1. INTRODUCTION

The Local Group dwarf spheroidal galaxies (dSphs) in the Milky Way subgroup offer a unique opportunity to investigate galaxy formation and evolution by studying the photometric properties of the resolved stellar populations. Since 2005, more than a dozen new dSphs have been discovered from the Sloan Digital Sky Survey (SDSS) data (e.g., Willman et al. 2005; Belokurov et al. 2007). The surface brightness of these systems is too low to be identified by the photographic plate; therefore, they are called ultra faint dwarf (UFD) galaxies. The UFD populations of three faint galaxies, the Boö I, CVn II, and Leo IV dSphs, are estimated to be as old as the Galactic globular cluster M92. We confirm that Boö I dSph has no intrinsic color spread in the MTO and no spatial difference in the CMD morphology, which indicates that Boö I dSph is composed of an old single stellar population. One of the brightest UFDs, CVn I dSph, shows a relatively younger age (~12.6 Gyr) with respect to Boö I, CVn II, and Leo IV dSphs, and the distribution of red horizontal branch (HB) stars is more concentrated toward the center than that of blue HB stars, suggesting that the galaxy contains complex stellar populations. Boö I and CVn I dSphs show the elongated and distorted shapes. CVn II dSph has the smallest tidal radius of a Milky Way satellite and has a distorted shape, while Leo IV dSph shows a less concentrated spherical shape. The simple stellar population of faint UFDs indicates that the gases in their progenitors were removed more effectively than those of brighter dSphs at the occurrence of their initial star formation. This is reasonable if the progenitors of UFDs belong to less massive halos than those of brighter dSphs.

Key words: galaxies: dwarf – galaxies: photometry – galaxies: structure – Local Group
allowed us to construct CMDs from the bright red giant branch (RGB) to below the old MSTO. The seeing, exposure time, air mass of each image, and ID of each field are listed in Table 1.

To estimate the contamination of the foreground Galactic stars and the background galaxies, the control field at 1° off from each galaxy center at the same Galactic latitude was taken during the same night for CVn I, II, and Leo IV dSphs (see Table 1). Unfortunately, a limited time prevented us from getting the images of the control field of Boö I dSph.

The raw data were processed using pipeline software SDFRED dedicated to the Suprime-Cam (Yagi et al. 2002; Ouchi et al. 2004) in the usual manner. Each raw image was bias-subtracted and trimmed, flat-fielded by self-flat image, corrected for distortion and atmospheric dispersion, checked and matched for the point-spread function (PSF), sky-subtracted, and combined. For the processed images, the DAOPHOT in the IRAF package was used to obtain the PSF photometry of the resolved stars (Stetson 1987).

SCAMP and SExtractor were used to compute astrometric solutions for the processed images with astrometric standard stars selected from the SDSS catalogs (Bertin & Arnouts 1996; Bertin 2006). The instrumental magnitudes of sources in the images were calibrated to the standard Johnson–Cousins photometric system using the photometric standard stars of Landolt (1992) observed during each run. The average extinction in the direction of each field is taken from Schlegel et al. (1998). The assumed extinction law is RV = 3.1 (Cardelli et al. 1989), and A/I = AV = 0.594 (Schlegel et al. 1998).

To estimate the accuracy and incompleteness of the photometric catalogs, the artificial star tests were performed on the images of each field in the ADDSTAR routine in DAOPHOT. The percentage of detected point sources at a given magnitude has been calculated by adding artificial stars, which were made from the PSF model, to the images, and the resulting images were processed in the same way as for the original ones. The 7000 artificial stars were added to each image for every 0.5 mag interval from 18 mag to 27 mag. This number is smaller than one-tenth of the detected sources of each image to avoid the blending of artificial stars with real sources. The detection ratio of the test, N(recovered)/N(added), of V- and Ic-band images of CVn I dSph is plotted in Figure 1. The artificial star test shows that our photometry is at least 90% complete at 25 mag in both V- and Ic bands in the whole region of all galaxies.

The mean photometric errors are based on the difference between the input magnitude and the output magnitude of the simulated stars in the artificial star test. These errors are plotted in the CMD of each field in the following sections.

To separate stars from the extended sources and noise-like objects, we used the image sharpness statistic sharpness and the goodness of fit statistic chi parameters of DAOPHOT; both are efficient in selecting point sources by the artificial star test. In the upper panels of Figure 2, the sharpness of all detected sources in the V-band long-exposure image of CVn I field is shown. We selected the sources whose sharpness is within...
Figure 3. CMDs of the star-like objects in all observed fields and the simulated CMD. The magnitude errors are estimated by the artificial star test. In panel (d), the TRILEGAL model is used to simulate the CMD of Galactic foreground stars in the direction of the BOO1 field.

3σ of the mean of the simulated stars (dashed lines). The chi values of all sources and the selected point sources are shown in the lower panels of Figure 2. The chi values of most of the selected sources are within 3σ of the mean of the simulated stars. The star/galaxy separation degrades at magnitude fainter than V ∼ 24.5 and Ic ∼ 24.0, on average.

Figure 3 shows the resulting CMDs of the star-like objects found in all central and control fields of galaxies. The CMD of the central field of each galaxy is extended below the MSTO (Figures 3(a), (c), (e), and (g)). In Figure 3(a), both red and blue horizontal branches (HBs) of CVn I dSph appear with the well-defined RGB and the blue straggler (BS) candidates that are not found in the control field (Figure 3(b)). The blue HB (BHB), the tight main sequence (MS), and the BS candidates of Boö I dSph are seen in Figure 3(c). The central CMD of CVn II dSph (Figures 3(e)) has distribution similar to that of the control fields (Figure 3(f)), but the BHB and the weak signal of RGB can be found in Figure 3(e). The CMDs of Leo IV dSphs (Figures 3(g) and (h)) have properties similar to those of CVn II dSph, but the BS candidates are also seen in Figure 3(g). The lack of bright stars in Figures 3(a), (e), and (f) is due to the poor observing conditions. We discuss the stellar populations in detail in Section 4.

In Figure 3(d), the TRILEGAL model code (Girardi et al. 2005) is used to simulate the CMD of Galactic foreground stars in the direction of the BOO1 field. We used this model CMD to estimate the contamination of Boö I dSph in Section 5. In the model CMD, the halo MS stars are distributed at (V − Ic)0 > 0.6 mag, which are also seen in those of the observed fields. The faint red objects distributed at V0 > 24.5 in the observed CMDs are the unresolved background galaxies, which do not appear in the model CMD. The background galaxies at (V − Ic)0 > 0.1 in Figure 3(b) are brighter than those found in the CVN1 field, probably due to the poor observing conditions.

3. DISTANCES

3.1. Canes Venatici I dSph

The magnitudes of the HB and the RGB tip (TRGB) were used to estimate the distances of the galaxies. For CVn I dSph, 36 BHB stars in the range of 22.05 < V0 < 22.35 and 0.1 < (V − Ic)0 < 0.3 were used to derive the average magnitudes $V_{\text{BHB}} = 22.17 \pm 0.05$ and the red HB (RHB) derived from 113 stars with 22.05 < V0 < 22.35 and 0.58 <
(V − Ic)0 < 0.85 as VHHB = 22.13 ± 0.06. The mean value is VBB = 22.15 ± 0.06, which is in good agreement with the average magnitude of the RR Lyrae stars VRR = 22.17 ± 0.02 estimated by Kuehn et al. (2008). The calibration of absolute magnitude M_{V,RR} is a function of the metallicity [Fe/H] (Cacciari & Clementini 2003). Using spectroscopic metallicity [Fe/H] = −2.08 ± 0.02 derived by Kirby et al. (2008), the absolute magnitude of RR Lyrae stars is estimated to be M_{V,RR} = 0.47 ± 0.05, from which the distance modulus of CVn I dSph is determined to be (m − M)0 = 21.68 ± 0.08.

The Ic-band magnitude of the TRGB can also be used as a distance indicator. M_{Ic,TRGB} is not sensitive to the metallicity at [Fe/H] < −0.7, nor to the age if it is older than several Gyrs (e.g., Lee et al. 1993). The number of the bright RGB stars in a UFD, however, is usually too small, and the bright RGB is heavily buried in the foreground contamination. Thanks to the relatively bright luminosity, the location of the TRGB of CVn I dSph was estimated. The position of TRGB was found at I_{TRGB} = 17.91 ± 0.06 from bright three RGB stars with 17.9 < (V − Ic) < 18.0 and 1.35 < (V − Ic)0 < 1.47. The distance modulus of CVn I dSph was then derived from the calibration of M_{Ic,TRGB} as a function of the metallicity [M/H] (Salaris et al. 1993; Bellazzini et al. 2004). Using the spectroscopic metallicity [Fe/H] = −2.08 ± 0.02 and assuming [α/Fe] ∼ 0 as found in classical dSphs (e.g., Shetrone et al. 2003), the absolute magnitude of TRGB in the Ic band was estimated to be M_{Ic,TRGB} = −3.51, from which the distance modulus was derived as (m − M)0 = 21.48 ± 0.17. We assumed the same [α/Fe] as those of Draco and Ursa Minor dSphs, because the luminosity of CVn I dSph is similar to these faint classical dSphs, although spectroscopic confirmation is required. If we adopt [α/Fe] of Galactic globular clusters ([α/Fe] ∼ +0.3), the distance modulus of CVn I dSph becomes (m − M)0 = 21.90 ± 0.17. These two values are slightly smaller ((m − M)0, [α/Fe] = −0.02 = 21.48 ± 0.17) and larger ([(m − M)0, [α/Fe] = +0.3 = 21.90 ± 0.17) than the value estimated based on the HB magnitude ((m − M)0, HB = 21.68 ± 0.08). This is due to the uncertainties of the [α/Fe] and I_{TRGB}. Therefore, we adopt the distance modulus of (m − M)0 = 21.68 ± 0.08 (216 ± 8 kpc) estimated by the HB luminosity. Our estimate is consistent with the previous estimate, (m − M)0 = 21.69 ± 0.10, by Martin et al. (2008a).

### 3.2. Boötes I dSph

The mean V-band magnitude of the BHB stars in Boö I dSph was derived from 17 stars with 19.5 < V0 < 19.7 and 0.0 < (V − Ic)0 < 0.3 as VBB = 19.63 ± 0.04. The average RR Lyrae star magnitude was extrapolated as VRR = 19.43 ± 0.09 using the magnitude difference of BHB and RR Lyrae stars (∆V = 0.2 ± 0.08) derived from metal-poor ([Fe/H] < −2.0) and old (> 12 Gyr) isochrones (Marigo et al. 2008). With the spectroscopic average metallicity [Fe/H] = −2.51 ± 0.13 derived by Norris et al. (2008), the absolute magnitude of RR Lyrae is M_{V,RR} = 0.36 ± 0.07; the distance modulus of Boö I dSph was determined to be (m − M)0 = 19.07 ± 0.11 (65 ± 3 kpc), which is in good agreement with (m − M)0 = 18.96 ± 0.12 (62 ± 4 kpc), given by Kuehn et al. (2008).

### 3.3. Canes Venatici II dSph

In the case of CVn II dSph, it is hard to identify each evolutionary stage, in particular the HB from the CMD in Figure 6. Therefore, the CMD of the central region was used to derive the magnitude of the HB. The mean V-band magnitude of the BHB stars was derived from eight stars with 21.3 < V0 < 21.9 and 0.0 < (V − Ic)0 < 0.3, within 5′ (corresponding to three times the half-light radius r_h estimated by Belokurov et al. 2007) from the center of CVn II dSph, as VBB = 21.64 ± 0.06. The average RR Lyrae star magnitude was extrapolated as VRR = 21.44 ± 0.09 in the same manner as in the case of Boö I dSph. Considering the spectroscopic average metallicity, [Fe/H] = −2.19 ± 0.05, derived by Kirby et al. (2008), the absolute magnitude of RR Lyrae is M_{V,RR} = 0.43 ± 0.07. The distance modulus of CVn II dSph was determined as (m − M)0 = 21.01 ± 0.11 (159 ± 8 kpc), which is in good agreement with the previous estimation, (m − M)0 = 21.02 ± 0.06 (160 ± 5 kpc), based on the RR Lyrae magnitude (Greco et al. 2008).

### 3.4. Leo IV dSph

Leo IV dSph has luminosity and distance similar to CVn II dSph. Therefore, the distance of Leo IV dSph was estimated in the same manner as CVn II dSph. The mean V-band magnitude of the BHB stars is VBB = 21.53 ± 0.06, which is derived from seven stars with 21.0 < V0 < 21.7 and 0.0 < (V − Ic)0 < 0.3, within 5′ (corresponding to twice of r_h, estimated by Belokurov et al. 2007) from the center of Leo IV dSph. The average RR Lyrae star magnitude was extrapolated as VRR = 21.33 ± 0.09. With the spectroscopic average metallicity, [Fe/H] = −2.58 ± 0.08, derived by Kirby et al. (2008), the absolute magnitude of RR Lyrae is M_{V,RR} = 0.34 ± 0.09; therefore, the distance modulus of Leo IV dSph is (m − M)0 = 20.99 ± 0.12 (158 ± 8 kpc), which is in excellent agreement with the previous estimation, (m − M)0 = 20.94±0.07 (154±5 kpc), based on the magnitude of RR Lyrae (Moretti et al. 2009).

### 4. STELLAR POPULATIONS

#### 4.1. Canes Venatici I dSph

CVn I dSph is one of the brightest UFDs (Zucker et al. 2006). The HB morphology and RGB slope in the CMD look like those of classical dSphs such as Draco dSph. In Figure 3(a), the well-defined RGB appears with the tip at V0 ∼ 19.2 and (V − Ic)0 ∼ 1.3, and the HB stars are seen at V0 ∼ 22.2. BHB and RHB are found at (V − Ic)0 ∼ 0.1 and (V − Ic)0 ∼ 0.7, respectively. The MS stars can be traced below V0 < 25, and a significant number of BS candidates are found at (V − Ic)0 < 0.3 and V0 < 24. The other hand, the foreground stars are heavily distributed at (V − Ic)0 > 0.6 mag, and the background galaxies are found as the distribution at V0 > 24.5. These objects are also found in the CMDs of all other target and control fields. The faint red objects at (V − Ic)0 > 0.1 in the control field are brighter than those found in the CVN1 field, probably due to the poor observing conditions.

Figure 4 shows the CMDs of the whole region (Figure 4(a)) and the central region within r_h (< 10′. Figures 4(b)–(d) of CVn I dSph. In Figure 4(a), the gray color shows all star-like objects, and the black points present the member candidates brighter than the 90% detection limits of V- and Ic-band photometry (dashed line). We used these candidates in studying the spatial distributions of CVn I dSph in Section 5. In Figures 4(b)–(d), contours are overplotted for the purpose of clarity. In Figures 4(c) and (d), theoretical isochrones and the fiducial sequence of the metal-poor Galactic globular cluster M92 are overlaid. The fiducial sequence of M92 was taken.
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Figure 4. \((V - Ic)_0-V_0\) CMDs of the whole region (a) and within the \(r_h\) region ((b)-(d)) of CVn I dSph. In panel (a), the dashed line represents the 90% detection limit of photometry. Black points are the member candidates of CVn I dSph, which are used to estimate the structural properties. In panels (c) and (d), the theoretical isochrones and the fiducial sequence of Galactic globular cluster M92 are overlaid.

The metallicity of M92 is \([\text{Fe}/\text{H}] = -2.28\) (Harris 1996), and its age is estimated as 14.2 ± 1.2 Gyr (Paust et al. 2007). The fiducial sequence of M92 from Clem et al. (2008) was converted from \(g', r', i'\) to the Johnson–Cousins \(V, Ic\) system using the transformation given by Jordi et al. (2006). We adopted the distance modulus \((m - M)_0 = 14.67\) and the reddening corrections \(E(B - V) = 0.02\) for M92 (Harris 1996). The locations of MSTO and RGB on the CMD are similar to those of M92, suggesting that the average metallicity of CVn I dSph is \([\text{Fe}/\text{H}] \sim -2.3\), which is consistent with the spectroscopic estimate by Kirby et al. (2008).

By overlaying theoretical isochrones in Figure 4(c), the average age of stellar population was estimated. Padova isochrones of \(Z = 0.0002\) and 10.0, 12.6, 13.7 Gyr (Marigo et al. 2008) were used by shifting to the distance of CVn I dSph. The metallicity we adopted corresponds to \([\text{Fe}/\text{H}] = -2.2\) with \([\alpha/\text{Fe}] = +0.3\), and \([\text{Fe}/\text{H}] = -2.0\) with \([\alpha/\text{Fe}] = 0.0\).

Figure 4(c) shows that the fiducial sequence from MSTO to RGB of CVn I dSph is best reproduced by the isochrone of 12.6 Gyr.

Martin et al. (2008a) found a dichotomy in the stellar populations of CVn I dSph that shows an old (>10 Gyr), metal-poor (\([\text{Fe}/\text{H}] \sim -2.0\)), and spatially extended population along with a younger (\(\sim 1.4-2.0\) Gyr), metal-rich, and centrally concentrated one. They suggested that the blue plume of stars at \(B - V \sim 0.1\) and \(23.5 < V < 25.0\) indicate the possible presence of a young stellar population. The deep Suprime-Cam photometry, however, shows no evidence for young stars; instead, it shows BSs clearly (see Section 6.3).

The HB morphology of CVn I dSph, which shows both BHB and RHB, is similar to that of the brighter classical dSphs.
such as Fornax and Sculptor dSphs. Tolstoy et al. (2004) and Battaglia et al. (2006, 2008) showed that Fornax and Sculptor dSphs have two distinct HB populations, the spatially extended metal-poor BHB stars and the centrally concentrated metal-rich RHB stars, which also appear to be kinematically distinct. The stellar population structure of CVn I dSph will be discussed in more detail in Section 6.1.

4.2. Boötes I dSph

Boötes I dSph has a moderate luminosity ($M_V \sim -5.8$) of UFD. Thanks to its small distance, the tight MS is clearly seen in the CMD in Figure 5. Figure 5 shows the CMD of the entire observed region (Figure 5(a)), and within the $12'5$ (corresponding to $r_h$) region (Figures 5(b)–(d)), with the theoretical isochrones (Figure 5(c)) and the fiducial sequence of M92 (Figure 5(d)) in the same manner as in the case of CVn I dSph. The sequences of MS, RGB, and HB of Boötes I dSph are quite similar to those of M92, suggesting that the average metallicity of Boötes I dSph is [Fe/H] $\simeq -2.3$, which is consistent with the spectroscopic estimate by Norris et al. (2008).

In Figure 5(c), Padova isochrones with $Z = 0.0001$ and 12.6 and 13.7 Gyr (Marigo et al. 2008) are shifted to the distance of Boötes I dSph. This metallicity corresponds to [Fe/H] = −2.5 with [$\alpha$/Fe] = +0.3, and [Fe/H] = −2.3 with [$\alpha$/Fe] = 0.0. Figure 5(c) shows that the fiducial sequence of MS is best reproduced by the isochrone of 13.7 Gyr, consistent with the age roughly estimated from the comparison with M92 in Figure 5(d). In fact, even the oldest isochrone shows slightly bluer color at MSTO than that of Boötes I dSph. This difference would be reduced if we adopted the more metal-rich isochrone, but it is not likely that the spectroscopically confirmed metallicity is significantly underestimated (Norris et al. 2008). Consequently, the main population of Boötes I dSph is estimated to be older than that of CVn I dSph. Figure 5(a) indicates that the MSTO color width is quite narrow, which implies no age spread of stars in Boötes I dSph. We discuss this in Section 6.2.

4.3. Canes Venatici II dSph

CVn II dSph is relatively faint and compact. The existence of BHB stars implies that CVn II dSph has an old and metal-poor
stellar population. The number of member candidates of CVn II dSph is extremely small, so we used the central region within $r_h$ to estimate the stellar population. Figure 6 shows the CMDs of CVn II dSph in the same manner as that of CVn I dSph. In the central CMD (Figures 6(b)–(d)), the stellar sequences of MS, RGB, and BHB are clearly seen. The narrow RGB is seen at $0.6 < (V-I_c)_0 < 1.2$ and $19 < V_0 < 24$, but the bright RGB stars are not seen because of the lack of short exposure images of the CVN2 field. The BHB stars are identified at $V_0 \sim 21.5$ and $(V-I_c)_0 \sim 0.25$. The MS stars can be found at $V_0 < 24.0$ and $(V-I_c)_0 \sim 0.6$ mag. Interestingly, there are no bright BS candidates in the central CMD (Figures 6(b)–(d)), either due to a real paucity of BS stars or to poor statistics.

Figure 6(d) shows that the fiducial line of MSTO to RGB of CVn II dSph is similar to those of M92, suggesting that CVn II dSph is quite old and metal-poor ([Fe/H] $\simeq -2.3$). The latter is consistent with the spectroscopic estimate by Kirby et al. (2008). The average age of stars found in the central ($<r_h$) region is estimated to be 13.7 Gyr by overlaying Padova isochrones in Figure 6(c). This age is the same as that of Boö I dSph. Therefore, most of the stars in CVn II dSph are estimated to have formed in the same epoch during which Boö I dSph was born.

4.4. Leo IV dSph

Figure 7 shows the CMDs of Leo IV dSph in the same manner as those of CVn I dSph. The stellar distribution in the CMD is similar to that of CVn II dSph; thus, it is rather difficult to identify stellar sequences in Figure 7(a). In the CMD of the central region (Figures 7(b)–(d)), MS, RGB, BHB, and BS stars are clearly seen. The narrow RGB is seen at $0.6 < (V-I_c)_0 < 1.2$ and $18.5 < V_0 < 24$. The BHB stars are seen at $V_0 \sim 21.5$ and $(V-I_c)_0 \sim 0.25$. The MS stars can be found at $V_0 < 24.0$ and $(V-I_c)_0 \sim 0.6$, and the BS candidates can be found at $23.0 < V_0 < 24.5$ and $0.0 < (V-I_c)_0 < 0.4$. The major difference between Leo IV (Figure 7(b)) and CVn II (Figure 6(b)) dSphs is the existence of BS and RHB candidates in Leo IV dSph. These populations do not appear in the central CMD of CVn II dSph. The spatial distribution of RHB candidates is not concentrated, but is uniformly distributed throughout the observed area; they could be the foreground stars.

The ridge line from MS to RGB of Leo IV dSph is similar to that of M92, suggesting that the average metallicity of Leo IV dSph is [Fe/H] $\simeq -2.3$, which is consistent with the spectroscopic estimate (Kirby et al. 2008). Similar to Boö I and CVn II dSphs, the average age of stellar population of Leo IV dSph is estimated to be 13.7 Gyr by overlaying Padova isochrones in Figure 7(c).

Sand et al. (2010) recently pointed out that blue plume stars in Leo IV dSph are young ($\sim 2$ Gyr) populations and are equivalent to those found in CVn I dSph by Martin et al. (2008a). The spatial distribution of these stars, however, clearly indicates that they are the BS stars, as we will discuss in Section 6.3.

5. STRUCTURAL PROPERTIES

Figure 8 shows the spatial distributions and the density contour maps of UFDs, which show various morphologies.
Figure 8. Spatial distribution of CVn I (upper), Boö I (upper middle), CVn II (lower middle), and Leo IV (lower) dSphs. Left: spatial distribution of the member candidates selected from each CMD. The tidal radii of CVn II and Leo IV dSphs are shown as solid lines. Right: isodensity contour of the member candidates. The solid and dashed arrows indicate the directions of Galactic center (Sgr A) and Galactic latitude toward the disk, respectively.

CVn I and Boö I dSphs show elongated and distorted shapes. CVn II dSph has a relatively high concentration, while Leo IV dSph shows a smooth and less concentrated spherical shape. The plotted sources are selected as the candidate stars of MS, RGB, HB, and BS from the CMDs, shown as black points in Figures 4(a), 5(a), 6(a), and 7(a). These stars are binned and smoothed by the Gaussian kernels to make the contour map. The contour levels are 2, 4, 6, 8, 12, and 14σ above the background.
level. The maps cover the central 2 kpc × 1.5 kpc of CVn I dSph, 600 pc × 500 pc of Boö I dSph, and 1.7 × 1.3 kpc of CVn II and Leo IV dSphs, respectively.

Because we do not have the control field of Boö I dSph, we choose the selection limit brighter than the degradation level of our star/galaxy separation to eliminate the background galaxy contamination in Boö I dSph. Therefore, the spatial distribution of Boö I dSph is constructed by these member candidates, which are bright enough to exclude the background contamination found in the distribution at $V_0 > 24.5$. The foreground contamination is estimated using the model CMD constructed by TRILEGAL shown in Figure 3.

The member candidates of each galaxy are used to derive the centroid from the density-weighted first moment of the spatial distribution, and the average ellipticity and the position angle using the three density-weighted second moments (e.g., Stobie 1980). Figure 9 shows the radial profiles derived from the average number density within elliptical annuli after correcting the effect of the contamination. The number density of foreground/background objects in the direction of each galaxy is estimated by counting the number of objects within the same criterion in the control field CMD, or the model CMD constructed by TRILEGAL in the case of Boö I dSph. We fit the radial profile with the standard King model (King 1962),

$$\Sigma(r) = \Sigma_{K,0} \left( \frac{1}{1 + (r/r_e)^2} \right) \left[ 1 - \frac{1}{1 + (r/r_c)^2} \right]^2, \quad (1)$$

with the exponential model,

$$\Sigma(r) = \Sigma_{E,0} \exp \left\{ -\left( \frac{r}{r_e} \right)^2 \right\}, \quad (2)$$

and with the Plummer model,

$$\Sigma(r) = \Sigma_{P,0} \frac{b^2}{(b^2 + r^2)^2}, \quad (3)$$

to estimate the core radius $r_c$, the tidal radius $r_t$, and the half-light radius $r_h$ ($= 1.68 \times r_e = b$). Hereafter we use the elliptical radius

$$r = \left( x^2 + \frac{y^2}{(1-e)^2} \right)^{1/2}, \quad (4)$$

where $e$ is the ellipticity of the galaxy, and $x$ and $y$ are the coordinates aligned with the major and minor axes, respectively. The estimated $r_h$ agrees well with the previous estimates derived from the SDSS data (Martin et al. 2008b). The core and tidal radii of these galaxies except for CVn II dSph are estimated for the first time by this study. The tidal radius of CVn I dSph, $r_t \sim 3.5$ kpc, is similar to that of Sextans dSph ($r_t = 4.0$ kpc) which is the largest among the Galactic satellites (Mateo 1998), while the tidal radius of CVn II dSph, $r_t \sim 300$ pc, is the smallest.

The absolute magnitude $M_V$ is calculated by using the luminosity of member candidates selected from the CMDs within $r_h$ in each galaxy. First, the luminosity is corrected for contamination; that is, the luminosity from the foreground/background objects estimated by the control field CMDs is subtracted. Next, the luminosity from fainter MS stars is added, and then the resulting luminosity is doubled to estimate the total flux. The errors include uncertainties of these corrections and the error of $r_h$ estimates. The best-fitting structural parameters are listed in Table 2.

The contour maps of UFDs show various appearances. CVn II dSph has an asymmetric shape and a structure extended toward the south. The core of CVn II dSph looks spherical in shape, but the outer region is elongated toward the north and south, which indicates ongoing tidal disruption. Leo IV dSph, on the other hand, shows the less concentrated than CVn II dSph and shows the spherical shape in the outer region. The slight overdensities are found in the southwest of Leo IV dSph. In CVn I dSph, the peak of the stellar density is somewhat offset toward the west from the expected center. The observed regions do not cover the whole area but cover only the area within the half-light radius of CVn I and Boö I dSphs, so it is unclear whether or not these features truly reflect genuine extent of these galaxies. The quite irregular shapes of these galaxies, however, indicate that they are suffering from strong tidal effects from the Milky Way. The shapes of UFDs apparently have no correlation with the projected direction of Galactic center and the Galactic latitude, which are shown as solid and dashed arrows, respectively, in Figure 8.

The tidal disturbance in the stellar distributions of UFDs provides a clue to understanding the properties of DM and the mass profiles of satellite galaxies. There is no apparent substructure or tidal debris around CVn II and Leo IV dSphs, the observed areas of which are extending beyond the tidal radii (Figure 8). However, the stellar densities show slight excesses at the edges of these galaxies in Figure 9. Similar excesses were also found in the outer regions of several other Galactic satellites, and theoretical studies show that Galactic tides acting on cuspy halo profiles of satellites and/or the CDM model tend to make higher central densities and excesses in outer regions of satellites in comparison with the cases of cored halos and/or the warm DM model (e.g., Mayer et al. 2002; Peñarrubia et al. 2010). Although spectroscopic confirmation is required to reveal whether the slight excesses in CVn II and Leo IV dSphs are real, the stellar density profiles of UFDs could provide some constraints on the properties of DM in UFDs.

| Parameter | CVn I | Boö I | CVn II | Leo IV |
|-----------|-------|-------|--------|--------|
| R.A. (J2000) | 13°28′00″ | 14°00′05″ | 12°57′08″ | 11°52′56″ |
| Decl. (J2000) | +33°33′07″ | +14°30′02″ | +34°19′17″ | –0°32′24″ |
| Position angle | 78°6 | 14°2 | 9°45 | 36°9 |
| Ellipticity | 0.30 | 0.22 | 0.23 | 0.04 |
| $r_c$ | 5.62 ± 0.40 | 10.3 ± 0.9 | 1.50 ± 0.16 | 1.79 ± 0.17 |
| $r_t$ | 54.5 ± 12.9 | 37.4 ± 5.5 | 6.33 ± 0.53 | 10.6 ± 1.08 |
| $r_h$ (Plummer) | 8.99 ± 0.20 | 12.8 ± 0.7 | 1.77 ± 0.10 | 2.44 ± 0.10 |
| $r_h$ (exponential) | 9.23 ± 0.39 | 12.5 ± 0.3 | 1.85 ± 0.09 | 2.55 ± 0.08 |
| $M_V$ | –7.93 ± 0.2 | –5.92 ± 0.2 | –5.37 ± 0.2 | –4.97 ± 0.2 |
| $(m - M)_B$ | 21.68 ± 0.08 | 19.07 ± 0.11 | 21.01 ± 0.11 | 20.99 ± 0.12 |
| Distance (kpc) | 216 ± 8 | 65 ± 3 | 159 ± 8 | 158 ± 8 |

6. DISCUSSIONS

It is well known that the classical dSphs show various star formation histories (e.g., Monelli et al. 2003; Battaglia et al. 2006; Tolstoy et al. 2009). Population complexities are found in bright dSphs such as Fornax, Leo I, and Carina dSphs, which contain intermediate age (< a few Gyr) and old (>10 Gyr) stars. Faint classical dSphs such as Ursa Minor show essentially single old populations (e.g., Carrera et al. 2002). In the case of UFDs, we have shown that Boö I, CVn II, and Leo IV...
dSphs have genuine old populations, while the brighter UFD, CVn I dSph, has a relatively younger population. This variety of stellar population is probably related to the internal and/or external mechanisms that regulated the star formation of very faint galaxies in the past.

6.1. The Population Gradient in CVn I dSph

With the structural parameters estimated above, the spatial distributions of stellar components of CVn I dSph are derived. Figure 10 presents the cumulative radial distributions of BHB, RHB, MS, and BS stars of CVn I dSph. The foreground/background contaminations are estimated from the control CMD and corrected. In Figure 10, the BHBs are clearly more extended than other components, and the RHBs are more concentrated toward the galaxy center. The color of HB star reflects the age and metallicity; the metal-rich or younger HB stars become redder than the metal-poor or older HB stars. Therefore, this radial difference of HB morphology suggests the population gradient in CVn I dSph. The spatial distributions of HBs are consistent with the result of Ibata et al. (2006) and Martin et al. (2007), who revealed the presence of two kinematically distinct populations in CVn I dSph.

From these results, we conclude that CVn I dSph has ancient (>10 Gyr) but at least two populations of different metallicity, spatial distribution, and kinematics.

6.2. Age Spread in Boö I dSph?

The deep Suprime-Cam photometry presents the sequence of MS to RGB in the CMD of Boö I dSph. The width of
well-defined RGB to MS is quite narrow, and the CMD morphology agrees well with the old metal-poor M92. This result implies that BoöI dSph has a purely old single population like Galactic old globular clusters. With the limited resolution of our photometry and the coarse grid of theoretical isochrones, it is difficult to conclude whether this galaxy formed before the reionization of the universe started. The location of BoöI dSph is close enough to the Milky Way; however, it is possible to obtain the magnitudes and colors of MSTO stars with small photometric errors, Δ(V − Ic)_0,MSTO = 0.03. Therefore, BoöI dSph is the best target to seek for the possible age spread.

The color width of MSTO is shown in Figures 11 and 12. Figure 11 shows the CMDs of the four regions located at the elliptical distance r of (panel (a)) 0′ < r < 6′, (panel (b)) 6′ < r < 10′, (panel (c)) 10′ < r < 14′, and (panel (d)) 14′ < r < 20′. Padova isochrone of Z = 0.0001 and 13.7 Gyr is overlaid as a solid line. These four CMDs look quite similar, and the number of stars belonging to BoöI dSph decreases from the innermost (Figure 11(a)) to the outside of the half-light radius region (Figure 11(d)).

The observed width of MSTO is the convolution of the intrinsic width and photometric errors. The intrinsic width of the MSTO could be broad due to multiple stellar populations (e.g., Monelli et al. 2003; Bedin et al. 2004), and the multiplicity of stellar populations can be examined from the width of the MSTO. Figure 12 shows the color distributions of MSTO stars in the magnitude range of 22.7 < V_0 < 22.9, found in four regions shown in Figure 11. The solid lines are Gaussian distributions with σ = 0.03, equal to the photometric error estimated from the artificial star tests. The color distributions of MSTO stars are all well represented by the photometric errors alone, which strongly suggests that BoöI dSph has no intrinsic age spread, at least in the limit of the Suprime-Cam photometry. A Kolmogorov–Smirnov test is applied to confirm that the MSTO color distribution of the four regions is the same as the distribution produced by the photometric errors alone. From this result, we conclude that BoöI dSph has a single old stellar population.

6.3. Blue Stragglers in UFD Galaxies

BS candidates are found in all four UFDs and distributed throughout the galaxies. Figure 13 shows the spatial distribution of BS candidates of each UFD galaxy, which shows no sign of concentration toward the galaxy center, and clumpy distribution. The BS criterion area in CMD, which is shown as a gray box above the MSTO in Figures 4(b), 5(b), 6(b), and 7(b), is contaminated by unresolved background objects and foreground white dwarf stars. These objects are seen outside the tidal radii of CVn II (r > 0.29 kpc) and Leo IV dSphs (r > 0.48 kpc) shown as the solid lines in Figure 13.

BS stars are universally found in Galactic globular clusters, open clusters, the halo field, and in several Galactic dSphs (e.g., Bailyn 1995; Piotto et al. 2004; Mapelli et al. 2007). They can form from stellar collisions in high-density regions, or through mass transfer in isolated primordial binaries. Mapelli et al. (2006) suggested that the spatial distribution of BS stars in globular clusters provides strong hints to their origin. The spatial distribution of collisional BS stars follows a peaked distribution at the cluster center. On the other hand, the mass-transfer BS stars follow the distribution of primordial binaries whose spatial distribution is similar to those of HB and RGB. In the case of dSphs galaxies with complex stellar populations, these blue stars can be either genuine BS stars or ordinary young (~several Gyr) MS stars. However, young populations are expected to have more clumpy and centrally concentrated distributions. Therefore, the distribution of BS candidates in UFDs implies that these stars are not young MS stars, but mass-transfer BS stars that evolved from primordial binaries, as found in other dSphs (e.g., Mapelli et al. 2007; Okamoto et al. 2008).

6.4. Comparison with the Classical dSphs

The stellar populations of UFDs are, in principle, quite old and metal-poor and are similar to those of the old metal-poor Galactic globular clusters. BoöI dSph shows no intrinsic spread in the width of MSTO, which indicates that BoöI dSph experienced a very short period of star formation. CVn II and Leo IV dSphs, which are fainter than BoöI dSph, are as old as BoöI dSph. The same is true for the other faint UFDs, Ursa Major I, II, Coma Berenices, and Hercules dSphs (Okamoto et al. 2008; Martin et al. 2008a; Sand et al. 2009; Muñoz et al. 2010). The brightest UFD, CVn I dSph, shows a slightly younger age compared with the other UFDs and different spatial distribution of BHB and RHB stars, implying the population gradient in this galaxy. CVn I dSph also shows two kinematically distinct populations (Ibata et al. 2006; Martin et al. 2007). This population complexity is similar to those found in the brighter classical dSphs. In general, the brighter Galactic...
Figure 13. Spatial distributions of BS candidates found in the CVn I (upper left), Boö I (upper right), CVn II (lower left), and Leo IV dSphs (lower right). The tidal radii of CVn II and Leo IV dSphs are shown as solid lines.

satellites have more complex stellar populations than those of the fainter Galactic satellites.

Two factors could be considered to explain this population difference. The first is accretion times, and the second is potential depths of satellites. If fainter satellites had been captured by the Milky Way before they finished star formation, the remains of the gas in the satellites were likely to be removed by ram-pressure stripping at the accretion. While they could hardly continue star formation after that, other small galaxies kept forming stars and became bright until they lost gas. Furthermore, early accreted satellites generally experienced a more significant mass loss than those accreted later, so they became faint (Gao et al. 2004). This may explain why UFDs are composed of only a few old stars, and why brighter dSphs show complex stellar populations. Numerical simulations, however, indicate that the locations of early infalling satellites are likely to be closer to the Galactic center than those of later infalling satellites (Cooper et al. 2010). In this scenario, early infalling satellites are expected to be fainter and closer to the Milky Way as compared with later infalling and brighter satellites. The real UFDs ($M_V < -6$) are widely distributed around the Milky Way (30–160 kpc), and there is no obvious correlation between the stellar population complexities and the current distances of Galactic satellites. Therefore, whether the early accretion caused progenitors to become present UFDs is somewhat controversial.

If we assume that the brighter satellites belonged to the more massive DM halos than those of fainter ones at their initial star formation, the deeper potential makes it possible to keep the gas and form the stars for the longer duration, against the suppression effects such as the ram-pressure, tidal stripping, supernova (SN) feedback, and photo-evaporation by reionization. Therefore, the satellite progenitors in higher mass halos tended to become brighter dSphs that had more complex stellar populations than those in lower mass halos. After accretion, the satellites in lower mass halos should also suffer from stronger tidal effects of the Milky Way, which could explain the current elongated and distorted shapes of UFDs. The mass estimations of Local Group dSphs, based on the velocity dispersion profiles of galaxies, revealed that the masses within $r_h$ of dSphs are proportional to the sizes and luminosities (Walker et al. 2009). This result supports the idea that the population complexity of Galactic satellites is mainly due to the difference in the potential depths of progenitors, and the faintness of UFDs directly reflects their shallow potentials. In this case, star formation in faint UFDs, especially at large distances, was not regulated by Galactic tides, but was regulated by either reionization or SN feedback, or influences of other small galaxies.

7. SUMMARY

From the deep and wide images taken with Subaru/Suprime-Cam, we demonstrate the single old stellar population of faint UFDs, Boö I, CVn II, and Leo IV dSphs as well as the population complexity of the relatively bright UFD, CVn I dSph. We confirm that Boö I dSph has no intrinsic color spread in the width
of MSTO, and no spatial difference in the CMD morphology. CVn I dSph, on the other hand, shows a relatively younger age (~ 12.6 Gyr), and different spatial distributions of HBB and RHB stars, implying a population gradient. The spatial distributions of BS candidates in UFDs reveal that they are not young MS stars but mass-transfer BS stars. These results indicate that the gases in the UFD progenitors were removed more effectively than the those of brighter dSphs when the initial star formation occurred. This is reasonable if the progenitors of UFDs belong to less massive halos than those of brighter dSphs at that moment.

The wide range of tidal radii and the distorted shapes of UFDs also imply that UFDs are strongly affected from Galactic tides. We covered the region beyond $r_1$ of CVn II and Leo IV dSphs. Although there are no extra stellar streams nor tidal debris around the galaxies, the radial profiles show stellar overdensities at the edges of these galaxies. Boö I and CVn I dSphs show elongated morphologies; however, the observed areas are not enough to reveal the real extent. Further wide and deep observations are required to clarify whether the highly elongated UFDs have spheroidal shapes or shapes like stellar streams. Our recent observation of the Hercules dSph, which covered the outer region of the galaxy, will provide an answer.

We demonstrate that UFDs are composed of old stellar populations. However, it is still unclear which mechanism makes such a faint galaxy. Explorations of further faint nearby UFDs and isolated distant UFDs are crucial to revealing the origin. Leo T dwarf is the only instance of the isolated UFD, so far, and is one of the brightest UFDs. If there are numerous undiscovered UFDs in Local Group, the stellar ages in these galaxies are a clue to understanding the regulation mechanisms of star formations in small galaxies at the reionization epoch.

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