-defined RGB tip, and the narrowing of the red tangle from the center toward the outer regions of the galaxy where young stars are absent, indicate that our interpretation is appropriate. Conclusive evidence could be obtained from the detection of old horizontal-branch stars or the turnoff of an old main sequence, but these are too far.

**Fig. 6.** — Synthetic CMDs providing snapshots of stellar evolution at $Z_{/50}$, computed for the distance, photometric errors, and completeness numbers of VII Zw 403. These CMDs serve as templates for the interpretation of the observed CMDs. We used a "compromise" metallicity, set between that of the oldest and the youngest stars, although the chemical evolution of this galaxy may not have been one of linear enrichment with time. The stars were randomly picked up from a grid in the mass range from 0.6 to 120 $M_\odot$ according to a standard Salpeter initial mass function; each panel displays 1000 surviving stars in the age interval indicated, while during the given age interval star formation was assumed to be constant. We found it educational to color-code different evolutionary phases: black, main-sequence stars; purple, very massive post-MS stars; blue, core He-burning (or blue-loop) stars; green, HRD crossing intermediate-mass stars; black, RSG and AGB stars; and red, RGB stars. In comparison with the data, these template CMDs illustrate the disappearance of the MS with age, the appearance of the RGB at ages above 1 Gyr, and the sinking of metal-poor AGB stars below the TRGB for ages above 3 Gyr. The synthetic CMDs do not reproduce the very red AGB stars that we observe; these only appear in models of about a 3–10 times higher metallicity.
faint to be reached with the HST. VII Zw 403 does not appear to have a globular cluster system.

Recently, the stellar halos of several dwarf Irregular (dIrr) and transition dIrr/dSph galaxies in the Local Group have been resolved into stars (WLM: Minniti & Zijlstra 1996; NGC 3109: Minniti, Zijlstra, & Alonso 1999; Antlia: Aparicio et al. 1997). These observations have been interpreted to indicate the presence of old and metal-poor Population II halos. VII Zw 403 joins the ranks of an increasing number of local star-forming dwarf galaxies with resolved old stellar halos. As pointed out by Mateo (1998), all suitably studied star-forming dwarfs of the Local Group show evidence of extended, smooth, and symmetric distributions for their older stars. Most BCDs show extended, smooth and red outer isophotes as well. Our results for VII Zw 403 imply that the identification of the background sheets with old stellar halos is justified for these BCDs.

The controversy over the age of BCDs—whether they are young or old galaxies—may be resolved in the following way. There is a continuum of star formation and chemical-enrichment histories among the BCDs. It is likely that the vast majority of BCDs have an ancient (>10 Gyr) stellar population substratum, and must thus be recognized as old galaxies. This is based on the observation that over 95% of BCDs in the Loose & Thuan (1986) sample show extended background sheets of red color. Comparing observations of the background-sheet colors for a sample of BCDs and dIrrs with the population synthesis models of Schmidt, Alloin, & Bica (1985), Schulte-Ladbeck & Hopp (1998) suggest that complex star formation histories prevail in these galaxies. Thus, depending on just how much mass is involved in the ongoing starburst, and how the morphology of the star-forming regions compares to that of the older stellar substratum, the colors of some BCDs might be
entirely consistent with those of “young” galaxies, in the sense that they are currently experiencing a strong starburst. If the outer isophotes are sufficiently red in color, they can be interpreted as indicating that such BCDs formed some stars at epochs comparable to that of Galactic globular cluster formation (Kunth, Maurogordato, & Vigroux 1988; Papaderos et al. 1996; Telles et al. 1997; Schulte-Ladbeck & Hopp 1998; Meurer 1999). The range of background-sheet colors suggests that the SFHs of most BCDs since their formation at high redshift have probably been diverse, depending on the frequency, duration, and intensity of the star formation events. This is similar to what has been derived for dwarf galaxies within our Local Group.

In a few of the extremely metal poor BCDs, the color gradients are small and the outer isophotes remain fairly flat. We have derived for dwarf galaxies within our Local Group. The young stars are at (Martin 1997; Izotov et al. 1999). The argument that such blue background-sheet colors indicate a galaxy is only now making its first generation of stars seems untenable to us in the light of population synthesis models. Where the young and old stellar populations are spatially coexistent, Schmidt et al. (1995) show that a starburst completely dominates integrated optical colors for up to 50 Myr, even if as little as 0.1% of the dwarf galaxy’s mass is involved; hence, a young burst may render the underlying old population undetectable. It is therefore possible (although in the absence of deep CMDs not yet demonstrated) that the old populations in these few extremely metal poor BCDs elude us because of a contrast problem.

On the other hand, the CMDs of the few BCDs that have been resolved with HST into single stars indicate that they do contain stellar generations that predate the present starburst. In Figure 6, we show the evolution of VII Zw 403 in a series of synthetic “snapshot” CMDs. These synthetic CMDs were computed with the above Z⊙/50 evolutionary tracks. We used the Bologna code, which was recently adapted by Greggio et al. (1998) for the simulation of HST data. The synthetic CMDs help to illustrate the general features of stellar evolution at low metallicity, and may also serve as templates for future CMDs of extremely metal poor BCDs. The panels of Figure 6 show very well that the observed changes in stellar population with radius (Fig. 3) can be interpreted as a change of the stellar ages with distance from the core. We use synthetic CMDs to place a lower limit on the age of the red giants that we see in the halo of VII Zw 403. We find that a well-defined TRGB first appears for ages >3 Gyr (and of course continues to be present up to 15 Gyr). Beyond an age of about 3 Gyr, we lose age resolution in the CMD, and we cannot constrain, from the location of the RGB alone, the presence of stars with ages in excess of 10 Gyr. Clearly, VII Zw 403 has had a rich history of star formation.

Aloisi, Tosi, & Greggio (1999) recently used synthetic CMDs to investigate deep HST CMDs of I Zw 18, the most metal-poor BCD known (Z⊙/50, from the ionized gas). They find that the present burst is not the first to occur in this galaxy either; the data require a prior burst 500 Myr to 1 Gyr ago. While by most accounts a galaxy with an age below 1 Gyr would be considered a young galaxy, these results for I Zw 18 are in contradiction to the primeval galaxy hypothesis of Izotov & Thuan (1999) based on abundance analyses.

Unfortunately, there are no extremely metal poor BCDs known that are close enough to allow for look-back times of a large fraction of the Hubble time. Whether we are observing a very small percentage of extremely metal poor BCDs while they are undergoing their very first starburst at the present epoch is an interesting suggestion, which remains to be investigated further; it will depend critically on the cycling of their gas (see below).

VII Zw 403 shows evidence for at least three “eras” of star formation. The RGB stars suggest the first event occurred at a look-back time of at least 3 Gyr and probably >10 Gyr, the AGB stars indicate that star formation also happened around 4 Gyr ago (with considerable uncertainty), and the young stars testify to activity that took place less than about 1 Gyr ago. The data also allow us to infer the chemical enrichment history of VII Zw 403. The RGB stars are consistent with a metallicity of the order of Z⊙/100, while the ionized gas and (by assumption) the young stars are at ≈Z⊙/20 (Martin 1997; Izotov et al. 1997). Curiously, an extended AGB is not expected unless Z/Z⊙ > 1/20 (see SCH98; Lynds et al. 1998). The enrichment history of VII Zw 403, at face value, is therefore inconsistent with closed-box models of galaxy evolution and seems to require the loss of enriched gas or the accretion of metal-poor gas. VII Zw 403 is isolated from massive neighbors, so an accretion scenario à la Silk, Wyse, & Shields (1987) seems unlikely. Papaderos et al. (1994) claim an X-ray detection of an outflow of hot gas from this galaxy. Employing our new distance, we can estimate the total gas (H i mass) from the measurements of Thuan & Martin (1981) and Tully et al. (1981) to be about 7×107 M⊙. This places VII Zw 403 in the mass range for which models suggest that gas may be blown out, but the entire gas reservoir may not be blown away (Mac Low & Ferrara 1999).

5. CONCLUSIONS

The BCD VII Zw 403 exhibits a radial population gradient. Young, blue stars and Hα emission are confined to the core. The core region has a diameter that equals the defining size of a BCD. Intermediate-age and old, red stars are distributed throughout an extended background sheet or halo. The halo stars show an RGB with a well-defined tip and are interpreted to be an old and metal-poor population, similar to that in Galactic globular clusters. BCDs were once recognized as “the first metal-poor systems of Population I to be discovered” (Searle & Sargent 1972). VII Zw 403 is the first BCD with compelling evidence for the existence of a Population II halo. VII Zw 403 is also the first BCD for which a direct comparison has been possible between the results from population synthesis of the integrated halo color and resolved stellar content. The detection of red giants at large distances from the starburst center verifies previous identifications of red halos with old stellar populations. If all BCD halos harbor old stars, then they must have formed at high redshift and survived reheating; BCDs would not require the delayed-formation scenario.

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