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Galaxies on Sub-Galactic Scales

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Abstract: The Sloan Digital Sky Survey has been immensely successful in detecting new Milky Way satellite galaxies over the past seven years. It was instrumental in finding examples of the least luminous galaxies we know in the Universe, uncovering apparent inconsistencies between cold dark matter theory and dwarf galaxy properties, providing first evidence for a possible lower mass limit for dark matter halos in visible galaxies, and reopening the discussion about the building block scenario for the Milky Way halo. Nonetheless, these results are still drawn only from a relatively small number of galaxies distributed over an area covering about 29% of the sky, which leaves us currently with more questions than answers. The study of these extreme stellar systems is a multi-parameter problem: ages, metallicities, star formation histories, dark matter contents, population fractions and spatial distributions must be determined. Progress in the field is discussed and attention drawn to some of the limitations that currently hamper our ability to fully understand the phenomenon of the 'ultra-faint dwarf galaxy'. In this context, the Stromlo Milky Way Satellite Survey represents a new initiative to systematically search and scrutinize optically elusive Milky Way satellite galaxies in the Southern hemisphere. In doing so, the program aims at investigating some of the challenging questions in stellar evolution, galaxy formation and near-field cosmology.

Keywords: galaxies: dwarf — galaxies: kinematics and dynamics — surveys — galaxies: stellar content — galaxies: evolution — Local Group — cosmology: theory — dark matter — stars: abundances

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1 Introduction

Tomographic studies facilitated by the depth and uniformity of modern wide-field CCD imaging has revolutionised the way we can map the stellar substructures in the extended Milky Way today. The Sloan Digital Sky Survey (SDSS, York et al. 2000), the first digital survey of the northern sky, has revealed among many other things a significant number of optically elusive satellite galaxies (Willman et al. 2005a,b; Belokurov et al. 2006a,b, 2007b, 2009, 2010; Sakamoto & Hasegawa 2006; Zucker et al. 2006b; Walsh et al. 2007; Liu et al. 2008; Grillmair 2009) as well as several large-scale stellar streams whose nature is still a mystery or subject of speculation (Grillmair 2006; Belokurov et al. 2006a, 2007a; Jurić et al. 2008; Vivas et al. 2008; Keller et al. 2009). The recently discovered satellite galaxies like Ursa Major II, Coma Berenices, Willman 1, and Bootes II are HI-deficient stellar systems with upper limits for their neutral hydrogen masses at a few $10^4 M_\odot$ (Grcevich & Putman 2009), orbiting the Milky Way within its virial radius of 250 kpc. They populate a mostly unexplored region of the galactic parameter space and seem to form a new galaxy class, the ultra-faint dwarf spherodal galaxies, so named because of their extremely small stellar contents and absence of gas. Star counts of $N_* \approx 10^{2\text{–}5}$ are well below the typical $>10^6$ stars found in classical dwarf spheroidals like Sculptor, Fornax and Carina (see Table 1). When compared to the Milky Way's globular cluster (GC) system these ultra-faints have similar luminosities to the fainter members ($-5 < M_V < -2$) and average heavy-element abundances significantly lower than the metal-poor mode ($\langle[\mathrm{Fe/H}]\rangle \simeq -1.5$ dex and $\sigma \simeq 0.3$ dex). The characteristic half-light radius of an ultra-faint dwarf spheroidal is 10–100 times larger than that of a typical GC, leading to projected star densities below 1 star per pc^2, so low that they are fully resolved and remain inconspicuously hidden in the sea of Galactic foreground stars. This property explains why observers failed to notice them before deep untargeted CCD imaging surveys over large areas of sky became technical feasible.

The 13–16 (ultra-faint) dwarf spheroidal galaxies detected over the SDSS footprint (Figure 1) already account for more than twice the total number of previously known Milky Way satellites and challenge traditional concepts about the low mass threshold of galaxy formation. It is conceivable that the newly detected dwarf satellites are in fact current-day survivors of an originally much larger population of small galaxies that was gradually annihilated during the formation of the Milky Way. Kinematical measurements also suggest that ultra-faint satellite galaxies are completely dominated by the

Table 1. Stellar overdensities, ultra-faint dwarf satellites, and dwarf spheroidals within the Milky Way's virial radius, sorted by increasing heliocentric distance

Name (1)	$D_\odot$ (kpc) (2)	M_V (mag) (3)	r_h (pc) (4)	ϵ (5)	$\langle$[Fe/H]$\rangle$ (dex) (6)	Discovery paper (7)
Segue 3	17 ± 1	-1.2 ± 0.5	3	0.3	-1.7	Belokurov et al. (2010)
Segue 1	23 ± 2	-1.5 ± 0.7	29	0.48	-2.5	Belokurov et al. (2007b)
SDSS J1058 + 2843[a]	24 ± 3	-0.2 ± 1.0	22	0.38	…	Liu et al. (2008)
Sagittarius	24 ± 2	-13.4	≈ 1550[b]	0.65[b]	-0.4	Ibata et al. (1994)
Ursa Major II	35 ± 1	-3.9 ± 0.5	140	0.63	-2.47	Grillmair (2006)[c]
Segue 2	35 ± 1	-2.5	34	0.15	≈ -2	Belokurov et al. (2009)
Willman 1	38 ± 7	-2.7 ± 0.7	25	0.47	≈ -2.1	Willman et al. (2005a)
Bootes II	42 ± 8	-2.7 ± 0.9	51	0.21	-2.0	Walsh et al. (2007)
Coma Berenices	42 ± 2	-3.8 ± 0.6	77	0.38	-2.60	Belokurov et al. (2007b)
All 150 MW globular clusters except six have heliocentric distances smaller than 50 kpc						
Bootes III	52 ± 4	-5.8 ± 0.5	≈ 400	0.5	≈ -2	Grillmair (2009)
Bootes I	66 ± 3	-6.3 ± 0.3	242	0.39	-2.55	Belokurov et al. (2006b)
Ursa Minor	66 ± 4	-8.9	150	0.56	-2.13	Wilson (1955)
Draco	82 ± 6	-8.8	221	0.33	-1.93	Wilson (1955)
Sculptor	79 ± 4	-11.1	94	0.32	-1.68	Shapley (1938)
Sextans	86 ± 4	-9.5	294	0.35	-1.93	Irwin et al. (1990)
Ursa Major I	95 ± 4	-5.5 ± 0.3	318	0.80	-2.18	Willman et al. (2005b)
Carina	101 ± 5	-9.3	137	0.33	-1.7	Cannon et al. (1977)
Hercules	132 ± 12	-6.6 ± 0.3	330	0.68	-2.41	Belokurov et al. (2007b)
Fornax	138 ± 8	-13.2	339	0.30	-0.99	Shapley (1938)
Leo IV	154 ± 5	-5.0 ± 0.6	116	0.22	-2.54	Belokurov et al. (2007b)
Canes Venatici II	160 ± 5	-4.9 ± 0.5	74[d]	0.52	-2.21	Sakamoto & Hasegawa (2006)
Pisces II	≈ 180	-5 ± 0.5	60	0.4	…	Belokurov et al. (2010)
Leo II	205 ± 12	-9.6	123	0.13	-1.62	Harrington & Wilson (1950)
Canes Venatici I	210 ± 7	-8.6 ± 0.2	564	0.39	-1.98	Zucker et al. (2006b)
Leo I	250 ± 30	-11.9	133	0.21	-1.43	Harrington & Wilson (1950)

[a]Little has been published since the stellar overdensity SDSS J1058 + 2843 was reported.
[b]Values refer to the bound central region of Sagittarius (Majewski et al. 2003).
[c]Comprehensive study of the UMa II dwarf can be found in Zucker et al. (2006a).
[d]Result from Martin et al. (2008b); a significantly larger half-light radius of 154 pc is quoted by Greco et al. (2008).
(2) References for RR Lyrae-based distances can be found in Clementini (2010). Distances for other galaxies are from Willman et al. (2005a), Belokurov et al. (2007b), Coleman et al. (2007), Liu et al. (2008), Walsh et al. (2008), Belokurov et al. (2009), Correnti et al. (2009), Belokurov et al. (2010), and Fadely et al. (2011).
(3) References for magnitudes are from Martin et al. (2008b), Correnti et al. (2009), Muñoz et al. (2010), Belokurov et al. (2010).
(4) Half-light radii are from Walker et al. (2009) and references therein. Deprojected radii can be found in McGaugh & Wolf (2010).
(5) References for ellipticity are from Irwin & Hatzidimitriou (1995), Majewski et al. (2003), Martin et al. (2008b), Correnti et al. (2009) and Belokurov et al. (2010).
(6) References for the mean metallicities are from Helmi et al. (2006), Bellazzini et al. (2008), Belokurov et al. (2009), Carlin et al. (2009), Correnti et al. (2009), Norris et al. (2010b), Willman et al. (2011), Kirby et al. (2011), Simon et al. (2011), and Fadely et al. (2011).
Note: all 150 MW globular clusters except six have heliocentric distances smaller than 50 kpc: Pal14 (73.9 kpc), NGC2419 (84.2 kpc), Eridanus (90.2 kpc), Pal3 (92.7 kpc), Pal4 (109.2 kpc), and AM1 (121.9 kpc) (see Harris 1996, 2010 edition).

ubiquitous, cosmologically important non-baryonic dark matter, with the stellar population contributing only a few percent to the overall mass (Mateo 1998, Wilkinson et al. 2004; Koch et al. 2007; Simon & Geha 2007; Walker et al. 2007). Although of humble appearance, these small stellar aggregates are rather special for another reason too. They contain some of the chemically most pristine stars with observed metallicities as low as [Fe/H] = −3.7 dex (Norris et al. 2010a,c; Simon et al. 2011), closing the gap to the rare metal-deficient halo stars like CD-38 245 (−4.5; Bessell & Norris 1984) or HE0107-5240 (−5.3; Christlieb et al. 2004). These properties of being the most dark-matter dominated galaxies (e.g. Gilmore et al. (2007) and harbouring extreme metal-poor stars, give Milky Way satellite galaxies a prominent role in three major astrophysical themes: *near-field cosmology*; *galaxy formation*; and *stellar evolution*, making them one of the most sought-after extragalactic objects today. The discovery of such unique cosmic laboratories has consequently led to a rapidly expanding research effort worldwide dedicated to their physical and chemical analysis. This work has made immense progress over the past few years but the limited sky coverage of SDSS of approximately 29% (Legacy: 8400 deg^2, SEGUE: 3200 deg^2, see Figure 1) leaves us with an incomplete picture of the ultra-faint dwarf galaxies. In the following sections of this paper we will review findings from recent work and highlight some of the outstanding questions that make us wonder what a more complete census of the Milky Way's satellite system has to offer.

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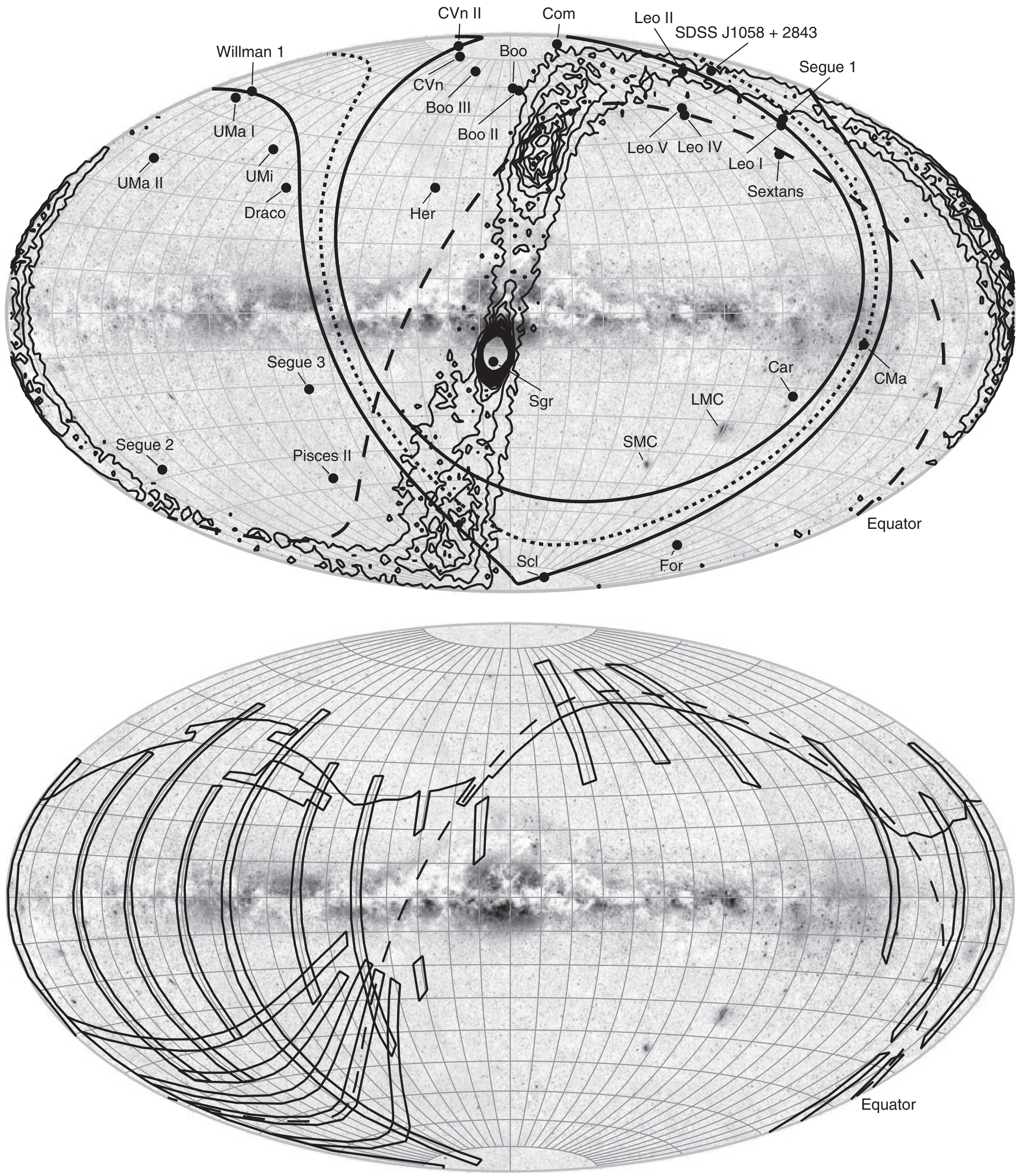

Figure 1 (Top) Aitoff projection in Galactic coordinates showing the distribution of the Milky Way satellite galaxies and other prominent stellar overdensities detected within the 250 kpc virial radius of the Milky Way. The direction of the Disk of Satellites (Kroupa et al. 2005) is highlighted with a dotted and two solid lines. The locus of the Sagittarius tidal stream as represented by the particle density of the Law et al. (2005) model for a spherical Milky Way halo is outlined with contours. (Bottom) SDSS imaging data footprint: the Legacy survey covers an area of $\approx 8400\,\mathrm{deg}^2$ mostly around the North Galactic Cap while SEGUE runs mostly in stripes of constant Galactic longitude covering $\approx 3200\,\mathrm{deg}^2$ at lower Galactic latitudes. The area below the equator (dashed line) will be searched for new ultra-faint dwarf galaxies to SDSS-comparable photometric depth by the upcoming Stromlo Milky Way Satellite Survey program.

2 Ultra-faints and the Concordance Cosmological Model

Prior to the SDSS survey in 2004, the population of Milky Way satellite galaxies stood at eleven: the Large and Small Magellanic Clouds and the nine classical dwarf spheroidal (dSph) satellites with luminosities brighter than $M_V \approx -9$. This small number gave rise to a crisis in theoretical cosmology that became known in the literature as the 'missing satellites' problem. It can be described as follows. Supercomputer calculations within the ΛCDM cosmology show that the dark matter substructure correlates well with the large-scale distribution of galaxies and

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galaxy clusters (Hawkins et al. 2003; Springel et al. 2005). The standard cold dark matter paradigm dominated by dark energy has been successful in explaining the distribution of the shining baryons on large cosmological scales. With the rapid advance of high-performance computing and the ability to simulate these processes at high resolution the paradigm also makes a generic prediction of the dark matter distribution on galactic and sub-galactic scales: the halo of large galaxies like our own Milky Way should host hundreds, and possibly as many as 1000, dark matter subhalos (Klypin et al. 1999; Moore et al. 1999, Diemand et al. 2005). If these subhalos have accumulated sufficient primordial hydrogen gas and turned it into stars like their more massive brethren they should be visible as small Milky Way satellite galaxies today. However, there were only eleven. Taking these numbers from computer simulations and observations at face value there is a difference of at least one order of magnitude — the 'missing satellites' problem.

As it turned out, the missing satellites problem was just one in a series of inconsistencies between high resolution ΛCDM cosmology simulations and observed properties of dwarf galaxies. Another currently poorly understood difference is the anisotropy problem. Dark matter subhalos, and their optical manifestation the dwarf galaxies, are expected to exhibit an isotropic spatial distribution around the Milky Way. This assumption should be true even if baryon evacuation physics, star-formation and energy-feedback mechanisms (e.g Dekel & Silk 1986; Dekel & Woo 2003, Woo et al. 2008; Font et al. 2011 significantly reduce the number of dark matter subhalos that contain an appreciable amount of visible baryons. However, most of the currently observed MW satellites are arranged in a plane, the so-called Disk of Satellites, inconsistent with an isotropic distribution at a high significance level (Kroupa et al. 2005). Metz et al. (2009) paid special attention to the selection bias introduced by the limited sky coverage of the Sloan Digital Sky Survey and reached the same conclusion. The possibility that the satellite galaxies + LMC + SMC share a common origin is an idea discussed in the literature for quite some time (Lynden-Bell 1976, 1982; Kunkel & Demers 1976; Kunkel 1979; Majewski 1994; Palma et al. 2002; Dinescu et al. 2004). Most recent observational support for such a scenario that was initially based solely on the distribution of classical and ultra-faint dwarf satellites, is coming from the finding that the combined angular momentum vector of the MW satellite galaxies with available proper motion measurements is co-aligned with the normal of the Disk of Satellites (Metz et al. 2008). There is now fairly good evidence that the satellite galaxy system of the MW is a rotationally supported structure, rotating with a velocity of 40 km s^{-1} (Deason et al. 2011a). In this context, it is also interesting to mention the findings of James & Ivory (2011) and Liu et al. (2011) that the presence of two luminous, star-forming satellite galaxies like the Magellanic clouds in close proximity to a the Milky Way type galaxy is statistically unusual.

To achieve such an anisotropic spatial distribution and angular momentum bias in the ΛCDM simulations requires little phase-mixing and relaxation, thus a recent accretion event is claimed to be responsible for the observations (Deason et al. 2011b). However, to explain other properties of the satellite galaxy population such as the observed radial distribution of gas-deficient and gas-rich dwarfs around the Milky Way and M31 (Grcevich & Putman 2009), dwarf galaxies are expected to enter the MW halo at a high redshift $z \sim 3$–10 (Nichols & Bland-Hawthorn 2011) or approximately 12 Gyr ago. It has also been suggested that the anisotropic satellite distribution is a consequence of the MW being embedded in an extended, prolate dark matter halo where its principal axis is orthogonal to the MW disk (Hartwick 2000; Banerjee & Jog 2011). But there is still much uncertainty and disagreement as to the shape and orientation of the MW dark matter halo. Important empirical input for calibrating such numerical simulations is provided by spatial information on stellar streams from tidally disrupted MW satellite galaxies (e.g. Belokurov et al. 2007a; Grillmair et al. 2009; Williams et al. 2011), in particular from the tidal structure that has been identified as debris of the Sagittarius dwarf, which traces the polar regions of the Milky Way (see Figure 1). For example, Fellhauer et al. (2006) modeled the bifurcation of the Sagittarius stream (Belokurov et al. 2006a) to constrain the shape of MW dark matter halo. A theoretical explanation of this feature is best matched with the halo being close to spherical. The same view is supported by a recent study (Jerjen et al. 2011) where traces of the Sgr stellar stream in the direction of the Virgo overdensity region (Jurić et al. 2008) were compared with the Sgr stream models by Law et al. (2005) and Law & Majewski (2010).

The obvious deficiency is that various ΛCDM simulations can explain different observations but the theory currently lacks a consistent solution to explain all observations on the galactic scale including the observed number and distribution of Milky Way dwarf satellites.

3 Kinematics and Dark Matter

The kinematic properties of the ultra-faint dwarf satellites is another burgeoning research field. Aaronson (1983), based on accurate velocities for three carbon stars in the Draco satellite, and Armandroff & Da Costa (1986), using velocities for 16 K-giant members of Sculptor, were among the first to suggest that the dwarf spheroidal satellites of the Milky Way probably contain substantial amounts of unseen matter. Subsequent systematic and extended work has shown that, under the assumption of isotropy in the velocity dispersion and dynamical equilibrium, the dwarf spheroidal and ultra-faint Milky Way satellites are indeed highly dark-matter dominated systems (Mateo et al. 1993; Hargreaves et al. 1994a,b; Simon & Geha 2007). Following on initial results by Mateo and collaborators (Mateo et al. 1993; Mateo et al. 1998), Strigari et al. (2008) have further proposed that the mass within 300 pc radius of a dwarf galaxy satellite is approximately constant $\approx 10^7\,M_\odot$ independent of the total luminosity (baryonic mass or number of stars). If the apparent constancy of the mass within 300 pc is correct, it would indicate a preferred minimum dark matter halo mass in which stars can form. However such a favoured dark matter halo mass is not expected or predicted in the simplest interpretation of current ΛCDM cosmology models as they are free of any preferred mass scale (e.g. Diemand et al. 2005). The existence of such a scale would thus more likely be related to physical processes at work at the earliest cosmological times that affect the ability of gas to remain gravitationally bound in dark matter halos, to cool, and subsequently form stars (e.g. Read et al. 2006, Okamoto & Frenk 2009). In this context there are still a number of important points that need clarification. For instance, as noted by Walker et al. (2009) and listed in table 2 of McGaugh & Wolf (2010), we have no evidence at present to indicate that the dark matter halos of the lowest luminosity systems actually reach a radius of 300 pc. Consequently, the true masses of at least some objects must be lower. The view of a shallow but significant increase of dark matter mass with luminosity is also supported by the new Font et al. (2011) model for Milky Way satellites. Detecting such a mild correlation between dark matter and baryonic mass as opposed to a constant dark matter mass clearly requires the analysis of a substantially larger number of ultra-faint galaxies not only to improve the statistical accuracy but also to weed out those objects whose true nature and physical state remain ambiguous.

Essentially all the inferred dark matter properties of MW satellite galaxies currently rest on the assumption that their measured velocity dispersions accurately reflect their masses and we know the mass distribution of these stellar systems. It is assumed that the systems are in dynamical equilibrium and the observed kinematics are not being influenced by the Galactic tidal field (Peñarrubia et al. 2008) or the presence of binary stars (Hargreaves et al. 1994a; McConnachie & Côté et al. 2010). The unambiguous identification of a genuine ultra-faint dwarf galaxy demands a great observational effort where a number of issues need to be carefully addressed before reaching a firm conclusion. The challenge is exemplified by the dispute around Segue 1 at a heliocentric distance of 23 kpc (Belokurov et al. 2007b) and with $M_V = -1.5 \pm 0.7$ one of the least luminous ultra-faint dwarfs known to date. Niederste-Ostholt et al. (2009) argued that Segue 1 is a tidally disrupted star cluster whose measured velocity dispersion of $4.3 \pm 1.2\,\mathrm{km\,s^{-1}}$ (Geha et al. 2009) has been inflated by contaminating stars from the Sagittarius stream (see Figure 1). A comprehensive spectroscopic analysis of a quasi-complete sample of all stars within 2.3 half-light radii of the galaxy was necessary (Simon et al. 2011) to lend considerable support to the hypothesis that Segue 1 is not a star cluster but an ultra-faint dwarf with a mass-to-light ratio of $M/L = 3400$, the darkest galaxy currently known.

For other ultra-faint dwarf galaxies like Ursa Major I and II, Bootes III and Hercules there is growing suspicion that their stellar kinematics are affected by the Galactic tidal field. Already in the discovery paper of Ursa Major II, Zucker et al. (2006a) noted that the galaxy's isophotes are irregular and distorted with evidence for multiple stellar clumps. Adding to this picture, Belokurov et al. (2007b) pointed out that the Orphan Stream lies along a great circle intersecting the position of Ursa Major II. Fellhauer et al. (2007) then found a good match utilizing numerical simulations of the disruption of a Ursa Major II model galaxy with the position, distance and morphology of the Orphan Stream, prompting these authors to propose Ursa Major II as possible progenitor of the stream. Hercules (Belokurov et al. 2006a) is another interesting stellar system in that context. It has a relatively bright luminosity of $M_V = -6.6$ and, similar to Ursa Major I and II, an unusually large ellipticity $\epsilon = 0.68$ (Coleman et al. 2007; Martin et al. 2009). The elongated stellar distribution must be treated suspiciously as N-body simulations by Muñoz et al. (2008) tell us that when interacting with their host galaxy, satellite galaxies generally maintain their spherical shape but satellites that are close to complete disruption, with only a small fraction (∼5%) of their initial mass still bound, can exhibit strongly flattened isophotes. From improved stellar kinematics Adén et al. (2009) estimated the current mass of Hercules at $M_{300} = 1.9 \times 10^6\,M_\odot$ and, based on the assumption that Hercules is tidally disturbed in its outer parts, Martin et al. (2010) determined the orbital properties of the Hercules stream. A second example of a system that appears to be in a transitional state between being a bound dwarf galaxy and a completely unbound tidal stream like Hercules is Bootes III (Carlin et al. 2009).

4 Stellar Populations

It is well established that the star formation history of dwarf spheroidals varies widely in the Local Group (Grebe 1997; Mateo 1998; Grebel 2000; Hernandez et al. 2000; Grebel 2001; Tolstoy et al. 2009; Weisz et al. 2011); some of the dSphs contain dominant intermediate age populations like Carina (Hurley-Keller et al. 1998) or even show signs of recent star formation (e.g. Leo I, Gallart et al. 1999) but they all have an old-age stellar component in common, comparable to that of Galactic globular clusters. For the dwarf satellites with distinct subpopulations, there is evidence that the younger and metal-rich component is more centrally concentrated than its old and metal-poor counterpart (Harbeck et al. 2001; Tolstoy et al. 2004; Ibata et al. 2006). Such population gradients are thought to be the consequence of deeper gravitational potential wells present in higher luminosity systems. More luminous dSphs can retain their gas for longer times, thus undergoing prolonged chemical enrichment in the galaxy centre (Dekel & Silk 1986). Extrapolating this picture into the regime of low-mass ultra-faint galaxies where stars are orbiting in rather

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dynamically gentle potentials one would expect the underlying stellar populations to be globular cluster–like (>10 Gyr old). This view of the entire population being old and metal-poor, with no evidence of more than one burst of star formation, has already been reached from the study of SDSS-based CMDs of newly discovered MW satellites (de Jong et al. 2008) and finds further support from the analysis of deeper CMDs where they become available (e.g. Hughes et al. 2008; Walsh et al. 2008). The only exception appears to be Canes Venatici I at a distance of 210 kpc. It also harbours a small (3–5%) much younger (1–2 Gyr) subpopulation (Kuehn et al. 2008; Martin et al. 2008a). Canes Venatici I, however, is not an ultra-faint dwarf galaxy but belongs to the brighter Milky Way satellites comparable in luminosity ($M_V = -8.6 \pm 0.2$) to the two classical dSphs Draco ($M_V = -8.8 \pm 0.2$) and Ursa Minor ($M_V = -8.9 \pm 0.2$). When the three star formation histories are compared, Draco is showing evidence for an intermediate-age stellar population (Aparicio et al. 2001) while Ursa Minor currently hosts the only pure old stellar population of all MW dwarf spheroidals (Carrera et al. 2002). These results are suggesting that the stellar mass of a few times $10^5\,M_\odot$ marks some kind of transition zone below which galaxies have only single age, old and metal-poor stellar populations.

Another rapidly growing research area involving stellar populations of ultra-faint dwarf satellites concerns the mean elemental abundance, the metallicity range within individual galaxies, and the extent of element-to-element abundance ratio difference exhibited by the ultra-faint dwarf satellite member stars. It has been known for some time that the more luminous dwarf spheroidal galaxies around the Milky Way, M31 (Grebel et al. 2003), and in other nearby groups (Lianou et al. 2010) follow a tight relationship between the luminosity of the system and the mean metallicity $\langle$[Fe/H]$\rangle$ of the member stars (see Table 1): the more luminous a satellite the higher its mean metallicity with values in the range -2 dex $<$ $\langle$[Fe/H]$\rangle$ < -1 dex. Recent work by Simon & Geha (2007) and Kirby et al. (2008, 2011) has shown that this trend continues without change into the regime of the ultra-faint dwarfs where mean metallicities are measured as low as -2.6 dex (Coma Berenices and Bootes I). The existence of this relation is usually interpreted as indicating that the degree of chemical element enrichment is controlled by the rate at which gas is lost from the galaxy, which in turn is governed by the depth of the potential well where the gas and stars reside (Dekel & Silk 1986; Dekel & Woo 2003; Woo et al. 2008). An interpretation of this kind, however, would become less straightforward if all dwarf satellites are embedded in dark matter halos of similar mass.

An intriguing question that follows from the relationship is why there apparently are no ultra-faint dwarf satellites with higher mean abundances. Cosmological models predict that in the formation of the Milky Way's halo a substantial number of satellites are tidally disrupted and their stars merged into the general field. The ongoing tidal disruption of the Sagittarius dwarf (Ibata et al. 1994, 2001; Martínez-Delgado et al. 2001; Majewski et al. 2003) is the most prominent current-day example of this process that seems to be a common phenomenon around nearby galaxies (e.g Malin & Hadley 1997; Martínez-Delgado et al. 2009). The inexistence of ultra-faint dwarfs with relatively high mean abundances suggests that the tidal disruption process must be quite efficient, with remnants whose mean abundance would reflect the original brighter luminosity being rare objects. Clearly populating the low stellar mass regime in the metallicity–luminosity parameter space with 10–20 more ultra-faint dwarf galaxies, which will be a direct outcome of the next generation of wide-field optical surveys (see next section), will allow this hypothesis to be investigated in greater detail.

Equally significant is the recognition by Norris et al. (2008) and Koch et al. (2008) studying Bootes I and Hercules, respectively, that given the low stellar masses and the low mean abundances, the chemical evolution of the ultra-faint dwarf satellites proceeds stochastically and inhomogeneously because only a relatively small number of supernovae is required to enrich the primordial gas to the observed abundance levels. Hence, it is likely we will see star-to-star differences in element abundance ratios that tag individual supernovae events. This scenario is also supported by the results on Bootes I by Feltzing et al. (2009). However, results from such high resolution spectroscopy of stars in ultra-faint dwarfs are still spares to date owing to the difficulty of identifying the brighter member stars in the CMD against the Galactic foreground and the fact that many of the ultra-faint dwarf galaxies with estimated total luminosities less than a single RGB star do not provide an environment where many stars brighter than the main sequence turnoff are formed. Nevertheless, the current results have already revealed the presence of small numbers of stars in ultra-faint dwarfs with abundance ratios that deviate strongly from those exhibited by the majority of stars in the oldest stellar populations of the Milky Way.

The more luminous dwarf spheroidal satellites, at least the ones that have survived to the present day, seem to have no strong connection to the Milky Way halo. They appear to lack very metal-poor stars when compared to the halo field stellar population (Helmi et al. 2006) but see also Starkenburg et al. (2010) and Frebel et al. (2010a) for a revised picture of Sculptor. These chemical differences, however, are not as marked for stars in ultra-faint dwarfs. For example, Norris et al. (2010a) have analyzed a high dispersion spectrum of an extreme metal-poor ([Fe/H] = -3.7) red giant star in Bootes I. They find ratios relative to iron for 14 elements that are very similar to those for Milky Way halo field stars of similar iron abundance. Identical conclusions are reached by Frebel et al. (2010b) reporting extreme metal-poor stars in Ursa Major II and Coma Berenices. Norris et al. (2010a) also reported an extremely metal-poor, extremely carbon-rich star ([Fe/H] = -3.5, [C/Fe] = 2.3) in Segue 1, similar to the

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very rare class of CEMP-no halo stars in the Milky Way. The emerging picture is consistent with other recent suggestions that the most metal-poor dwarf spheroidal and ultra-faint dwarf satellites could be the building blocks of the Galaxy's outer halo. More high-resolution, high signal-to-noise, spectroscopic observations of stars in ultra-faint dwarf galaxies will help to better understand the role of ultra-faint dwarf satellites in the formation of the Milky Way and whether the majority of extreme metal-poor stars in the MW halo were indeed once born in satellite galaxies.

5 Search for Ultra-faints in the Southern Hemisphere

The Sloan Digital Sky Survey (York et al. 2000) has been vitally important for the detection of new Milky Way satellite galaxies (Willman et al. 2005a,b; Belokurov et al. 2006a,b, 2007b, 2009, 2010; Sakamoto & Hasegawa 2006; Zucker et al. 2006b; Walsh et al. 2007; Liu et al. 2008; Grillmair 2009) leading to rapid advances in finding the least luminous, most dark matter dominated galaxies in the Milky Way halo. Observers can now provide detailed selection criteria (e.g. Koposov et al. 2008; Walsh et al. 2009) for modellers while simulations of the gas accretion and star formation processes in low mass dark halos are becoming increasingly sophisticated, allowing for more accurate predictions of the number of visible MW satellites (e.g. Li et al. 2010; Font et al. 2011). However, all these results are drawn from only a relatively small area of sky. In particular, statistical quantities such as the galaxy luminosity and mass functions, the Galactocentric distance distribution, and the total number of satellites are still poorly constrained because they depend sensitively on the properties of the few available least luminous dwarfs (Koposov et al. 2008; Tollerud et al. 2008).

At present some of the most interesting questions that are emerging from recent work cannot be fully addressed. Firstly, the region of the sky surveyed by SDSS is known not to contain any additional ultra-faint MW satellites to well established limits (e.g. Koposov et al. 2008; Walsh et al. 2009). The detected high signal-to-noise satellites candidates have been carefully investigated and the remaining candidates, less prominent in terms of their angular size and central star density (see figure 5 in Walsh et al. 2009) for which follow-up observations are available, have been shown to be either stellar condensations in the diffuse components of streams (Jerjen et al. 2011) or spurious detections (Willman et al. 2011, in preparation). Secondly, not all stellar overdensities turn out to be galaxies: the true nature of the recently reported low luminosity Segue 3 (Belokurov et al. 2010) at 17 kpc was revealed in a deep imaging and spectroscopic follow-up study to be an old, metal-poor star cluster with no evidence of dark matter (Fadely et al. 2011).

The most promising next steps forward in the field thus are deeper optical/near-IR surveys and surveys that scrutinise other parts of the sky, particularly the Southern hemisphere where SDSS statistics predict 20–30 hidden Milky Way satellite galaxies. Given these (and many other) research opportunities it is not surprising that almost every major observatory worldwide is in the process of developing and commissioning survey telescopes, e.g. Pan-STARRS, ESO-VISTA, ESO-VST, and on an even larger scale the Large Synoptic Survey Telescope. The future 8 m Large Synoptic Survey Telescope scheduled for operations in 2020 will be able to detect ultra-faints like Segue 1, Willman 1 and Bootes II out to the Milky Way virial radius of 250 kpc, thereby reducing the luminosity-distance bias in the current set of known satellites due to limited photometric depth (see Table 1).

The 1.35 m SkyMapper telescope[1] of the Australian National University is among the first of this new breed of specialised telescopes which are capable of scanning the sky more quickly and sensitively than ever before using a state-of-the-art 16k × 16k CCD mosaic camera with a 5.7-sq degree field of view (Figure 2). SkyMapper, currently being commissioned at Siding Spring Observatory, is dedicated to carry out the six-colour multi-epoch Southern Sky Survey over the next five years, which will generate a photometric catalogue with positions and absolute brightnesses for approximately one billion stars and galaxies down to $g = 22.9$ mag (S/N = 5, AB magnitude) across the entire Southern hemisphere. The employed filter set consists of u, g, r, i, z utilized by SDSS, complemented by a narrow-band v filter similar to DDO38, that is 320 nm wide and covers 367 to 398 nm (Bessell et al. 2011). A comprehensive technical overview of the telescope and the camera, a description of the survey strategy and the data acquisition and reduction pipeline can be found in Keller et al. (2007).

The object catalogue from the Southern Sky Survey is expected to have photometric limits that are 0.5–0.9 mag fainter than SDSS and will be analysed as part of the Stromlo Milky Way Satellite (SMS)[2] Survey, the first CCD-based search for optically elusive Milky Way satellite galaxies in the Southern hemisphere. The SMS collaboration aims at contributing to a number of scientific challenges that have emerged from recent work including the following:

1. Constructing the spatial distribution map of the ultra-faint Milky Way dwarf satellites in the Southern hemisphere to a completeness limit comparable to SDSS, and the provision of a catalogue with their fundamental parameters including coordinates, distances, luminosities, and structural parameters. Such a database allows a statistical comparison with other Galactic halo objects like globular clusters.
2. Measuring the luminosity function of the ultra-faint satellite galaxies, paying special attention to detection

[1] http://www.mso.anu.edu.au/skymapper/index.php
[2] http://msowww.anu.edu.au/~jerjen/SMS_Survey.html

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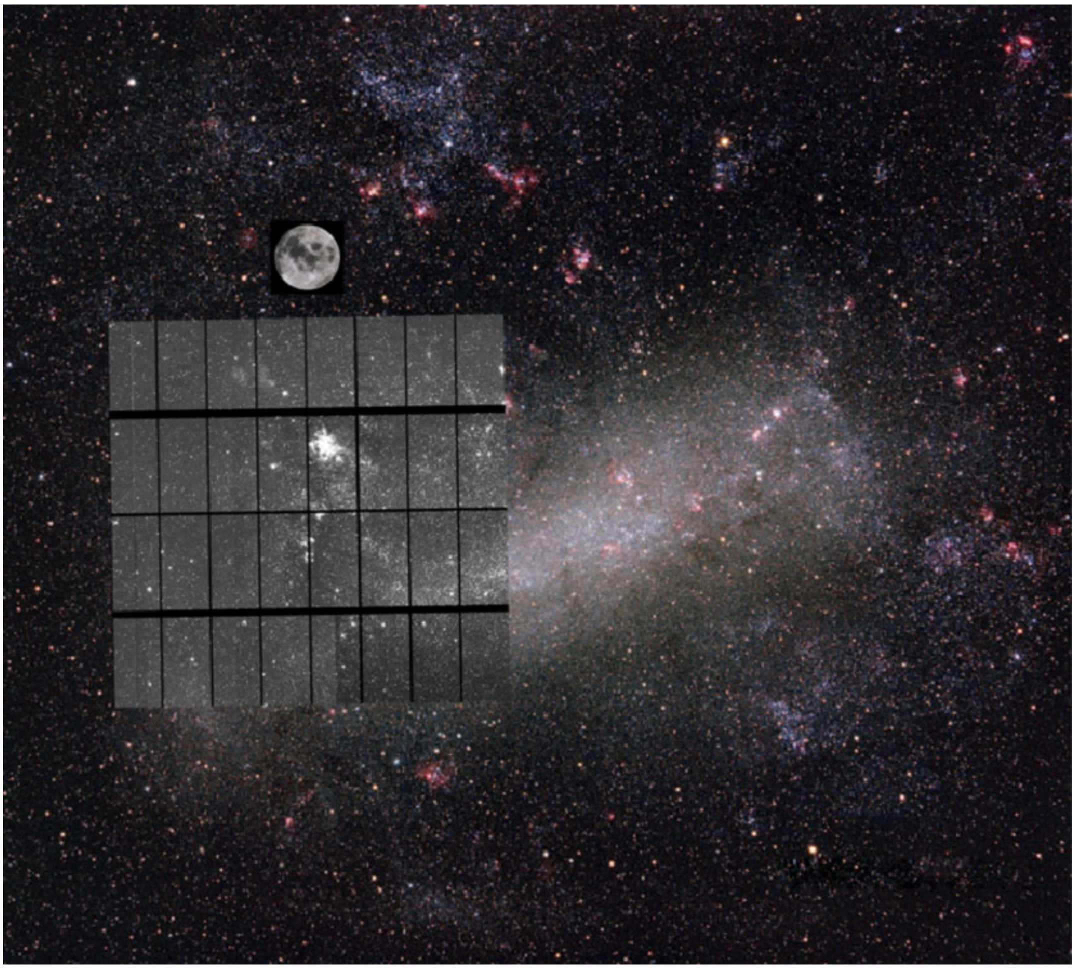

Figure 2 Image taken of the outskirts of the Large Magellanic Cloud shows the footprint of the 16k × 16k CCD mosaic SkyMapper camera with its 5.7-sq degree field of view. A picture of the Moon is also presented at the same scale (credit: Stefan Keller and the SkyMapper team — background image: David Malin, AAO).

efficiency, and extending our knowledge of the galaxy luminosity function from the classical dwarf spheroidals into the regime of completely dark matter dominated galaxies. The shape of the luminosity function provides a strong constraint on the minimum dark matter mass in which gas can cool and form stars.

3. Investigating the 2D-morphology of the ultra-faint galaxies to determine whether the star density profiles follow predictions from the virial theorem or show extra-tidal stars which would suggest they are non-virialised systems or in the stage of tidal destruction.
4. Defining homogeneous samples of ultra-faint galaxies and other large-scale halo structures that will give a snapshot of the dynamical evolution of these objects. Mapping the dwarf galaxy infall patterns around the Milk Way will also yield estimates of the Milky Way's dark matter halo shape and will critically test the statistical robustness of the Disk of Satellites phenomenon.
5. Reconstructing the velocity profile of selected southern hemisphere Milky Way satellites from medium resolution multi-object spectroscopy to infer the dark matter halo mass distribution, to test the 'constant dark matter mass' hypothesis, and to estimate the significance of dark matter in the structure, formation and evolution of the Milky Way.
6. Estimating the mean age and metallicity distribution of the ultra-faint dwarfs in order to reveal how gas infall and outflow affected their star formation histories. Probing the luminosity-metallicity and other scaling relations in the $\log(L/L_\odot) < 5$ regime. Such information will constrain models of galaxy formation and evolution.
7. Determining the star-to-star abundance spread and obtaining detailed element ratio distributions in the least luminous Milky Way satellites to understand their chemical evolution, and to investigate possible links to the formation of the Milky Way via searches for the most extreme metal-poor member stars.
8. Providing a reference database for use in conjunction with other surveys. Other veins of information can be tapped by correlating the detected satellite galaxies with sources found at other wavelengths (gamma-ray, infrared, radio) by existing or planned surveys (e.g. ESO-VHS, ASKAP, GAIA).

The SMS program starts with a strong computational component where detections of dwarf galaxy candidates are coming directly from the data-mining of the Southern Sky Survey catalogue. It continues with two comprehensive imaging and spectroscopy follow-up programs that are critical to reach the above mentioned goals.

(a) Detection of galaxy candidates Searching for new satellite candidates is a computer intensive process. A satellite dwarf galaxy will reveal its presence through an unusual concentration of faint stars in the sky, projected against the Milky Way foreground screen. These typically old, metal-poor stars (see Table 1) will populate well-defined areas in the colour-colour [e.g. $(g-r)$ vs. $(r-i)$] and the colour–magnitude diagrams. The Southern Sky Survey catalogue will contain positions and photometry for approximately one billion stars but only about 0.01 percent will be from a satellite galaxy, assuming 20 new detections with a mean stellar content of $N_* = 80{,}000$ ($M_V \approx -5$) and a typical star detection rate of 5%. The strategy and efficiency of our detection algorithm has been discussed in Walsh et al. (2009). It is built upon the method of Willman et al. (2002) and Willman (2003) which utilised the photometric catalogs from SDSS and led to the discoveries of Willman 1 (Willman et al. 2005a), Ursa Major (Willman et al. 2005b), and Bootes II (Walsh et al. 2007b). The concept is also similar to the approaches taken by Belokurov et al. (2007) and Koposov et al. (2008). To enhance the satellite-to-foreground contrast an automated pre-selection of stars in the colour-magnitude parameter space is conducted employing sets of theoretical isochrones for old stellar populations. This process is repeated to scan through the different heliocentric distance shells. Regions that exhibit a significantly higher level of stellar densities when compared to their surrounding control fields are locations of potential galaxy candidates.

(b) Imaging Follow-up To gather more information on the true nature of the detected stellar overdensity (satellite galaxy, star cluster, hotspot in stellar stream, or false positive detection), a 1-2 mag deeper CMD of the extended region is required. For a dwarf satellite candidate at a distance of 150 kpc, we need to reach g and r-band magnitudes of ≈ 25 at a signal-to-noise of 10 for an unambiguous confirmation and a more detailed population analysis (e.g Belokurov et al. 2007b). Such a photometric depth can be achieved in a reasonable amount of time with the IMACS at the Magellan telescope or Suprime-Cam at Subaru. Less distant ultra-faint candidates such as Segue 1 ($m-M = -16.8$, $M_V = -1.5$) can be imaged with wide-field cameras at smaller telescopes, e.g. the MPG/ESO 2.2 m telescope. The follow-up imaging observations are an essential part of the SMS program and will be on-going for the duration of the project.

(c) Spectroscopic Follow-up After a satellite galaxy or star cluster is confirmed via imaging follow-up, we will observe stars in the object and its surrounding field to the faintest possible limit with multi-object spectrographs at the AAT (AAOmega and HERMES) and the 6.5 m Magellan telescope (MMFS and M2FS). The feasibility of using the AAT/AAOmega in this role has been demonstrated with the observations of Bootes I by Norris et al. (2008). With velocities accurate to 2-3 km s^{-1} the central velocity dispersion and dispersion profile of the object can be determined as well as its mass and dark matter content estimated. While photometric quantities such as half-light radius and total luminosity can help to discriminate between an ultra-faint satellite galaxy and a star cluster, additional information on the presence or absence of dark matter is crucial for a final assessment. The painstaking work required as part of such an analysis is exemplified by Fadely et al. (2011). The brighter confirmed stars in the satellite galaxies can then be targeted at much higher spectroscopic resolution using for example the UVES spectrograph at the VLT. These data will enable a comparative study of the chemical signature of stars in dwarf satellites and Milky Way halo.

After some technical delays the commissioning of the SkyMapper telescope is now underway. Updates of the Stromlo Milky Way Satellite Survey program are posted on the webpage.[3]

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[3] http://msowww.anu.edu.au/~jerjen/SMS_Survey.html

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