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The formation history of the Ultra-Faint Dwarf galaxies

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Abstract. We present early results from a *Hubble Space Telescope* survey of the ultra-faint dwarf galaxies. These Milky Way satellites were discovered in the Sloan Digital Sky Survey, and appear to be an extension of the classical dwarf spheroidals to low luminosities, offering a new front in the efforts to understand the missing satellite problem. Because they are the least luminous, most dark matter dominated, and least chemically evolved galaxies known, the ultra-faint dwarfs are the best candidate fossils from the early universe. The primary goal of the survey is to measure the star-formation histories of these galaxies and discern any synchronization due to the reionization of the universe. We find that the six galaxies of our survey have very similar star-formation histories, and that each is dominated by stars older than 12 Gyr.

Key words. Galaxies: dwarf – Galaxies: evolution – Galaxies: formation – Galaxies: photometry – Galaxies: stellar content

1. Introduction

One of the most prominent issues with the Lambda Cold Dark Matter paradigm is the "missing satellite problem" – the fact that the predicted number of dark-matter halos exceeds the number of observed dwarf galaxies (e.g., Moore et al. 1999). As one possible solution, Bullock et al. (2001) hypothesized that reionization suppressed star formation in most dwarf spheroidals, making them unobservable in visible light. Along these lines, Ricotti & Gnedin (2005) proposed three different evolutionary paths for dwarf galaxies: "true fossils" that formed most (>70%) of their stars prior to reionization, "polluted fossils" with significant post-reionization star formation due to subsequent mass accretion and tidal shocks, and "survivors" where star formation largely began after reionization. Around the same time, the discovery of additional faint satellites and tidal debris around the Milky Way (e.g., Willman et al. 2005; Zucker et al. 2006; Belokurov et al. 2007) and Andromeda (e.g., Zucker et al. 2007; McConnachie et al. 2009) demonstrated that the census of nearby dwarf galaxies was incomplete, and provided potential examples of fossil galaxies. Indeed, the first color-magnitude diagrams (CMDs) of the ultra-faint dwarf (UFD) galaxies revealed that they are dominated by old (>10 Gyr) stars (e.g., Sand et al. 2009, 2010; Okamoto et al. 2008, 2012; Adén et al. 2010; Muñoz et al. 2010). Furthermore, the kinematics of these galaxies imply they are dominated by dark matter (e.g., Kleyna et al. 2005; Muñoz et al. 2006; Simon & Geha 2007), and the abundances indicate they are very metal-poor (e.g., Frebel et al. 2010; Norris et al. 2010; Kirby et al. 2011). Current simulations of galaxy formation assume that most luminous dwarf galaxies formed their stars over an extended period, but that most dark matter halos had star formation truncated by reionization, or never formed stars at all (e.g., Tumlinson 2010; Muñoz et al. 2009; Bovill & Ricotti 2009, 2011a,b; Koposov et al. 2009).

Against this backdrop, we proposed a large *Hubble Space Telescope (HST)* imaging program to better characterize the star formation history (SFH) in a representative sample of six UFD galaxies. Our sample spans a range of galaxy luminosities, but avoids the brightest UFDs (which may represent a transition to classical dwarf spheroidals) and the faintest UFDs (which do not provide enough stars for a robust SFH determination). The primary goal of the program is to measure relative ages in these galaxies to better than 1 Gyr uncertainty. Such tight age constraints are difficult when fitting optical CMDs for both age and metallicity, but our program leverages the independent measurement of the metallicity distribution function in each galaxy, as determined from Keck/DEIMOS spectroscopy. Relative ages among the UFD sample can determine to what extent their SFHs have been synchronized via reionization, and also tie their ages to those of other ancient populations (e.g., Galactic globular clusters). Because the *HST* photometry extends well below the main-sequence turnoff (MSTO), these data also provide insight into the initial mass function (IMF) in these old, dynamically-unevolved populations. We interpret our CMDs using both empirical population templates observed in the same bands, and also a high-fidelity isochrone library employing the latest physics and extended to low metallicity ([Fe/H] =−4). Here, we present a preliminary analysis of the *HST* data from each galaxy in the program.

2. Observations

Our survey observed six UFD galaxies using two cameras on *HST*: the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3). We used the F606W (broad *V*) and F814W (*I*) filters on each camera, with ACS surveying an area centered on each galaxy ($202'' \times 202''$ per tile), and WFC3 observing in parallel in the galaxy outskirts ($162'' \times 162''$ per tile). For the nearby (<100 kpc) satellites in the sample (Bootes I, Coma Berenices, Ursa Major I), we surveyed a relatively wide area (5–12 tiles in each camera) to a shallow depth (2 or 3 orbits, faint limit of $V \sim 28$ mag). For the distant (>130 kpc) satellites in the sample (Hercules, Leo IV, and Canes Venatici II), we surveyed a narrow pencil beam (1 or 2 tiles in each camera) more deeply (10–16 orbits, faint limit of $V \sim 29$ mag). The varying depth and area of each survey was intended to provide a sample of a few hundred stars in the vicinity of the MSTO with a photometric precision of ~0.01 mag, thus providing tight constraints on age when coupled with independent knowledge of the metallicity distribution from Keck.

The ACS images were processed through the standard pipeline, including a pixel-based correction for charge transfer inefficiency (CTI; Anderson & Bedin 2010). The images

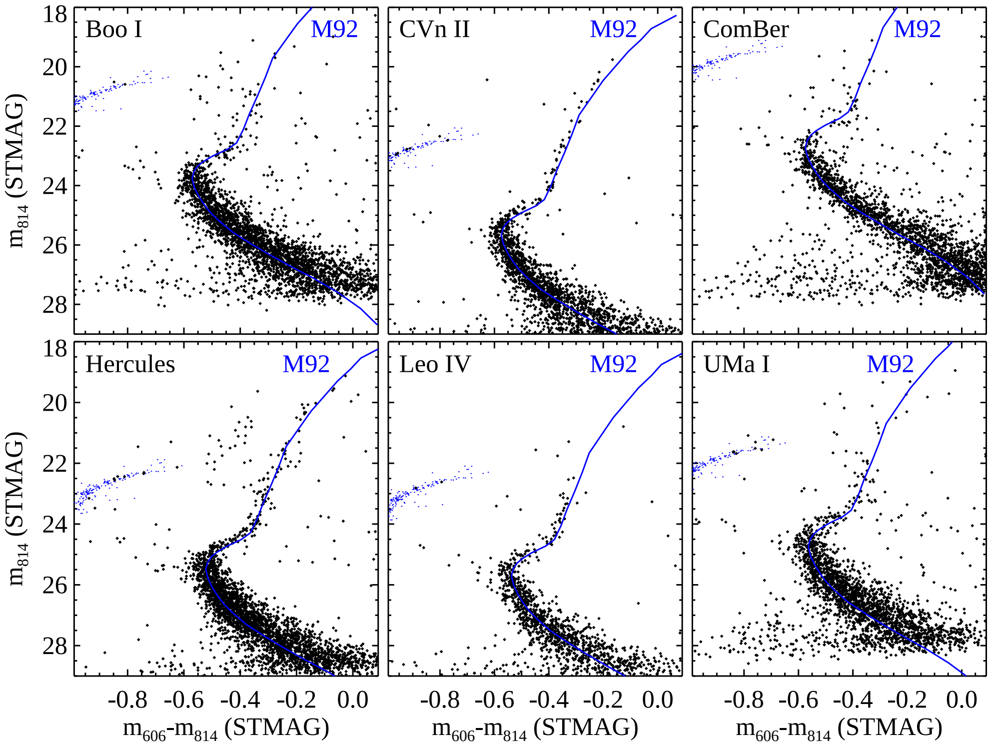

Fig. 1. The CMD of each UFD in our *HST* survey (*black points*). For comparison, we show the ridge line (*blue curve*) and HB locus (*blue points*) from the CMD of M92 (Brown et al. 2005), an ancient (12.75 Gyr; VandenBerg et al. 2013) metal-poor (−2.3; Harris 1996) globular cluster observed in the same bands on the same *HST* camera but shifted in color and magnitude to account for differences in reddening and distance. The UFDs are clearly dominated by ancient metal-poor stars. The area and depth of observations for each galaxy were varied to provide a few hundred stars in the vicinity of the MSTO, and are largely responsible for the varying amount of field contamination present in each CMD. Despite this field contamination, a prominent BSS can be discerned in each galaxy CMD.

were then coadded using the DRIZZLE package (Fruchter & Hook 2002), including correction for geometric distortion, resampling of the point spread function (PSF), and masks for cosmic rays and detector artifacts. We performed PSF-fitting photometry using the DAOPHOT-II package (Stetson 1987), producing a catalog for each galaxy in the STMAG system: $m = -2.5\times \log_{10} f_\lambda - 21.1$. Taking a star at an old (13 Gyr) metal-poor ([Fe/H]=−2.5) MSTO for reference, the offsets between the STMAG system and the familiar Johnson system (tied to Vega) are $I = m_{814} - 1.31$ mag and $V = m_{606} - 0.14$ mag. The catalogs were cleaned of background galaxies and stars with poor photometry. We performed artificial star tests to evaluate photometric scatter and completeness, including CTI effects, with the same photometric routines used to create the photometric catalogs. The CMD for each UFD in our survey is shown in Figure 1.

3. Analysis

Although the populations of the UFDs span more than 2 dex in metallicity (e.g., Kirby et al. 2011), the bulk of the stars fall at metallicities of $-2 > \text{[Fe/H]} > -4$. The population of the ancient (12.75 Gyr; VandenBerg et al. 2013), metal-poor (−2.3; Harris 1996) globular cluster M92 is thus an important point of comparison. In Figure 1, we show compared to each UFD CMD the ridge line and horizontal branch (HB) from the CMD of M92, observed in the same ACS bands (Brown et al. 2005). It is clear that the CMD of each UFD looks like the CMD of an ancient globular cluster, and that each is dominated by an old (age >12 Gyr) population of metal-poor ([Fe/H] < −2) stars. A prominent blue straggler sequence (BSS) is present in each galaxy – ubiquitous in old populations.

The luminosity difference between the MSTO and the HB is a well-known age indicator – the MSTO luminosity decreases with age, while the the HB luminosity is relatively constant with age. For populations with similar chemical compositions (as is the case here), the color difference between the MSTO and the base of the red giant branch (RGB) is also an age indicator (VandenBerg et al. 1990), because the MSTO becomes redder at increasing age while the RGB is relatively insensitive to age. To empirically demonstrate the extent of synchronization in the SFHs of the UFDs, we show in Figure 2 the composite CMD from our entire sample, with each UFD shifted to the frame (distance and reddening) of Hercules. The fact that each UFD CMD is similar to that of Hercules indicates that their SFHs are largely synchronized, with mean ages agreeing to ∼1 Gyr; better constraints on the degree of synchronization will come from refinements to the quantitative SFH fitting, which we are pursuing.

Using synthetic CMD analysis, Brown et al. (2012) found that the mean age of Hercules was only 0.1 Gyr younger than that of M92. The absolute age of M92 itself is driven by uncertainties in both distance and [O/Fe]; indeed, the 12.75 Gyr age of VandenBerg et al. (2013) is nearly 1 Gyr younger than previous estimates, due primarily to the adoption a higher [O/Fe] and a larger distance modulus. Our synthetic CMD analyses of each UFD CMD are underway, and indicate that the bulk of the population is older than 12 Gyr in each galaxy. However, we are still exploring how best to handle the membership probabilities for

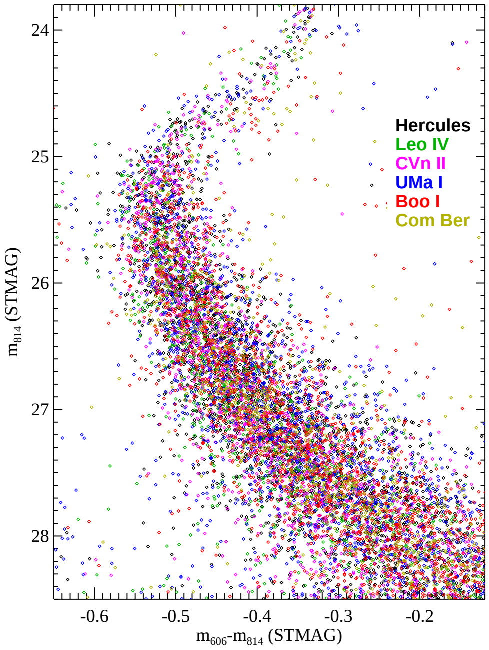

Fig. 2. The composite CMD of all six UFD galaxies in our survey (*points*), with the CMDs of 5 galaxies (*colored points*) shifted to the frame of Hercules (*black points*). The CMDs are nearly indistinguishable from each other, with similar luminosity differences between the MSTO and HB, and similar color differences between the MSTO and RGB base. These similarities imply that their star formation histories are synchronized to ∼1 Gyr.

the spectroscopic sample. Specifically, minority populations of relatively metal-rich stars (−1 > [Fe/H] > −2) in the metallicity distribution function may represent field contamination or a small continuation of star formation beyond the dominant burst. We are also investigating the IMF of each galaxy; our analysis of the first two galaxies observed in our survey (Hercules and Leo IV) found that their IMFs are flatter than those in the Galactic field and luminous dwarf satellites (Geha et al. 2013).

4. Summary

The *HST* photometry of these six UFD galaxies demonstrates that they are dominated by truly ancient stars (>12 Gyr old), and that their

SFHs are largely synchronized (with our initial estimates indicating agreement at the level of ∼1 Gyr). The uniformly ancient populations of the UFDs stand in contrast to other dwarf galaxies in the local universe, most of which formed the bulk of their stars prior to $z \sim 1$ (Weisz et al. 2011). The synchronization of SFH in the UFDs suggests that a global phenomenon is at work, such as reionization, instead of other stochastic mechanisms for truncating the SFH, such as gas depletion or supernova feedback. The distinction between these interpretations will be clarified as we refine the SFH fits. We are improving several aspects of our analysis, including the assumed variation in [O/Fe] as a function of [Fe/H], and the selection criteria used to construct the metallicity distribution function for each galaxy. These improvements will determine to what extent any residual star formation may have continued beyond the dominant burst in each galaxy. Given what we know now, the UFDs are the best examples of fossil galaxies, and lend credence to the hypothesis that many of the "missing satellites" remain undiscovered because they have formed little to no stars.

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