

“GALAXY,” DEFINED

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ABSTRACT

A growing number of low luminosity and low surface brightness astronomical objects challenge traditional notions of both galaxies and star clusters. To address this challenge, we propose a definition of galaxy that does not depend on a cold dark matter model of the universe: A galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton’s laws of gravity. After exploring several possible observational diagnostics of this definition, we critically examine the classification of ultra-faint dwarfs, globular clusters, ultra-compact dwarfs, and tidal dwarfs. While kinematic studies provide an effective diagnostic of the definition in many regimes, they can be less useful for compact or very faint systems. To explore the utility of using the [Fe/H] spread as a complementary diagnostic, we use published spectroscopic [Fe/H] measurements of 16 Milky Way dwarfs and 24 globular clusters to uniformly calculate their [Fe/H] spreads and associated uncertainties. Our principal results are: (i) no known, old star cluster less luminous than $M_V = -10$ has a significant ($\gtrsim 0.1$ dex) spread in its iron abundance; (ii) known ultra-faint dwarf galaxies can be unambiguously classified with a combination of kinematic and [Fe/H] observations; (iii) the observed [Fe/H] spreads in massive ($\gtrsim 10^6 M_\odot$) globular clusters do not necessarily imply that they are the stripped nuclei of dwarfs, nor a need for dark matter; and (iv) if ultra-compact dwarf galaxies reside in dark matter halos akin to those of ultra-faint dwarfs of the same half-light radii, then they will show no clear dynamical signature of dark matter. We suggest several measurements that may assist the future classification of massive globular clusters, ultra-compact dwarfs, and ultra-faint galaxies. Our galaxy definition is designed to be independent of the details of current observations and models, while our proposed diagnostics can be refined or replaced as our understanding of the universe evolves.

Subject headings: galaxies: star clusters — galaxies: dwarf — galaxies: kinematics and dynamics

1. INTRODUCTION

It has been nearly a century since the term “galaxy” (de Sitter 1917; Crommelin 1918; Shapley 1919) was first applied to the spiral nebulae that were later found to be true extra-galactic stellar systems (Slipher 1917; Hubble 1926, see also Graham 2011 and references therein). The term “cluster” has been used to refer to Milky Way (MW) open and globular cluster star systems since their initial discoveries more than 200 years ago (Messier 1781). In the early 20th century, the primary differences between objects classified as galaxies and star clusters were (i) the milky[‡] appearances of galaxies versus the grainy appearances of star clusters, and (ii) the “island universe” environments of galaxies versus the association of star clusters with the MW system. In the intervening years, galaxies and star clusters have largely been classified based on their physical sizes: galaxies have typical sizes of hundreds of pc to tens of kpc whereas star clusters have typical sizes of a few pc, with a scatter to tens of pc.

The lion’s share of known star clusters and galaxies can be classified by this simple “I know it when I see it” size-based distinction. However, there are a growing number of astronomical objects that are not so easily

classified—those at extreme low luminosities and surface brightnesses, and those filling gaps previously observed in size–luminosity space (Misgeld & Hilker 2011). These objects currently hold the most promise to shed new light on galaxy formation at the bottom of the hierarchy and the distribution of dark matter to the smallest possible size and mass scales. For example, ultra-compact dwarfs (UCDs) have luminosities ($-13 < M_V < -9$) similar to those of both dwarf spheroidal galaxies and luminous globular clusters (GCs), but sizes ($10 \text{ pc} < r_{\text{half}} < 100 \text{ pc}$) intermediate to both populations and dynamical mass-to-light ratios of $\sim 2 - 5^\S$, larger than those typical of GCs (e.g., Hilker et al. 1999; Drinkwater et al. 2003; Hasegan et al. 2005; Evstigneeva et al. 2007; Mieske et al. 2008; Chilingarian et al. 2011; Brodie et al. 2011). Some ultra-faint MW satellites (e.g., Segue 1, Segue 2, Boötes II, Willman 1) have also challenged our notion of galaxies. These objects have luminosities ($-3 < M_V < -1$) lower than those of nearly any known old star cluster or dwarf galaxy, physical sizes ($20 \text{ pc} < r_{\text{half}} < 40 \text{ pc}$) between those of most star clusters and dwarf galaxies, and dynamical mass-to-light ratios as high as 3000 (Simon et al. 2011). While tidal dwarfs[¶] may provide a piece to this puzzle, they have proved difficult to study and classify themselves (see Duc 2012 for a review).

[§] All mass-to-light ratios are in V unless otherwise stated.

[¶] We use “tidal dwarf” rather than “tidal dwarf galaxy” throughout this paper, to avoid presupposing a galaxy definition for this class of objects.

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[‡] The word “galaxy” derives directly from the Greek word for “milky”.

The origin and properties of systems such as UCDs, extreme MW dwarf satellites, and tidal dwarfs are fundamental to many open questions in galaxy formation and cosmology. They might hold unique clues to relationships between different classes of hot stellar systems (e.g., giant elliptical galaxies, dwarf elliptical galaxies, dwarf spheroidal galaxies, UCDs, nuclear star clusters, GCs; Dabringhausen et al. 2008; Wolf et al. 2010; Misgeld & Hilker 2011; Zaritsky et al. 2011). They might be our best luminous tracers of sub-galactic dark matter. Having a well-defined classification scheme will be essential to these studies, since imminent and upcoming wide-field surveys, including Pan-STARRS 1 (Kaiser et al. 2002), the Southern Sky Survey (Keller et al. 2007), the Dark Energy Survey (The Dark Energy Survey Collaboration 2005) and LSST (Ivezic et al. 2008), are expected to reveal large numbers of previously unseen low surface-brightness systems.

As the rate of discoveries and the diversity of the known cosmic zoo increases, the question “What is a galaxy?” is being discussed at conferences and in the literature (e.g., Gilmore et al. 2007; Kroupa 2008; van den Bergh 2008; Forbes & Kroupa 2011). The most common distinction currently made between galaxies and star clusters is the presence of dark matter—galaxies reside at the centers of dark matter halos and star clusters do not (e.g., Simon et al. 2011; Tollerud et al. 2011; Willman et al. 2011). One strength of this definition is that it facilitates studies of dwarf galaxies in a cosmological context: it allows a straightforward connection between the set of objects classified as galaxies and a comparison with the predictions of dark matter plus galaxy formation models. One weakness of this physically motivated definition is the fact that the cold dark matter model is a theory rather than a physical law.

Other recently proposed definitions for a galaxy have included $r_{\text{half}} > 100$ pc, a relaxation time longer than a Hubble time, or complex stellar populations (Forbes & Kroupa 2011). Although each of these definitions have their own strengths (namely that they are straightforward to diagnose), they each also have shortcomings**. For example, size-based classifications are becoming increasingly arbitrary as size–luminosity space is becoming continuously populated with objects (Misgeld & Hilker 2011). The concept of “complex” stellar populations has also become ill-defined now that light element abundance spreads have been identified in a large fraction of MW GCs (e.g., Gratton et al. 2004; Cohen & Meléndez 2005; D’Antona et al. 2005; Carretta et al. 2009b), which were once thought to be pristine examples of simple stellar populations.

In this paper, we tweak past definitions of the term “galaxy” with the aim of appealing to a sufficiently broad cross-section of astronomers that consensus might be reached. In §2, we motivate the importance of having a clear definition of galaxy within the astronomical community, and then present a physically motivated definition. In §3, we consider kinematics and complementary indirect diagnostics such as [Fe/H] spread and population-based diagnostics that might be used to test

whether an object is a galaxy. In §4 we examine the known properties of ultra-faint dwarfs, UCDs, GCs, and tidal dwarfs in the context of our proposed definition.

2. GALAXY DEFINITION

The classification of astronomical objects is more than a semantic pursuit. Words matter. The terminology we choose to describe our research affects how appealing and accessible it sounds to funding agencies and the public. Words also dramatically affect the research community’s ability to draw global conclusions from diverse sets of astronomical objects. For example, massive star cluster ω Cen may be the remnant of a stripped, nucleated dwarf galaxy (Lee et al. 1999; Bekki & Freeman 2003). However, it is cataloged as a GC and thus is not considered in studies of the MW’s dwarf galaxy population. Well-defined, well-chosen classification schemes therefore improve our understanding of the universe by facilitating meaningful comparisons between models and observations. Conversely, ill-defined, ill-chosen classification schemes can muddy our understanding of astrophysical phenomena.

Although no single definition of galaxy will be optimal for all purposes, we propose a physically motivated definition that will facilitate studies of galaxies both in and out of a cosmological context:

A galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton’s laws of gravity.

In a dark matter context (whether cold, warm, self-interacting, or other), this definition loosely translates to measuring whether an object contains dark matter. Alternatively, the definition can be interpreted to delineate those objects for which non-standard theories of gravity could be relevant (e.g., Milgrom 1983; Sotiriou & Faraoni 2010). For such theories, our definition would require distinct observable consequences of non-standard gravity to be imprinted on an astrophysical system for it to be classified as a galaxy. In the interest of simplicity, we focus Sections 3 and 4 of this paper on diagnosing our proposed galaxy definition in a dark matter-based context. However, we encourage others to more explicitly explore these diagnostics in alternative contexts.

We refer to Newton’s laws on a macroscopic scale; this part of the definition should be considered to include objects that require general relativity to be understood. We recognize that galaxies can have a significant amount of baryonic mass in non-stellar forms such as gas and dust. It is uncertain whether the local universe harbors any “dark galaxies” that contain gas but are entirely free of stars (Minchin et al. 2005; Duc & Bournaud 2008). Whether these objects should be classified as galaxies is an open question that we do not confront here but that deserves further debate.

A purely descriptive astronomical classification (such as relaxation time) may be relatively straightforward for either observers or theorists to implement. A weakness of the definition proposed here thus lies in finding adequate diagnostics to measure whether the properties of the lowest luminosity and most compact objects are explicable with baryons and Newton’s Laws (see §3 for a discussion of possible diagnostics).

** See also the related, informal discussion linked at the URL <http://arxiv.org/abs/1101.3309>.

Because galaxy formation itself is hierarchical in a cold dark matter universe, there is no trivial distinction between a single galaxy with satellite galaxies (such as the MW) and a galaxy group or cluster. As a diagnostic, Busha et al. (2012) propose that a bound collection of galaxies is a “galaxy” rather than a galaxy cluster if at least 50% of the stellar light is associated with one central object. This diagnostic is ultimately driven by the decreasing efficiency of galaxy formation in more massive dark matter halos.

The Busha et al. (2012) diagnostic helps guide intuition when exercising reasonable common sense in applying our definition to astrophysical systems. For example, the intracluster star population of a galaxy cluster is composed of a gravitationally bound collection of stars whose dynamics cannot be explained by orbits within a Newtonian potential well dominated by cluster baryons. Such a system should not be classified as a galaxy because it is physically associated with a galaxy cluster. Similarly, the Milky Way’s stellar halo is a merely a component of the Milky Way—not its own galaxy.

3. GALAXY DIAGNOSTICS

In this and in the following section, we focus on objects for which a galaxy classification (or lack thereof) tends to be ambiguous.

3.1. *Stellar kinematics*

The most direct way to determine whether an object contains dark matter, or whether its properties are otherwise inconsistent with Newtonian gravity, is to conduct a kinematic study. The present day mass of a system is typically derived from its kinematics using formalism based on Newton’s laws of gravity and the assumption of dynamical equilibrium. This dynamical mass can then be compared with the total mass present in the form of stars, stellar remnants, and gas. If dynamical mass exceeds the baryonic mass, then dark matter must be present or one of the dynamical assumptions—such as Newtonian gravity or virial equilibrium—must be flawed.

There are many regimes in which dynamical studies can be translated with few assumptions into Newtonian masses (e.g., Walker et al. 2009a; Wolf et al. 2010). Wolf et al. (2010) showed that the half-light mass of a dispersion supported system could be robustly calculated with only mild assumptions about the orbital anisotropy of its constituent stars. They derive $M_{half} = 4G^{-1} \langle \sigma_{los}^2 \rangle r_{half}$. Here M_{half} is the total mass within the 3D deprojected half-light radius, $\langle \sigma_{los}^2 \rangle$ is the luminosity weighted square of the line of sight velocity dispersion, and r_{half} is the 2D projected half-light radius. Such calculations have yielded $(M/L)_{half}$ as high as ~ 3000 for a MW satellite galaxy (Segue 1, Simon et al. 2011).

It is not always possible to diagnose a galaxy definition based on dynamical $(M/L)_{half}$ alone. Many authors have looked at the relationship between M/L and other system properties (such as luminosity, see e.g. Figures 3 and 5 in Tollerud et al. 2011 and Figure 4 in Wolf et al. 2010.) While typical star clusters stand out as having low $(M/L)_{half}$ (~ 1 -5) for their luminosities ($L \sim 10^{4-6} L_{\odot}$), dispersion supported galaxies ($L \sim 10^{8-10} L_{\odot}$) have similar $(M/L)_{half}$ as star clusters. In such cases, a com-

bination of $(M/L)_{half}$ and other population arguments may be used to diagnose a galaxy classification (see also §3.3). Alternatively, dynamical modeling including tracers at larger distances can reveal M/L outside of r_{half} .

If the existence of dark matter is the correct interpretation of galaxy dynamics, then dynamical classification of galaxies may be robust to the effect of tidal mass loss. Simulations show that galaxies tidally stripped of mass should maintain a high dynamical mass-to-light ratio. For example, Peñarrubia et al. (2008) showed that the mass-to-light ratios of tidally evolving dwarf galaxies increase over time, assuming they reside in cuspy dark matter halos. Even if the dark matter halos hosting dwarf galaxies are cored, their central dark matter density slopes remain constant during tidal evolution (Peñarrubia et al. 2010).

3.1.1. *Special Considerations*

Generally, dynamical $M/L \gtrsim 5$ may be taken to diagnose a galaxy classification, because such M/L are larger than expected from typical stellar populations. However, a number of challenges face attempts to determine whether an observed dynamical M/L of a system is consistent with expectations from baryons alone - especially for systems with $M/L \lesssim 10$, low intrinsic velocity dispersions, or low surface brightness. Some of these challenges are fairly obvious, as the dynamical M/L expected for a purely baryonic population varies significantly with: age, metallicity, initial mass function, dynamical state, and gas content. In this section, we highlight several specific examples which are less commonly discussed in the literature. See also §4.2.1 for a more nuanced discussion of dynamical M/L in the context of UCDs.

Several effects can cause an overestimate in dynamical mass, and thus an overestimate of M/L . For example, the orbital motions of binary stars can inflate a system’s observed velocity dispersion. A recent, multi-epoch velocity study of Segue 1 suggests that binaries should not pose a major problem for the dynamical classification of systems with intrinsic velocity dispersions of at least a few km s^{-1} (Martinez et al. 2011; Simon et al. 2011). However, binaries do materially impact lower velocity dispersion systems (Bradford et al. 2011), and models based on more extreme assumptions than previously considered identify regions of parameter space where binaries could impact Segue 1-like velocity dispersion systems (McConnachie & Côté 2010). Tidally unbound and MW foreground stars can also contaminate spectroscopic samples of a MW companion’s stars and inflate its observed velocity dispersion. The effect of such contaminants can be mitigated by a combination of careful simulations of the MW foreground and its color-magnitude-velocity distribution (Willman et al. 2011), the use of spectroscopic abundance indicators, statistical approaches to identifying object members (e.g., Walker et al. 2009b), and approaches to eliminating tidally stripped stars that have been informed by N-body simulations (Klimontowski et al. 2007).

Other effects may alternatively cause an underestimate of stellar mass, and thus an overestimate of the presence of non-stellar mass. For example, Hernandez (2012) shows that the lowest luminosity systems ($L \sim 500 L_{\odot}$) can have $(M/L)_{stellar}$ between 1 and 10 simply from the stochastic effects of sampling an IMF with

a small number of stars. A tidally stripped, dynamically relaxed (and therefore mass-segregated) GC can also have a super-stellar M/L once the majority of its mass has been lost. Models of star cluster evolution that include the effects of mass segregation and the Galaxy's tidal field have shown that high fractions of stellar remnants accumulate in the center as a cluster is stripped of mass (Vesperini & Heggie 1997; Giersz 2001; Baumgardt & Makino 2003). Although possible, it should be rare to observe a system so tidally stripped that its global M/L is significantly inflated by this mechanism. For example, although Palomar 5 is estimated to be ~ 100 Myr from complete destruction (less than 1% of its total lifetime), it is observed to have $M/L_{dyn} < 1$ (Odenkirchen et al. 2002; Dehnen et al. 2004). Observational limitations may also generate ambiguity in the dynamical classification of the lowest luminosity ($L < 1000 L_{\odot}$) and low velocity dispersion ($< 3 \text{ km s}^{-1}$) systems. For example, Segue 3 ($L = 90^{+90}_{-40} L_{\odot}$, $d \sim 17$ kpc) contains only a few dozen member stars brighter than $r = 22$. 32 of Segue 3's stars were observed with Keck/DEIMOS to obtain velocity measurements with uncertainties per exposure per star of $\sim 3\text{--}10 \text{ km s}^{-1}$ (Fadely et al. 2011). With a σ_{los} of 0.3 km s^{-1} expected based on stars and Newtonian gravity alone, its measured velocity dispersion of $1.2 \pm 2.6 \text{ km s}^{-1}$ is dynamically consistent with either a galaxy or a star cluster interpretation. Even with techniques which retrieve stellar velocities from medium-resolution spectra with uncertainties $< 1 \text{ km s}^{-1}$ (Koposov et al. 2011), star-poor systems need to reside within ~ 20 kpc for there to be a sufficient number of stars bright enough to spectroscopically observe with high S/N with a 10m-class telescope.

3.2. $[Fe/H]$ Spread

Another way to directly constrain the potential well in which a system formed is the presence of an $[Fe/H]$ spread. The use of $[Fe/H]$ as a diagnostic for our proposed galaxy definition is supported by a combination of models of supernova winds in low-mass systems and the observed abundances of stars in well-studied dwarfs and GCs. Iron is produced by supernovae (both Type II and Ia), so a dispersion in $[Fe/H]$ implies that the system was able to retain supernova ejecta to form multiple generations of stars. The energetic winds of supernovae can only be retained in a gravitational well of sufficient depth. Estimates for the GC mass needed to retain SN ejecta are $> \text{few} \times 10^6 M_{\odot}$ (e.g., Dopita & Smith 1986; Baumgardt et al. 2008). Observed $[Fe/H]$ spreads of over 1 dex combined with inferred stellar masses of $\sim 1000 M_{\odot}$ or less have thus contributed to a galaxy classification for both Segue 1 and Willman 1 (Martin et al. 2007; Norris et al. 2010; Simon et al. 2011; Willman et al. 2011).

3.2.1. Calculating $\sigma_{[Fe/H]}$

To empirically investigate the difference in $[Fe/H]$ spread, $\sigma_{[Fe/H]}$, between well-studied dwarf galaxies and GCs, we estimate the spread and associated uncertainty for each of 16 dwarfs and 24 GCs with publicly available, spectroscopic $[Fe/H]$ measurements. We only used $[Fe/H]$ measurements based on actual iron lines, rather

than studies that infer iron abundance from the calcium triplet or photometry. We used Bayesian Markov Chain Monte Carlo techniques to fit a normal distribution to the stellar $[Fe/H]$ values for each object, taking into account the reported measurement uncertainties and assuming flat priors.^{††} We summarize the standard deviation of each sample, $\sigma_{[Fe/H]}$, as the median of its posterior distribution, together with a 68.2% credible interval (analogous to the usual 1σ confidence interval). Calculated values of $[Fe/H]$, $\sigma_{[Fe/H]}$, associated uncertainties, and references are summarized in Table 1. The uncertainties on the variances are an increasing function of decreasing sample size, because small samples poorly sample the underlying $[Fe/H]$ distribution.

A few notes on unusual cases: For Segue 1, we included the star from Simon et al. (2011) with only an upper limit to its $[Fe/H]$ as a censored datum in our analysis. We used the largest set of $[Fe/H]$ values for ω Centauri (Johnson & Pilachowski 2010). However, this sample is biased against the most metal-rich subpopulation because it is magnitude-limited in V . We thus consider our estimate of its $[Fe/H]$ spread to be a lower limit. The Marino et al. (2011) data for M22 does not contain uncertainties, and so our reported $\sigma_{[Fe/H]}$ is an upper limit. Our analysis does not include the Terzan 5 GC despite claims of an $[Fe/H]$ spread in this object (Ferraro et al. 2009; Origlia et al. 2011), owing to its \sim solar abundance (and thus different origin than the old metal-poor stellar populations we are primarily considering) and the possibility that the sample may be partially contaminated by bulge stars. We also did not include NGC 5824, in which Saviane et al. (2012) have reported $\sigma_{[Fe/H]} \sim 0.11 - 0.14$ dex, because this measurement is based on the Calcium triplet (thus revealing a Ca spread, not necessarily an Fe spread). The GC NGC 2419 is known to display a ~ 0.2 dex spread in Ca, but none in Fe (Cohen et al. 2010).

Although reasonable indicators of the dispersion in $[Fe/H]$, the values in Table 1 should be considered with caution before comparing in detail with models. The accuracy of our estimates of the variance of $[Fe/H]$ (and its uncertainty) rely on (i) the appropriateness of the underlying Gaussian model, (ii) clean membership samples, and (iii) accurate uncertainties for individual stars. For the fainter dwarfs in this set the first condition rarely holds (e.g., Kirby et al. 2011), so our estimated variances should be taken as indicators of the spread in metallicity rather than as exact values. The faintest dwarfs may also have a small number of interloper stars in their membership samples (see also §3.2.4). The third condition—estimating accurate uncertainties—is most relevant for GCs, because their measured $\sigma_{[Fe/H]}$ are comparable to (or less than) the measurement uncertainties for single stars. For this paper, we have included the random uncertainty in the Fe I abundance as the standard error of the mean, while Carretta et al. (2009a) included no measurement uncertainties in their calculation of $[Fe/H]$ spread. The practical effect is that the intrinsic $[Fe/H]$ spreads we derive for GCs in this paper are slightly smaller than those in Carretta et al. (2009a), by typically 0.01 dex. Like Carretta et al. (2009a), we em-

^{††} The relevant (simple) code is available on request.

phasize that their and our values are upper limits to be true $[\text{Fe}/\text{H}]$ spreads because of our limited ability to model the full measurement uncertainties on each star (see Carretta et al. 2009a for detailed discussion of the relevant modeling issues).

3.2.2. $\sigma_{[\text{Fe}/\text{H}]}$ in $M_V \gtrsim -10$ Objects

Figure 1 shows $\sigma_{[\text{Fe}/\text{H}]}$ for MW dwarf galaxies (filled, black circles) and MW GCs (open red circles) as a function of absolute magnitude. Uncertainty bars show the 68.2% confidence intervals. We show objects with dynamical classifications of galaxy or star cluster as different symbols in Figure 1 to highlight the regime in which $\sigma_{[\text{Fe}/\text{H}]}$ results in the same inference about a system’s potential well as a dynamical study. This tests whether $\sigma_{[\text{Fe}/\text{H}]}$ may be used as a galaxy diagnostic in cases where dynamical studies are inconclusive.

This figure shows a striking difference between the $[\text{Fe}/\text{H}]$ spreads observed for dwarf galaxies and GCs. The dwarfs all have spreads of 0.3–0.7 dex (even higher for Segue 1), whereas none of the GCs less luminous than $M_V = -10$ have substantial $[\text{Fe}/\text{H}]$ dispersions. After the upper limit of $\sigma_{[\text{Fe}/\text{H}]} = 0.1$ dex estimated for M22, the next highest spread is 0.08 dex estimated for NGC 6441. Although these values are small, they are formally greater than zero with $> 99\%$ probability (as calculated above). These estimates may reflect the detection of minor star-to-star variations in $[\text{Fe}/\text{H}]$ in GCs less luminous than $M_V = -10$. However, in light of the caveats given above, they may yet be found to be consistent with no star-to-star variation in $[\text{Fe}/\text{H}]$.

For objects less luminous than $M_V = -10$, the dichotomy between $\sigma_{[\text{Fe}/\text{H}]}$ of dwarf galaxies and GCs underscores that the dwarf galaxies formed within much deeper potential wells than the GCs. We conclude that a $\sigma_{[\text{Fe}/\text{H}]} > 0.2$ dex in such systems would be sufficient to diagnose a galaxy classification because it would not be explicable with a combination of baryons and Newtonian gravity (without invoking substantial mass loss). While iron is not the only element that may provide relevant insight to the gravitational potential wells of objects in this luminosity regime, it is clear that iron spread provides a powerful diagnostic of the provenance of such objects.

3.2.3. $\sigma_{[\text{Fe}/\text{H}]}$ in $M_V \lesssim -10$ Objects

The interpretation of the $\sigma_{[\text{Fe}/\text{H}]}$ spreads observed in the two GCs more luminous than $M_V = -10$, M54 and ωCen , is less straightforward. One interpretation of the spreads in M54 and ωCen is that they are the nuclear star cluster cores remaining from a stripped dwarf galaxy (M54: Sgr core, Sarajedini & Layden 1995; ωCen , Lee et al. 1999; Bekki & Freeman 2003). It remains to be seen whether the properties of the gravitationally bound remains of such a stripped galaxy would satisfy our definition of a galaxy, and be formally classified as such. Recent observations have discovered a significant amount of tidal debris that may be associated with ωCen (Majewski et al. 2012). Sgr is already a classified galaxy, so M54 would not be considered a separate entity.

An alternative interpretation of the $[\text{Fe}/\text{H}]$ spreads in these $M_{\text{star}} > 10^6 M_\odot$ clusters is self-enrichment by SNe without the additional gravitational influence of dark matter or a non-Newtonian effect. This interpretation is complicated by the fact that M54 and ωCen

do not actually have the highest escape velocities of the GCs in our sample. Using the fitted relation between central velocity dispersion and central escape velocity, $v_{\text{esc},0}/\sigma_0 = 3.7 + 0.9(c - 1.4)$, from Gnedin et al. (2002), we find that 8 of the 62 GCs with velocity dispersions reported in the 2010 edition of Harris (1996) have central escape velocities larger than M54’s $v_{\text{esc},0} \sim 45 \text{ km s}^{-1}$ (not including ωCen). 5 of these (47 Tuc, NGC 2808, NGC 6388, NGC 6441, and M15) are in our sample and do not display $[\text{Fe}/\text{H}]$ spreads $\gtrsim 0.1$ dex. NGC 6441 and 6388 have escape velocities of 72 and 76 km s^{-1} , respectively, larger than ωCen ’s escape velocity of 61 km s^{-1} . A caveat to this analysis is that these values are measured at the present day. At earlier times, these GCs were all more massive but have since undergone stellar evaporation and tidal mass loss; some may have also had different sizes. All of these factors could have affected their relative abilities to retain supernova ejecta.

Observations of GCs in other galaxies provide tentative support for self-enrichment in iron in $M_V < -10$ GCs. For example, HST/ACS photometry of three of the most massive GCs in M31 are suggestive of spreads in $[\text{Fe}/\text{H}]$ on the red giant branch (Fuentes-Carrera et al. 2008). The dynamical masses of these GCs range from $2 - 6 \times 10^6 M_\odot$, comparable to or larger than ωCen (Strader et al. 2011). The M31 cluster G1 ($3 \times 10^6 M_\odot$) also may have a significant $[\text{Fe}/\text{H}]$ spread (Meylan et al. 2001).

Separately, a number of groups have identified evidence of self-enrichment in extragalactic GCs. Precise photometry of blue, metal-poor GCs in a variety of galaxies (Harris et al. 2006; Mieske et al. 2006; Strader et al. 2006; Spitler et al. 2006; Forbes et al. 2010; Mieske et al. 2010) shows a correlation between magnitude and color for metal-poor GCs. This mass–metallicity relationship is not observed in all galaxies studied, but a typical relation is $Z \sim M^{0.4}$, where Z is the mean metallicity of the GC and M is its mass. The onset of the correlation appears to be between $\sim 2 \times 10^5$ and $10^6 M_\odot$. The slope and onset mass of the correlation can be reasonably explained by models in which the GCs self-enrich in iron (Bailin & Harris 2009; Strader & Smith 2008).

If (nearly) all GCs with stellar masses above few $\times 10^6 M_\odot$ display $[\text{Fe}/\text{H}]$ spreads, then it is likely these spreads accrue from self-enrichment without the help of an additional gravitational field. More extensive spectroscopic and photometric campaigns to quantify the $[\text{Fe}/\text{H}]$ spreads of extragalactic GCs will be essential to develop a fuller picture of the connection between $\sigma_{[\text{Fe}/\text{H}]}$ and the formation channel(s) of objects with $M_V < -10$.

3.2.4. A Relationship Between $\sigma_{[\text{Fe}/\text{H}]}$ and M_V For Dwarfs?

Figure 1 displays another striking trend in addition to the dwarf/GC dichotomy: the apparent increase in $\sigma_{[\text{Fe}/\text{H}]}$ with decreasing luminosity (see also §6.2 of Kirby et al. 2011). While the dispersion in $[\text{Fe}/\text{H}]$ for most MW dwarf galaxies with $M_V < -8$ (the classical dwarfs) is 0.3–0.4 dex, the dispersion for most of the lower luminosity dwarfs (the ultra-faint dwarfs) is 0.5–0.6 dex. The most likely explanations for this apparent trend are: (i) a true physical difference in the $\sigma_{[\text{Fe}/\text{H}]}$ of the least luminous systems, (ii) a systematic bias in the calculated $\sigma_{[\text{Fe}/\text{H}]}$ as the model assumptions become

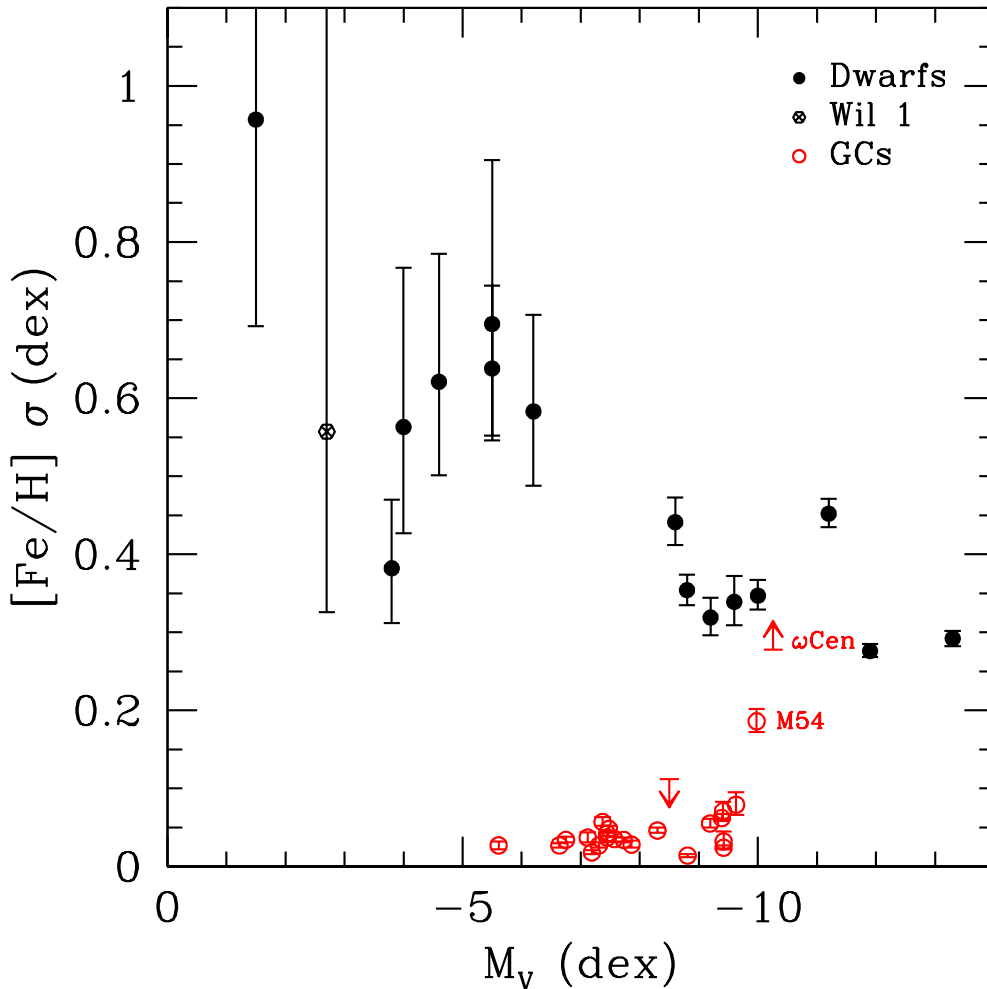


FIG. 1.— The dispersion in $[\text{Fe}/\text{H}]$ measured for MW dwarf galaxies (black, filled) and globular clusters (red, open), calculated assuming an underlying Gaussian distribution. The systems shown with dwarf galaxy symbols in this figure have been independently classified as galaxies by dynamical studies. Willman 1 does not have a definitive dynamical classification, and so is shown as an open hexagon with a cross. By this figure, a galaxy classification can be indirectly inferred from Willman 1’s spread in $[\text{Fe}/\text{H}]$. The presence of a spread in $[\text{Fe}/\text{H}]$ can diagnose a galaxy definition because it constrains the depth of the potential well in which a system formed, as supernova ejecta must be retained to form further generations of stars. Error bars show the estimated uncertainty on each dispersion given the $[\text{Fe}/\text{H}]$ measurement uncertainties on the individual member stars. Values and references are summarized in Table 1. Figure 7 of Carretta et al. (2010a) shows a figure similar in spirit to this, but for a smaller set of objects and without measurement uncertainties.

increasingly poor with decreasing luminosity, or (iii) a result of a low level of foreground contamination that disproportionately affects spectroscopic samples of the lowest surface brightness systems. The faintest dwarfs have tails at the metal-rich ends of their metallicity distribution functions that are not present in the classical dwarfs. It is not yet clear whether those metal-rich tails are physical or a result of mild contamination in the samples. Exploring the relative likelihood of these three scenarios is beyond the scope of this paper, but will be imperative to pursue in the future.

3.3. Indirect Diagnostics: Population Arguments

Population arguments rely on the assumption of a single classification for all astrophysical objects known to populate a particular region of parameter space. Such arguments are handy because, for example, it would be both impractical and unnecessary to conduct a detailed analysis of each of the 200 million galaxies cataloged by

the eighth Sloan Digital Sky Survey data release (Aihara 2011) before classifying them as such. The most common population-based classification is simply the size-based classification that is naturally made for galaxies with scale size $\gtrsim 1$ kpc. All objects satisfying this “I know it when I see it” criterion that have been studied in sufficient detail have been kinematically shown to satisfy our proposed definition of galaxy (not including tidal dwarfs, see §4.4.) Some kinematic studies of galaxies have postulated that no unseen matter or modification of Newtonian gravity may be needed to explain their dynamics (e.g., Romanowsky et al. 2003). However, such studies have always been shown to be flawed on theoretical grounds (e.g., Dekel et al. 2005) or were refuted by subsequent observational studies.

Attempts have been made to connect, or distinguish, galaxies and star clusters using scaling relations that combine their metallicities, effective sizes, internal velocities, luminosities or derivatives thereof. Such studies

have recently focused on variants of the Fundamental Plane such as the Fundamental Manifold (Forbes et al. 2011; Zaritsky et al. 2011) and the Fundamental Curve (Tollerud et al. 2011). These scalings reveal similarities and differences in the ways baryons coalesce within different types of systems. However, the scalings do not seem to shed light on the classification of objects as a star cluster or a dwarf galaxy, in a way more meaningful than M/L within r_{half} (e.g., Forbes et al. 2008; Tollerud et al. 2011; Zaritsky et al. 2011). One simple difference between galaxies and globular clusters as a population is the metallicity-luminosity relation observed for galaxies (but not star clusters, UCDs, or nearby tidal dwarfs) over a wide range of stellar masses (e.g. Skillman et al. 1989; Tremonti et al. 2004; Woo et al. 2008; Kirby et al. 2011). Although the metallicity and luminosity of an individual object would not be sufficient to classify it as a galaxy or star cluster, consideration of the metallicities and luminosities of a population of objects may aid in its classification (see also §4.2.2). It is also worthwhile to consider the placement of individual ambiguous objects with respect to observed scaling relations. Inconsistency with well-established relationships on a case-by-case basis may be a sign that some of the cautions raised in §3.1.1 are affecting the kinematics, effective mass, or size measured for an object.

Another approach to population-based classification is to include a broad set of properties such as spatial distribution, metallicity, and orbits when looking for subtle trends within a diverse set of observables. The combination of such a set of clues may help reveal whether some object or type of object with an ambiguous classification has an origin (and thus, possibly, classification) more similar to that of star clusters or of dwarf galaxies. Brodie et al. (2011) recently conducted a thorough analysis of UCDs around M87 in the Virgo cluster. They combined size–luminosity, age–metallicity, spatial distribution, and orbital dynamics to infer the possible co-existence in size and luminosity of three sub-populations of UCDs: the stripped nuclei of dEs, remnants from more massive red galaxies (either their nuclei or merged clusters), and genuine star clusters.

Although we do not aim to be exhaustive, throughout §4 we will mention some specific indirect diagnostics that may contribute to a galaxy classification.

4. SOME EXAMPLES THROUGHOUT THE COSMIC ZOO

In this section, we use the diagnostics in §3 to consider the classification of four populations of astrophysical objects: extreme ultra-faint dwarf galaxies, UCDs, GCs, and tidal dwarfs.

4.1. Ultra-faint dwarfs with $r_{half} < 50$ pc

We begin our discussion with extreme ultra-faint dwarfs, because their classification is starting to converge in the literature. The term “ultra-faint dwarfs” refers to the dwarf galaxies with absolute magnitudes fainter than $M_V \sim -8$. Currently, such objects are only known around the Milky Way and M31 because they are difficult to detect, although the Next Generation Virgo Cluster Survey should soon reveal them in Virgo. The most extreme of these objects (Segue 1, Segue 2, Boötes II, Willman 1) are observed to have $M_V \sim -2.5$ and $r_{half} \sim 30$ pc.

These extreme objects have total luminosities less than individual bright red giant branch stars. Their sizes are intermediate between typical GCs and low luminosity dwarf spheroidal galaxies. Despite their extreme and unusual properties, direct and/or indirect diagnostics support a galaxy definition for all four of these objects. With an $(M/L)_{half} \sim 3400$ and $\sigma_{[Fe/H]} = 0.75^{+0.42}_{-0.23}$ dex (Table 1), Segue 1 is a galaxy as diagnosed by both its kinematic and its $\sigma_{[Fe/H]}$. Taken at face value, the dynamics of Willman 1’s stars require a high dynamical mass relative to its stellar mass. However, its irregular kinematic distribution hinders drawing a robust classification from kinematics alone (Willman et al. 2011). Regardless, the substantial spread in $[Fe/H]$ among three member stars in Willman 1 ($0.56^{+0.58}_{-0.23}$ dex, Table 1) demonstrates its galaxy classification. A dynamical study based on small numbers of stars in Segue 2 (Belokurov et al. 2009) is consistent with a galaxy classification, although the uncertainties are still large. Finally, tidal arguments for Boötes II have suggested that it may need a substantial dark matter component for it to be self-bound (Walsh et al. 2008).

It is essential that all (candidate) extreme ultra-faint dwarfs close enough to study with 10m-class telescopes are spectroscopically investigated. Surveys like DES and LSST have the potential to uncover large numbers of objects like Segue 1 to distances beyond the reach of today’s spectroscopic resources. If a sufficient number of nearby Segue 1-like objects are demonstrated to be galaxies, then systems discovered to share that region of size–luminosity space in the future might be classified as galaxies without extensive follow-up. Even now, it is not yet certain whether Segue 2 and Boötes II should be counted as galaxies or remnants thereof. Their classifications will greatly impact the predicted number of luminous dwarfs orbiting the Milky Way and our (currently minimal) knowledge of the bottom of the galaxy luminosity function.

As a population, the MW’s ultra-faint dwarfs follow luminosity-metallicity and luminosity- (M/L) relations (e.g., Geha et al. 2009). These scaling relations rule out pathological explanations for the ultra-faints as a population, such as clumps in tidal streams or stellar streams at orbital apocenter. When in doubt for any particular object, hypothesis testing against the spatial-kinematic predictions of a specific model can be used to effectively vet a galaxy classification. For example, Zolotov et al. (2011) showed that the highly elliptical Hercules dwarf spheroidal is inconsistent with a cusp catastrophe hypothesis.

4.2. UCDs

Like “ultra-faint dwarf”, the term UCD has no formal definition. It is generally used to refer to systems with $-13 \lesssim M_V \lesssim -9$ and $10 \text{ pc} < r_{half} < 100 \text{ pc}$. This population of objects has proved particularly challenging to classify. With up to 100 UCDs possibly orbiting M87 alone (Brodie et al. 2011), whether or not these should be counted as galaxies bears great importance for understanding the dwarf galaxy population of the Virgo Cluster in a cosmological context. Thus far, studies seem to be converging on the conclusion that multiple formation channels may be re-

quired to explain the UCDs as a population, such as very massive star clusters or as the stripped nuclei of dwarf galaxies (Brodie et al. 2011; Chiboucas et al. 2011; Chilingarian et al. 2011; Da Rocha et al. 2011). In this section, we do not review the work relying on population arguments or detailed studies of individual UCDs (e.g., Maraston et al. 2004; Fellhauer & Kroupa 2005; Norris & Kannappan 2011) to reach this conclusion. We instead discuss the efficacy of UCD kinematic studies in a cosmological context and consider possible future kinematic and $[\text{Fe}/\text{H}]$ UCD classification diagnostics.

4.2.1. UCD Kinematics

Dynamical studies of UCDs do not provide a clear diagnosis of a galaxy classification. UCD3, the most luminous UCD in the Fornax cluster ($M_V = -13.55$, $r_{\text{half}} = 87$ pc), is the only UCD with spatially resolved kinematics (Frank et al. 2011). UCD3 has less than a 33% mass contribution from dark matter within 200 pc, and $M/L = 3.6 \pm 0.3$, if it is assumed that mass follows light. This M/L may be consistent with the M/L of its stellar population (Chilingarian et al. 2011, however see Mieske et al. 2006 and Firth et al. 2009 who estimate a lower stellar M/L). The spatially unresolved dynamical studies of other UCDs yield dynamical $M/L = 2 - 5$, plausibly (but not certainly) consistent with their stellar M/L (e.g., Hilker et al. 1999; Drinkwater et al. 2003; Hasegan et al. 2005; Evstigneeva et al. 2007; Mieske et al. 2008; Chilingarian et al. 2011). The dynamical M/L of Virgo cluster UCDs seem to be systematically higher than Fornax cluster UCDs (Mieske et al. 2008). The inflated Virgo UCD M/L s may be explained by unusual IMFs; a top-heavy IMF can yield a large fraction of dark stellar remnants (Dabringhausen et al. 2009, 2012), while a bottom-heavy IMF is rich in low-mass M dwarfs with high individual M/L .

It is not surprising that dynamical studies of UCDs do not easily yield a galaxy classification, even if (for example) they do presently reside in dark matter halos. To quantify this, we must begin with a reasonable hypothesis for the amount of dark matter expected within the half-light radii of UCDs if they reside in dark matter halos. There are no simulations of sufficient spatial resolution to predict the expected amount of dark matter in the innermost ~ 30 pc of a dark matter halo, and the highest resolution simulations do not include the effect of baryons, star formation, or feedback. Moreover, there are known differences between the central mass densities observed for dwarf galaxies and the central dark matter densities predicted for dwarf galaxies using dark matter only simulations (Boylan-Kolchin et al. 2011, 2012) that have, in some cases, been resolved with baryonic physics (e.g., Governato et al. 2010; Pontzen & Governato 2012). Similarly, Tollerud et al. (2011) find that the observed central mass densities of UCDs are not consistent with residing in the Navarro-Frenk-White profile dark matter halos predicted by dark matter simulations.

We therefore rely on an empirical hypothesis for the possible dark matter content of UCDs: they contain the same amount of dark matter within their half-light radii as known dwarf galaxies with the same half-light radii. We consider two MW dwarfs: Segue 1 (Martin et al. 2008; Simon et al. 2011, $\sigma_{\text{los}} = 3.7^{+1.4}_{-1.1}$

km s^{-1} , $M_V = -1.5^{+0.6}_{-0.8}$, $r_{\text{half}} = 29 \pm 6$ pc) and Coma Berenices (Simon & Geha 2007; Muñoz et al. 2010, $M_V = -3.6 \pm 0.6$, $r_{\text{half}} = 74 \pm 4$ pc). Using the Wolf et al. (2010) formula, we calculate $M_{\text{Segue1, half}} = 3.7^{+2.9}_{-2.3} \times 10^5 M_\odot$ and $M_{\text{ComBer, half}} = 1.5 \pm 0.5 \times 10^6 M_\odot$. To obtain the half-light dark matter masses of these objects, we simply subtract out their approximate stellar masses assuming a stellar M/L of 2. Because Segue 1 and Coma Berenices are highly dark matter dominated, the derived dark matter masses depend little on our assumed value of $(M/L)_{\text{star}}$.

We use the half-light dark matter masses of Segue 1 and Coma Berenices to predict the possible dynamical $(M/L)_{\text{half}}$ of UCD-luminosity systems with half-light radii of 30 pc and 75 pc. Figure 2 shows the resulting predictions, as a function of absolute magnitude and assuming a stellar $M/L = 2$ for the UCDs. UCDs are typically observed to have $-13 < M_V < -9$ and $10 \text{ pc} < r_{\text{half}} < 100 \text{ pc}$ (see e.g. Madrid et al. 2010; Brodie et al. 2011; Misgeld et al. 2011). We predict that UCDs in dark halos would have dynamical M/L within their half-light radii of 2–3, consistent with observations. Given the large uncertainties in deriving stellar M/L , this prediction confirms that dynamics will not be able to unambiguously reveal the presence of dark matter in most individual UCDs. Less luminous UCDs have less baryonic mass, and so will be more dynamically affected by the presence of dark matter if they reside in halos similar to those of more luminous UCDs. We also predict that among UCDs of similar luminosity, those with larger scale-sizes should have systematically higher dark matter fractions. This prediction makes sense, because larger half-light radii enclose a larger fraction of an object’s dark matter halo, if UCDs of similar luminosity reside in similar dark matter halos. Current observations do not bear a clear signature of this predicted relationship (Mieske et al. 2008). However, because of possible system-to-system variations and uncertainties in stellar M/L , it is impossible (to date) to draw robust conclusions about the dynamical evidence for dark matter or lack thereof.

In making the quantitative predictions in Figure 2, we have assumed that UCDs contain the same amount of dark matter within their half-light radii as known dwarf galaxies with the same half-light radii. The dark matter halos inhabited by UCDs may instead have higher mass density than those inhabited by MW ultra-faint dwarfs, owing to gravitational contraction. Alternatively they may have lower mass density, owing to the far greater amount of feedback from star formation and death experienced by UCDs with orders of magnitude more stars than ultra-faint dwarfs. Nevertheless, Figure 2 demonstrates a reasonable model in which dark matter is not dynamically detectable in most UCDs, but may be detectable in the least luminous UCDs. The relationship we predict between half-light radius and dynamical mass is dependent only on the assumption that similar luminosity UCDs inhabit similar dark matter halos.

4.2.2. UCD $[\text{Fe}/\text{H}]$

Even if it is possible to assess $\sigma_{[\text{Fe}/\text{H}]}$ in UCDs with $M_V < -10$, it would not easily aid in their classification (see §3.2). Brodie et al. (2011) have recently argued that objects with lower stellar masses are also part of

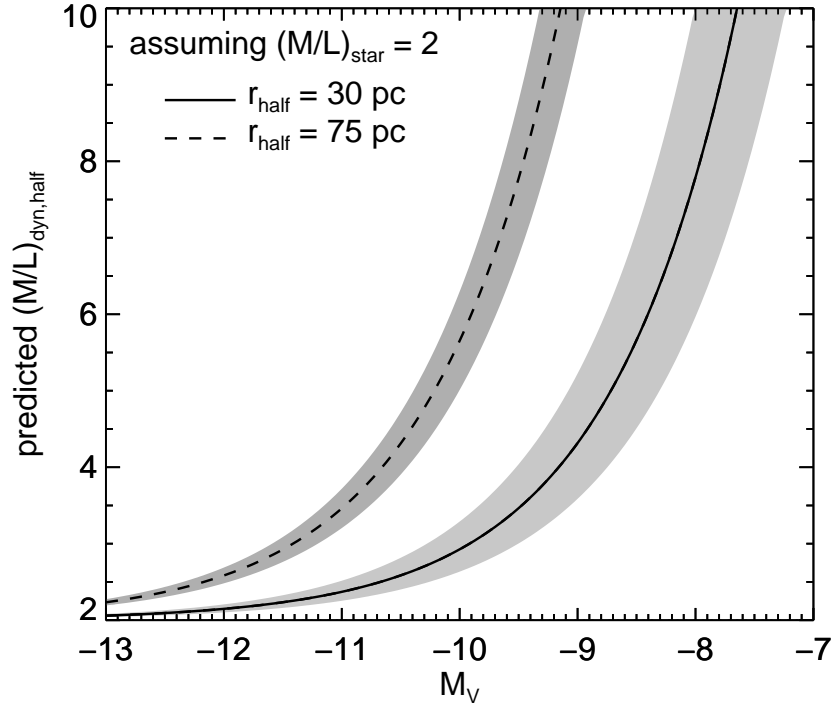


FIG. 2.— The predicted $(M/L)_{half}$ of UCDs with $r_{half} = 30$ or 75 pc, assuming they reside in dark matter halos like those inferred for Segue 1 and ComBer, respectively. Typical UCDs should not display dynamical evidence for dark matter, even if they do reside in the centers of dark matter halos.

the UCD population around M87 in Virgo. NGC 2419, a MW GC, has a size (21 pc, Harris 1996) and absolute magnitude ($M_V = -9.42$, Harris 1996) consistent with the lower luminosity UCDs around M87. At face value, NGC 2419’s lack of an $[\text{Fe}/\text{H}]$ spread (Table 1) suggests that star clusters may form with the sizes and luminosities of at least some UCDs. However, NGC 2419’s spread in Ca (~ 0.2 dex) may be difficult to reconcile with the inferred depth of its potential well. Unlike spreads in lighter elements, a Ca spread might require enrichment by supernovae (Cohen et al. 2010).

It would be extremely interesting if future studies could measure (or set limits on) the $[\text{Fe}/\text{H}]$ spread of a set of lower luminosity UCDs to see whether they all lack a spread in $[\text{Fe}/\text{H}]$, as observed for typical star clusters. Another hint to a possible UCD–dwarf galaxy connection—or lack thereof—may be their average $[\text{Fe}/\text{H}]$. UCDs fall above the metallicity–luminosity relationship followed by dwarf galaxies (e.g., Chilingarian et al. 2011, see also discussion in §3.3). If the UCDs are stripped remnants of nucleated dwarfs then they once would have been more luminous and may have fallen on observed metallicity–luminosity relationships.

4.3. Globular Clusters

A combination of dynamics, $\sigma_{[\text{Fe}/\text{H}]}$, and several indirect diagnostics show that GCs, as a population, do not satisfy our definition of galaxy and do not presently inhabit dark matter halos. We briefly discuss this evidence here, because we should neither take for granted that canonical GCs do not satisfy our proposed definition of galaxy, nor take for granted that they should be ignored in efforts to map dark matter substructure

around the MW and other galaxies. For example, the spatial distribution of MW halo GCs is consistent with the predicted present-day distribution of early forming dark matter peaks (Brodie & Strader 2006; Moore et al. 2006). This similarity could be interpreted as evidence that GCs themselves reside in the center of present day dark matter halos and, if so, should be included in studies that rely on dwarf galaxies as luminous tracers of the spatial and mass distribution of dark matter.

No dynamical study of GCs has yielded a dynamical mass in excess of stellar mass, even for lower surface density (Palomar 13, Bradford et al. 2011) and tidally disrupting clusters (Palomar 5, Odenkirchen et al. 2002). In light of the dynamical arguments presented for UCDs, GCs would be unlikely to exhibit straightforward dynamical evidence for dark matter even if they did reside in dark matter halos. The $[\text{Fe}/\text{H}]$ analysis in §3.2 and shown in Figure 1 instead provides direct evidence that GCs do not satisfy the definition of a galaxy—the iron abundances of their stars is explicable with only stellar mass and Newtonian gravity.

Additional indirect diagnostics also demonstrate that GCs would be classified as star clusters with our proposed definition. The presence of tidal streams around numerous MW GCs (e.g. Leon et al. 2000) provides upper limits to their present-day masses; this is additional evidence that their present-day dynamics are consistent with their observed stellar masses and Newtonian gravity. Another diagnostic is the existence of GCs in low-mass dwarf galaxies, such as the Fornax dwarf spheroidal. If its GCs were embedded in dark matter halos, then their dynamical friction timescale for destruction would be < 1 Gyr, far shorter than their observed

ages (Conroy & Spergel 2011). One final diagnostic may be the outer density profiles of GCs, as demonstrated by Conroy et al. (2011) for the case of NGC 2419 and MGC1.

Light element abundance spreads are common in GCs, and usually attributed to enrichment by asymptotic giant branch stars or the winds of rotating massive stars (e.g., Renzini 2008; Ventura & D’Antona 2009). These ejecta are less energetic than those of supernovae and can be retained by the gravity of stars alone. The ubiquity of these abundance variations, often identified through the anti-correlation of Na and O, has led to the suggestion that such variations should *define* the class of GCs (Carretta et al. 2010b). We do not advocate for this suggestion, since little is known about the abundance patterns of low-mass GCs, which may differ from those of more massive clusters, and star clusters with masses $\lesssim 10^4 M_\odot$ in the Large Magellanic Cloud do not appear to self-enrich (Milone et al. 2009). Furthermore, more massive objects that might be confused with GCs, such as UCDs or dwarf nuclei, lack detailed abundance observations.

Existing diagnostics do not preclude the hypothesis that some massive ($M_V < -10$) GCs may reside in dark matter halos. This possibility must be considered when comparing observations against cosmological models. Extended star clusters ($M_V \sim -7$ to -8 , $r_{half} \sim 20$ – 30 pc, Tanvir et al. 2012), such as those observed around M31 (Huxor et al. 2005), also present a challenge to classification. The M31 extended GCs would make particularly interesting targets for spectroscopic [Fe/H] studies, because their current stellar masses and escape velocities are too low to expect self-enrichment in iron.

4.4. Tidal Dwarfs

The term “tidal dwarf” (TD) refers to a gravitationally bound, galaxy-sized object (few kpc scale) formed as a result of the tidal interaction of two galaxies (Bournaud 2010). These objects form from a combination of star formation in gaseous tidal tails and of the agglomeration of existing stars from the interacting parent galaxies (Kaviraj et al. 2012). Candidates for such objects were originally observed in the Antennae and in compact galaxy groups (Mirabel et al. 1992; Hunsberger et al. 1996). Although many candidate TDs have been discovered since then, it remains difficult to determine whether TD candidates are truly self-bound (Duc et al. 2000).

Dynamical studies of TDs do not provide a definitive classification of these objects. Their kinematic properties are difficult to study, in part because TDs are typically observed while still embedded in ambient tidal material from which they formed/are forming. Some studies find their dynamical masses to be consistent with their stellar and gas (both neutral and molecular) contents (Duc et al. 2000; Braine et al. 2001; Bournaud et al. 2004; Duc et al. 2007), while others find dynamical masses 2–3 times higher than expected from observed stars and gas (Bournaud et al. 2007). In all cases, the uncertainties are substantial. Even in a cold dark matter interpretation of galaxies, TDs are not expected contain (much) dark matter (e.g., Barnes & Hernquist 1992). Unlike gas, the dark matter in TD progenitor material cannot dissipate energy and has a velocity dispersion exceeding the escape ve-

locity of the forming TD (Bournaud 2010), unless some dark matter is present in a cold, rotating, galaxy disk (Purcell et al. 2009; Read et al. 2009). Identifying a sample of relatively older (>1 Gyr) TDs and conducting uniform dynamical studies will help reveal whether: (i) TDs are simply composed of gas and stars orbiting in a Newtonian potential, (ii) galaxy disks do contain a dark matter component which can be accreted by forming TDs, or (iii) TDs demonstrate a dynamical regime governed by non-Newtonian gravity. If (ii) or (iii) is verified, then TDs would be classified by galaxies by our definition.

The possible contribution of ancient TDs formed at high redshift to today’s dwarf galaxy population, in particular around the Milky Way, is controversial. Observations of the universe at low or intermediate redshift imply that that TDs could not contribute more than $\sim 10\%$ of the dwarf galaxies in the local universe (e.g., Wen et al. 2012; Kaviraj et al. 2012). TDs forming in the local universe also do not exhibit the relationship between stellar mass and metallicity (Weilbacher et al. 2003) that is observed in the MW dwarfs (Kirby et al. 2011). Moreover, kinematic studies of nearby TDs do not imply the high dynamical M/L observed for MW dwarf satellites. Others propose that the MW’s dwarf galaxies may be dominated by tidal dwarfs formed at very high redshift when merger rates were far higher, and that the high M/L inferred for MW dwarfs are actually a misinterpretation of the observed kinematics (e.g. Kuhn & Miller 1989; Metz & Kroupa 2007; Kroupa et al. 2010). It remains to be seen whether models of ancient TDs evolving into $z = 0$ dwarfs could fall on the same metallicity-luminosity relation followed by both MW dwarfs and spheroidal galaxies over a wide range of masses.

5. DISCUSSION AND CONCLUSIONS

To compound the ambiguities inherent to classifying objects such as extreme ultra-faint MW dwarfs and UCDs, observers have neither agreed upon a definition of galaxy nor reached consensus on how to interpret observations in hand. To facilitate comparisons between dwarf galaxy predictions and the increasingly complex sets of observations of candidate dwarf galaxies, the field needs an agreed-upon definition for galaxy. We have accordingly proposed a physically motivated definition that does not insist on a cold dark matter interpretation of data: *A galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton’s laws of gravity.*

We have explored possible diagnostics of this galaxy definition (primarily in the context of a cold dark matter dominated universe), primarily kinematic studies and [Fe/H] spread. Although kinematic studies generally provide the most direct way to infer a galaxy definition, it can be difficult to measure the dynamical mass of low luminosity and/or low velocity dispersion ($< \text{few km s}^{-1}$) systems. Even once robustly measured, interpreting relatively modest dynamical M/L ($\lesssim 10$) may face several stumbling blocks: those that could have generated overestimates of dynamical mass (e.g., binary stars, contaminants in spectroscopic sample) and those could generate underestimates of stellar mass (e.g., sparse sampling of the stellar luminosity function, an overabundance of stellar remnants). While these effects do not appear to

be a major problem for objects currently classified as galaxies, including the Milky Way’s dwarfs, they should be carefully considered as discoveries at the extremes of the cosmic zoo continue. Systems such as UCDs and massive GCs also may not bear a kinematic signature of dark matter or non-Newtonian gravity, even if present, because their baryons are so densely packed.

$\sigma_{[\text{Fe}/\text{H}]}$ provides an complimentary means to diagnose a galaxy definition for systems less luminous than $M_V = -10$. Using public spectroscopic $[\text{Fe}/\text{H}]$ measurements, we recalculated the average systemic $[\text{Fe}/\text{H}]$ and associated dispersions for 24 Milky Way GCs and 16 Milky Way dwarf galaxies. All dwarf galaxies show spectroscopic $[\text{Fe}/\text{H}]$ spreads of ~ 0.3 dex or more. No GC less luminous than $M_V = -10$ shows a notable ($\gtrsim 0.1$ dex) $[\text{Fe}/\text{H}]$ spread. The $\sigma_{[\text{Fe}/\text{H}]}$ diagnostic has already been applied to the Segue 1 (Simon et al. 2011) and Willman 1 dwarf galaxies (Willman et al. 2011). One possible caveat with the $\sigma_{[\text{Fe}/\text{H}]}$ diagnostic is the possibility that the mergers of multiple star clusters could yield an iron abundance spread. This merging star cluster hypothesis, which would produce a multimodal $[\text{Fe}/\text{H}]$ distribution, should be carefully considered when classifying objects by $[\text{Fe}/\text{H}]$ dispersion alone.

The Fundamental Plane and its variants do not presently provide an alternative means to diagnose a galaxy definition for low luminosity systems. However, these scaling relations do provide a useful benchmark against which to compare ambiguous objects. For example, an outlier from known scaling relations may signal a problem with its calculated velocity dispersion or estimated stellar mass (such as the issues discussed in §3.1.1.) Well behaved scaling relations can also help rule out pathological explanations for sets of objects, especially when metallicity is included. For example, the metallicity–luminosity relation followed by the Milky Way’s lowest luminosity dwarfs helps rules out alternative hypotheses for their existence as a population, such as tidal tails at apocenter and clumps in streams.

There are some classes of objects not discussed in this paper, but which would be worth new consideration in the context of our proposed galaxy definition. For example, dwarf ellipticals (dEs) do not typically show strong kinematic evidence for non-baryonic mass in their central regions (e.g. Wolf et al. 2010; Forbes et al. 2011). However, recent kinematic studies of stars and globular clusters in their outer regions (Beasley et al. 2009; Geha et al. 2010) have consistently suggested that M/L increases with radius and that stars alone cannot account for the observations. Therefore, the current data favors the classification of dEs as galaxies by our definition. If future observations of dEs do not support this emerging consensus, then this classification should be revisited.

After examining massive globulars, UCDs and tidal dwarfs in detail, we find that they can not yet conclusively be classified given existing diagnostics of our galaxy definition. Their ultimate classification must be guided by future observational data. If UCDs and tidal dwarfs are inconsistent with a galaxy definition, this does not mean that they should automatically be classified as star clusters. Both of these classes of objects are interesting and stand on their own as worthy to investigate, given their unique properties and possibly formation channels.

For tidal dwarfs, in particular, we advocate that these objects are not lumped in with galaxies or clusters but that they remain their own distinct class of objects.

We have suggested several measurements, some of which are possible now, that could facilitate the classification of these, and other, extreme objects:

- Observational constraints on the $[\text{Fe}/\text{H}]$ spread in extended GCs and any UCD fainter than $M_V = -10$ (§3.2.2, §4.3);
- Adaptive optics spectroscopy to measure the $[\text{Fe}/\text{H}]$ of individual stars in massive M31 GCs (§3.2.3, §4.3);
- Dynamical studies of the lowest luminosity ($M_V \gtrsim -9$), largest scale sized UCDs ($r_{\text{half}} \gtrsim 30$ pc) (§4.2);
- Measuring dynamical masses of a larger sample of UCDs to look for a positive correlation between half-light radius and half-light M/L , at set UCD luminosity (§4.2);
- Dynamical and chemical studies of extreme MW satellites Boötes II and Segue 2 (§4.1).

Basic cold dark matter plus galaxy formation models predict a dichotomy between systems that form in the centers of dark matter halos and systems that form in the monolithic collapse of gas clouds that are not the primary baryonic components of dark matter halos. Our best present interpretation of the observations in this context reveals that systems forming at the center of a dark matter halo bear an observable imprint of this formation channel, such as the kinematic or chemical diagnostics discussed here. This observable imprint would translate to a galaxy classification by our proposed definition. The fact that systems classified as galaxies may be equivalent to the set of astrophysical systems that formed in dark matter halos can be used as strong guidance to theorists when selecting against which astrophysical systems to compare their predictions. However, even in a dark matter context, we cannot take for granted that systems classified as galaxies by our definition are inclusive of all systems that formed in dark matter halos and exclusive of systems that formed otherwise.

As our understanding of the universe grows, it may be possible for systems that formed inside of dark matter halos to fail the galaxy diagnostics discussed here. For example, it would not be unreasonable to conceive that a very low-luminosity fossil galaxy could form all of its stars over a sufficiently short timescale that no opportunity for self-enrichment by supernovae could occur, leading to a minimal spread in $[\text{Fe}/\text{H}]$. If this is the case, then alternative diagnostics need to be identified for such “first” galaxies. No objects meeting our definition of a galaxy via kinematics, but without a spread in $[\text{Fe}/\text{H}]$, have yet been discovered, but it is plausible they exist. Cosmological globular clusters, if they exist, may be such objects (Griffen et al. 2010). Conversely, it may be possible for stellar systems that formed inside of a dark matter halo to lose most or all of their dark matter. In this scenario, a(n almost) stellar-only system may exist with the chemical imprint of formation within a dark matter halo. Although simulations of dwarf galaxies in both cuspy and cored halos show that this is unlikely (see

§3.1), simulations of globular clusters within dark matter halos have shown that it may be possible to remove most of the dark matter in systems close to disruption (e.g. Mashchenko & Sills 2005).

Our proposed galaxy definition is itself independent of our observational knowledge and currently favored theories for structure formation; it can thus remain unchanged even as our understanding of the complex universe evolves. However, the particular diagnostics of this definition as investigated in this polemic may indeed need to be revisited as our knowledge of extreme objects grows—both observationally and theoretically. For example, the possible use of spreads in elements other than iron (such as calcium) to diagnose a galaxy classification is something that should continue to be scrutinized as our knowledge of such abundance patterns grow.

BW acknowledges support from NSF AST-0908193. BW also thanks NYU’s Center for Cosmology and Particle Physics and Drexel University’s Physics department for hosting her during the writing of of this paper. We thank Dr. Pierre-Alain Duc, the referee, for comments that helped improve the quality and clarity of this paper. We thank Michele Bellazzini, Joerg Dabringhausen, Ross Fadely, Duncan Forbes, Amanda Ford, Marla Geha, Amina Helmi, David Hogg, Evan Kirby, Pavel Kroupa, George Lake, Erik Tollerud, and Enrico Vesperini for stimulating conversations and emails leading up to and during the preparation of this paper. This research has made use of NASA’s Astrophysics Data System Bibliographic Services.

TABLE 1
[Fe/H] PROPERTIES OF MW GLOBULAR CLUSTERS AND DWARFS

Name	[Fe/H] dex	±34% CL dex	$\sigma_{\text{[Fe/H]}}$ dex	+34% CL dex	-34% CL dex	M_V	N_{star}	Ref	type
ω Cen	-1.647	0.009	0.271 ^a	0.007	0.007	-10.3	855	J10	GC
M54	-1.559	0.021	0.186	0.016	0.014	-10.0	76	Car10	GC
NGC 6441	-0.334	0.018	0.079	0.016	0.013	-9.6	25	G07	GC
NGC 104	-0.743	0.003	0.024	0.003	0.002	-9.4	147	Car09b	GC
NGC 2419	-2.095	0.019	0.032	0.013	0.009	-9.4	38	Coh10	GC
NGC 2808	-1.105	0.006	0.062	0.005	0.004	-9.4	123	Car06	GC
NGC 6388	-0.404	0.014	0.071	0.012	0.010	-9.4	36	Car09b	GC
NGC 7078	-2.341	0.007	0.055	0.006	0.005	-9.2	84	Car09b	GC
NGC 5904	-1.346	0.002	0.014	0.002	0.002	-8.8	136	Car09b	GC
M22	-1.764	0.016	0.099 ^b	0.013	0.011	-8.5	37	M11	GC
NGC 1851	-1.157	0.005	0.046	0.004	0.003	-8.3	124	Car11	GC
NGC 1904	-1.545	0.005	0.028	0.005	0.004	-7.9	58	Car09b	GC
NGC 6752	-1.564	0.004	0.034	0.003	0.003	-7.7	137	Car07b	GC
NGC 6809	-1.970	0.004	0.035	0.003	0.003	-7.6	156	Car09b	GC
NGC 3201	-1.495	0.004	0.042	0.004	0.003	-7.5	149	Car09b	GC
NGC 6254	-1.557	0.005	0.048	0.004	0.003	-7.5	147	Car09b	GC
NGC 7099	-2.358	0.006	0.037	0.006	0.005	-7.5	65	Car09b	GC
NGC 4590	-2.230	0.007	0.057	0.006	0.005	-7.4	122	Car09b	GC
NGC 6218	-1.313	0.004	0.027	0.004	0.003	-7.3	79	Car07a	GC
NGC 6121	-1.200	0.003	0.018	0.003	0.002	-7.2	103	Car09b	GC
NGC 6171	-1.066	0.008	0.037	0.007	0.006	-7.1	33	Car09b	GC
NGC 288	-1.219	0.004	0.034	0.004	0.003	-6.8	110	Car09b	GC
NGC 6397	-1.994	0.004	0.027	0.003	0.003	-6.6	144	Car09b	GC
NGC 6838	-0.806	0.006	0.027	0.005	0.005	-5.6	39	Car09b	GC
For	-1.025	0.012	0.292	0.010	0.010	-13.3	675	K10	dwarf
Leo I	-1.450	0.011	0.276	0.009	0.008	-11.9	827	K10	dwarf
Scl	-1.726	0.024	0.452	0.019	0.017	-11.2	376	K10	dwarf
Leo II	-1.670	0.024	0.347	0.020	0.018	-10.0	258	K10	dwarf
Sex	-1.966	0.039	0.339	0.033	0.030	-9.6	141	K10	dwarf
Dra	-1.946	0.024	0.354	0.020	0.019	-8.8	298	K10	dwarf
CVn I	-1.962	0.038	0.441	0.032	0.029	-8.6	174	K10	dwarf
UMi	-2.112	0.027	0.319	0.025	0.023	-9.2	212	K10	dwarf
Herc	-2.518	0.140	0.583	0.124	0.095	-6.2	21	K08	dwarf
UMa I	-2.334	0.128	0.638	0.106	0.086	-5.5	31	K08	dwarf
Leo IV	-2.363	0.230	0.695	0.210	0.149	-5.5	12	K08	dwarf
Cvn II	-2.444	0.178	0.621	0.164	0.120	-4.6	15	K08	dwarf
UMa II	-2.357	0.204	0.563	0.204	0.136	-4.0	9	K08	dwarf
ComBer	-2.640	0.100	0.382	0.088	0.070	-3.8	23	K08	dwarf
Will	-2.110	0.367	0.557	0.577	0.231	-2.7	3	W11	dwarf
Seg 1	-2.735	0.389 ^c	0.752	0.417	0.227	-1.5	7	N10, S11	dwarf

NOTE. — The reference column gives the source of individual [Fe/H] measurements used to estimate the dispersion in each object. For Segue 1, only the one star (Seg 1-7) is taken from Norris et al. (2010). Values of M_V for the dwarfs are from Sand et al. (2011) and references therein. Values of M_V for the GCs are from Harris (1996, 2010 edition). The posterior distribution of [Fe/H] sufficiently symmetric that we only quote a single value for ±34% CL, taking the average of the + and - values in the small number of cases with a few thousandth of a dex difference between the two.. Reference key: J10 = Johnson & Pilachowski (2010), Car11 = Carretta et al. (2011), Car10 = Carretta et al. (2010a), Coh10 = Cohen et al. (2010), Car09b = Carretta et al. (2009b), Car06 = Carretta et al. (2006), M11 = Marino et al. (2011), Car07a = Carretta et al. (2007a), G07 = Gratton et al. (2007), Car07b = Carretta et al. (2007b), K10 = Kirby et al. (2010), K08 = Kirby et al. (2008), W11 = Willman et al. (2011), N10 = Norris et al. (2010), S11 = Simon et al. (2011)

^a This value is a lower limit (see §3.2.1).

^b This value is an upper limit (see §3.2.1).

^c Unlike the other objects, the metallicity of Segue 1 has asymmetric uncertainties: $-2.735^{+0.373}_{-0.405}$

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