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Review Article

In Pursuit of the Least Luminous Galaxies

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The dwarf galaxy companions to the Milky Way are unique cosmological laboratories. With luminosities as low as $10^{-7}L_{\mathrm{MW}}$, they inhabit the lowest mass dark matter halos known to host stars and are presently the most direct tracers of the distribution, mass spectrum, and clustering scale of dark matter. Their resolved stellar populations also facilitate detailed studies of their history and mass content. To fully exploit this potential requires a well-defined census of virtually invisible galaxies to the faintest possible limits and to the largest possible distances. I review the past and present impacts of survey astronomy on the census of Milky Way dwarf galaxy companions and discuss the future of finding ultra-faint dwarf galaxies around the Milky Way and beyond in wide-field survey data.

1. Introduction

The least luminous known galaxies have historically been those closest to the Milky Way. Whether visually or with automated searches, resolved stars reveal the presence of nearby dwarf galaxies with surface brightnesses too low to be discovered by diffuse light alone. Even until recently, nearly all cataloged dwarfs fainter than $M_V = -11$ resided within the Local Group of galaxies (LG) [1]. In 1999 the LG contained 36 known members, of which eleven are Milky Way (MW) satellites [2]. Four of these eleven MW dwarf galaxies are less luminous than $M_V = -10$, more than 10 000 times less luminous than the Milky Way itself. Although such low luminosity dwarfs almost certainly contribute a cosmologically insignificant amount to the luminosity budget of the Universe, all eight of the Milky Way's classical dwarf spheroidal companions ($-9 > M_v > -13$, not including Sagittarius or the Magellanic Clouds) have been studied in extensive detail. ("Classical" will be used in the paper to refer to the Milky Way dwarf companions known prior to 2003.) There is now a new class of "ultra-faint" dwarf companions to the Milky Way known to have absolute magnitudes as low as $M_V \sim -2$ ([3], see Section 3). The resolved stellar populations of these near-field cosmological laboratories have been used to derive their star formation and chemical evolution histories [4] and to model their dark mass content in detail (see article by Strigari in this volume and references therein). These complete histories of individual systems complement studies that rely on high redshift observations to stitch together an average view of the Universe's evolution with time.

The need for an automated, "systematic, statistically complete, and homogeneous search" for LG dwarf galaxies has been known for some time [5]. A combination of theoretical results and the advent of digital sky surveys have initiated a renaissance in the pursuit of a well-measured sample of the least luminous galaxies. This renaissance began in 1999, when simulations were used to highlight the discrepancy between the number of dark matter halos predicted to orbit the MW and the eleven observed to be lit up by dwarf galaxies orbiting the MW [6, 7]. As the resolution of simulations has increased over the last ten years, so has the magnitude of this apparent discrepancy. The most recent simulations predict tens ($\mathrm{M_{halo}} > 10^6 M_\odot$, [8]) or even hundreds of thousands ($\mathrm{M_{halo}} > 10^5 M_\odot$, [9]) of dark matter halos around the Milky Way. In light of this "missing satellite problem", great attention has been paid to the total number of Milky Way dwarf galaxies. However, this is only one metric with which to learn about the properties of dark matter. The intrinsically faintest dwarfs (which can only be found and studied close to the Milky Way) likely inhabit the least massive dark matter halos that can host stars. Such dwarfs may thus provide

the most direct measurement of the mass spectrum, spatial distribution, and clustering scale of dark matter.

What was initially viewed as a problem now provides an opportunity to simultaneously learn about dark matter and galaxy formation physics. Many studies have invoked simple models of galaxy formation within low-mass dark matter halos to successfully resolve the apparent satellite discrepancy within the context of ΛCDM (e.g., [10–13]). See the review article in this volume on "Dark matter substructure and dwarf galactic satellites" by A. Kravtsov for more details on the original missing satellite problem and on resolutions to this problem based on models of star formation in low-mass halos.

To untangle the extent to which dark matter physics, galaxy formation physics, and incompleteness in the census of dwarf galaxies contribute to this missing satellite "opportunity" requires a *well-defined* dwarf galaxy census that is as *uniform* as possible to the *faintest limits*. For example– *Well defined:* to compare observations of the MW dwarf population with models requires a detailed, quantitative description of the current census. Quantitative assessments of the detectability of MW dwarfs in recent survey data, plus an assumed spatial distribution of dwarfs, enabled extrapolation of the known population to predict a total number of ∼100–500 dwarf satellites [14, 15]. *Uniform:* because the very least luminous MW dwarfs ($M_V \sim -2$) can currently only be found within 50 kpc, it is presently unclear whether dwarfs can form with such intrinsically low luminosities, or whether the tidal field of the Milky Way has removed stars from these nearby objects. The epoch of reionization and its effect on the formation of stars in low-mass dark matter halos also leaves an imprint on both the spatial distribution [16, 17] and mass function of MW satellites [13, 18]. Other studies have claimed that the spatial distribution of MW satellites is inconsistent with that expected in a Cold Dark Matter-dominated model [19, 20]. Robust tests of these models are not possible without improving the uniformity of the MW census with direction and with distance. *Faintest limits:* reaching the low luminosity limit of galaxy formation is necessary to probe the smallest possible scales of dark matter, the scales on which the model faces the greatest challenges. Moreover, a census to faint limits over a large fraction of the MW's virial volume may yield enough dwarfs to rule out dark matter models with reduced power on small scales, although numerical effects presently inhibit concrete predictions of such models [21].

The specific observational requirements to fully exploit the population of MW dwarfs (and beyond) to effectively test dark matter theories and/or to learn about galaxy formation therefore include the following:

(i) a census of dwarfs (we apply the term "dwarf" only to stellar systems that, through direct or indirect evidence, are known to be dark matter dominated either now or at any point in the past) that is minimally biased with respect to Galactic latitude, distance (at least out to the virial radius of the Milky Way), star formation history, and structural parameters,

(ii) a statistically significant sample of lowest luminosity dwarfs,

(iii) a sample of the least luminous dwarfs in a range of environments.

This article focuses on the roles of wide-field, optical imaging surveys of the past, present, and future in the pursuit of a minimally biased census of the least luminous galaxies. In particular, it focuses on automated analyses of resolved star counts as a method to reveal these systems. Since the visual searches of the 20th century, new digital sky survey data have substantially progressed the completeness and uniformity of the MW satellite census. Although this progress has already revolutionized the landscape of dwarf galaxy cosmology, it has also revealed great incompleteness in our knowledge of the least luminous galaxies. Imminent and future surveys such as the Southern Sky Survey [22], PanSTARRS 1 (http://pan-starrs.ifa.hawaii.edu/public/) the Dark Energy Survey [23], and the Large Synoptic Survey Telescope [24] are poised to ultimately achieve the observational requirements needed for MW dwarf galaxy cosmology.

2. Discovering Milky Way Dwarf Galaxies, Pre-SDSS

All Milky Way dwarf galaxies known prior to 1990 were discovered in visual inspections of photographic survey data. Sculptor ($M_V = -11.1$) and Fornax ($M_V = -13.1$) were discovered in 1938 by Shapley [25, 26] in images obtained with a 24-inch telescope at Harvard's Boyden Station. Leo I ($M_V = -11.9$), Leo II ($M_V = -10.1$), Ursa Minor ($M_V = -8.9$), and Draco ($M_V = -9.4$) were discovered in the 1950's in the images obtained with a 48-inch Schmidt telescope as part of the original Palomar Observatory Sky Survey (POSS) [27, 28]. The last Milky Way companion discovered by an eyeball search was Carina (1977, $M_V = -9.4$), found on photographic plates obtained in the Southern hemisphere counterpart to the Palmar Observatory surveys—the ESO/SRC Southern Sky Survey [29]. Magnitudes listed above are from [30], except for Sculptor [1].

At the time of Carina's discovery, it was hypothesized that "The only possibility for detecting new systems of this type would seem to be in regions of relatively high foreground stars density and will probably require careful scanning under low-power magnification or detailed star counts" [29]. This hypothesis was validated by the discovery of Sextans in 1990 ($M_V = -9.5$) [31] as an overdensity of star counts from automated plate machine (APM) scans of the same POSS and ESO/SRC survey data that had been carefully inspected decades earlier. Sextans was discovered as part of the first large-scale, automated search for Milky Way companions [32]. The serendipitous discovery of the eleventh Milky Way companion, Sagittarius, in 1994 [33] as a moving group of stars was the final Milky Way dwarf discovered in the photographic survey data of the 20th century.

Since the discoveries of the eleven classical Milky Way dwarf satellites, Kleyna et al. [34] and Whiting et al. [35] conducted systematic searches of the COSMOS/UKST survey of the southern sky and the POSS-II and ESO/SRC survey data, respectively. Whiting's eyeball, all-sky search resulted in the discoveries of the Local Group dwarfs Antlia ($M_V = -11.2$) and Cetus ($M_V = -11.3$), but not new Milky Way satellites. The closest predecessor to the modern searches described in Section 3, Kleyna et al. searched for overdensities of resolved stars in spatially smoothed, pixellated maps of star counts. Although their survey revealed no new dwarf galaxies, they performed the first detailed characterization of the Milky Way dwarf satellite census. The detection limits of these searches are discussed in Section 4.

3. Mining for the Lowest Luminosity Dwarfs in the SDSS Era

Although the searches for dwarfs in the survey data available in the 20th century were impressively successful, empirical evidence suggested that the census of Milky Way dwarf galaxies may not yet be complete [2, 16]. Since then, the Sloan Digital Sky Survey (SDSS, [36]) revolutionized the field of dwarf galaxy cosmology with the discoveries of 14 MW dwarfs (and possible dwarfs) as overdensities of resolved stars: 2005—Ursa Major [37] and Willman 1 (originally known as SDSSJ1049+5103, [38]); 2006—Boötes I [39], Ursa Major II [40], Canes Venatici I [41]; 2007—Segue 1, Coma Berenices, Leo IV, Canes Venatici II, Hercules (all announced in [42]), Leo T [43], Boötes II [44]; 2008—Leo V [45]; 2009—Segue 2 [46]. Follow-up observations confirmed most of these to be the most dark matter dominated (central M/L up to 1000 [3, 13]), least luminous ($-1.5 > M_V > -8.6$ [47]), and among the least chemically evolved galaxies known in the Universe [48, 49]. Among these 14, Willman 1, Segue 2, and Boötes II have not yet been shown to be dwarf galaxies rather than star clusters or unbound remnants thereof. The ultra-faint dwarfs are also predicted to be the most detectable sources of gamma-rays from dark matter annihilation [50, 51]. In parallel with these Milky Way discoveries, 11 new M31 satellite galaxies have been discovered, primarily in large INT and CFHT surveys of M31 (And IX - And XX, $-6.3 > M_v > -9$ [52–58]).

The accomplishments of the SDSS dataset seem particularly remarkable given that the data were obtained with 1-minute exposures taken on a 2.5 m telescope, with a resulting r-magnitude limit of 22.2. In general, pushing the census of resolved dwarf galaxies to lower luminosities and greater distances can be accomplished by (1) obtaining photometry of stars to fainter apparent magnitudes, (2) more efficiently suppressing the noise from point sources contaminating the signal from stars belonging to a dwarf galaxy, and/or (3) reducing spurious detections, the primary source of which had been cluster galaxies misclassified as point sources [32, 34]. The features of the SDSS that facilitated (2) and (3) were its multiband photometry and accurate star-galaxy separation. The digital camera and uniformity of the survey also played key roles in its richness as a hunting ground for dwarfs.

With a median luminosity of $M_V \sim -5$ ($10^4 L_\odot$), the ultra-faints are up to ten million times less luminous than the Milky Way. All but Willman 1 and Leo T of the new Milky Way satellites are invisible in the SDSS images, even in hindsight. How was the presence of these invisible galaxies revealed? The seventh data release of SDSS, DR 7 [59], includes 11 663 deg^2 of imaging and over 100 million cataloged stars. The searches that resulted in the discoveries of the ultra-faint dwarfs were based only on analyses of these cataloged stars. The methods applied were all similar in spirit, starting with the search of Willman et al. [60]. The search technique summarized here is the specific method used in the most recent automated search, that of Walsh et al. (WWJ [61]).

(i) *Apply a Color-Magnitude Filter to Point Sources.* The primary source of noise in searches for dwarfs in SDSS-depth data is MW stars. Figure 1(b) shows that MW stars are smeared out in color and magnitude. The red plume contains thin disk main sequence stars, the bright blue plume contains thick disk main sequence turnoff (MSTO) stars, and the faint blue plume contains halo MSTO and MS stars. However, the stars belonging to a dwarf galaxy will occupy a well-defined region of color-magnitude space. All stars with colors and magnitudes inconsistent with a dwarf galaxy (at a particular distance) can thus be filtered out. WWJ used Girardi isochrones to define a color-magnitude (CM) filter for stars between 8 and 14 Gyr old and with $-1.5 < [\mathrm{Fe/H}] < -2.3$. This filter is shown Figure 1(a) for a dwarf galaxy with $d = 20$ kpc. Unlike the matched filter technique of [62], stars outside of the filter are simply removed from the analysis. No weighting is done, because the filter is not intended to exactly match stars from a specific stellar population. The CM filter was shifted to 16 values of m–M between 16.5 and 24.0 to search for dwarfs with $20 \lesssim d \lesssim 600$ kpc. Figure 1(a) shows that a 20 kpc color-magnitude filter contains substantial noise from both thick disk and halo stars. Figure 1(d) shows that a 100 kpc filter resides primarily between the two plumes and includes contamination from faint halo stars. The horizontal branch (HB) extension of this 100 kpc filter passes through MSTO halo stars, suggesting that this HB extension may include more noise than signal from the least luminous systems. Although the analysis of WWJ was automated and included no visual component, the result of this processing step is illustrated in Figures 2(a) and 2(b). The Ursa Major I ultra-faint dwarf ($M_V = -5.5$, $d = 100$ kpc) is not visible in the star count map on the left. After CM filtering, a slight overdensity of point sources becomes visible.

(ii) *Create Spatially Smoothed Image of Stellar Surface Density.* As originally done in searches for nearby dwarf galaxies performed in the 1990's [32, 34], the number density map of stars passing CM filtering is smoothed with a spatial kernel to enhance the signals from resolved objects with angular scale sizes expected for nearby dwarf galaxies. WWJ used only a 4.5′ scale length filter, while [14] applied filters of two different angular sizes. The result of this analysis step is illustrated Figure 2(c), which shows that Ursa Major I appears prominent in a spatially smoothed map of CM-filtered stars.

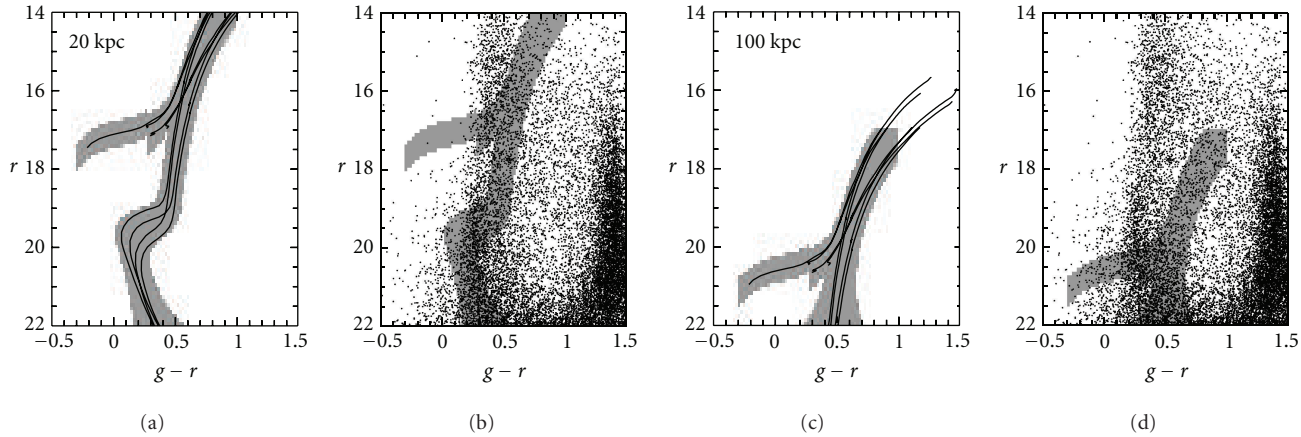

Figure 1: A color-magnitude (CM) filter used to suppress the noise from foreground stars while preserving the signal from dwarf galaxy stars at a specific distance. (a) and (c) CM filters for an old and metal-poor stellar population at a distance modulus of 16.5 and 20.0, respectively. The solid lines show Girardi isochrones for 8 and 14 Gyr populations with [Fe/H] = −1.5 and −2.3. (b) and (d) These CM filters overplotted on stars from a 1 deg^2 field to illustrate the character of the foreground contamination as a function of dwarf distance. Data are from SDSS DR7.

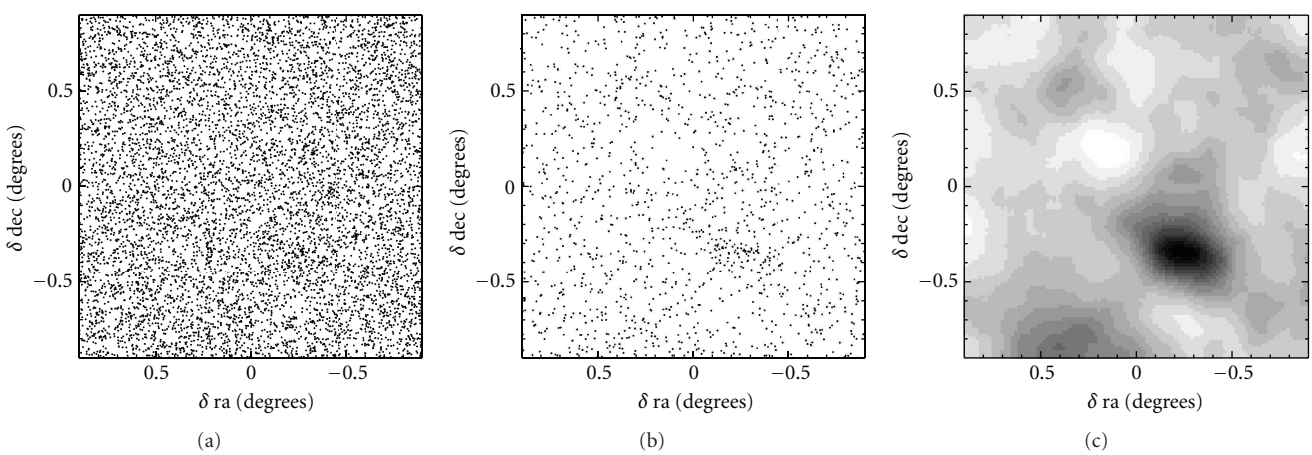

Figure 2: (a) Map of all stars in the field around the Ursa Major I dwarf satellite, $M_V = -5.5$, $d = 100$ kpc. (b) Map of stars passing the CM filter projected to $m - M = 20.0$ shown in Figure 1(c). (c) Spatially smoothed number density map of the stars in (b). The Ursa Major I dwarf galaxy has a $\mu_{V,0}$ of only 27.5 mag arcsec^2 [63]. Data are from SDSS DR7.

(iii) *Identify Statistically Significant Overdensities.* A search of 10 000 deg^2 of SDSS data, optimized for dwarfs at 16 different distances, and a single choice of stellar population and scale size require evaluating the statistical significance of 600 million data pixels that do not necessarily follow a Gaussian distribution of signal. Setting the detection threshold to select candidate dwarf galaxies was done by simulating numerous realizations of the search, assuming a random distribution of point sources and permitting only one completely spurious detection. The threshold is set to be a function of point source number density after CM filtering.

(iv) *Follow-up Candidates.* Regions detected above the detection threshold are considered candidates for MW dwarf galaxies. Although the threshold is set to prevent the detection of any stochastic fluctuations of a randomly distributed set of point sources [61], the detections are only "candidates" because resolved dwarf galaxies are not the only possible overdensities of point sources expected in the sky. For example, fluctuations in the abundant tidal debris in the Milky Way's halo or (un)bound star clusters could be detected. It is essential to obtain follow-up photometry to find the color-magnitude sequence of stars expected for a dwarf galaxy and also follow-up spectroscopy to measure the dark mass content (dark matter is required to be classified as a galaxy) based on the observed line-of-sight velocities.

This search algorithm is very efficient. In the WWJ search, the eleven strongest detections of sources unclassified prior to SDSS were 11 of the 14 (probable) ultra-faint Milky Way dwarfs. All of these but Boötes II were known prior to the WWJ search. See references in Section 3 for details of the follow-up observations that confirmed these objects to be dwarf galaxies. Follow-up observations of as-yet unclassified SDSS dwarf galaxy candidates are on-going by several groups, including a group at the IoA at

Cambridge (M. Walker, private communication) and at the MPIA (N. Martin, private communication). The *Stromlo Missing Satellites* team (PI H. Jerjen) is also now obtaining and analyzing observations of the ∼ two dozen candidates from the WWJ search of 9500 square degrees of SDSS DR6.

Because most probable candidates for dwarf galaxies have already been followed up, it is possible that SDSS I has already been completely mined for ultra-faint dwarfs. Nevertheless, it is essential to concretely classify all objects identified down to the detection threshold used to quantify the limits of a survey. If there are dwarf galaxies hiding in the low significance detections, then they must be included when interpreting the properties of the global population down to the observational limits. If there are no dwarf galaxies anywhere close to the detection thresholds, then there may not be many unseen dwarfs with luminosities (distances) slightly fainter than (a bit more distant than) those of similar dwarfs in the known population.

4. Current Limitations of the Census of Milky Way Dwarfs

As discussed in Section 1, a well-defined census of dwarfs is essential to use the MW dwarf galaxy population as a probe of dark matter and galaxy formation physics. Astronomers have used a variety of approaches to characterize the completeness of the Milky Way dwarf census for more than 50 years, beginning with Wilson [28] in 1955 who observed that "The uniform coverage of the sky provided by the (Palomar Observatory) Sky Survey allows an estimate to be made of the probable total number of Sculptor-type galaxies in the local group."

Until this day, little is known about the possible population of MW dwarfs at $|b| < 20°$ [32, 34], which includes 1/3 of the volume around our galaxy, owing to obscuration by the Galaxy's disk. A substantial fraction of the SDSS footprint is at $b > 30°$; so no progress has yet been made on this severe observational bias at optical wavelengths. Searches for satellites near the Galactic plane at radio and near-infrared wavelengths (2MASS) are less affected by disk obscuration than optical studies. Although two satellites have tentatively been discovered at these wavelengths (high-velocity cloud Complex H in HI survey data [64], Canis Major in 2MASS [65]), searches for MW dwarfs at nonoptical wavelengths have not yet been very fruitful or quantified in detail.

Likewise, the limitations of the Southern hemisphere dwarf galaxy census remain unchanged since the searches conducted with photographic plate data. Kleyna et al. [34] derived detailed detection limits for their search by inserting simulated galaxies with the physical scale size of Sculptor into the COSMOS survey data. They found that the Southern sky at $b < -15°$ was complete to dwarfs closer than 180 kpc and as faint as 1/8 $L_{\rm Sculptor}$, corresponding to $M_v = -8.8$. Whiting et al. also quantitatively characterized the completeness of their visual search for dwarfs in the Southern Sky and estimated a limiting surface brightness ($25 < \mu_{\rm lim} < 26$ mag arcsec^{-2}), with a 77% completeness of dwarfs above this surface brightness limit [35].

It is thus likely that no dwarf similar to any of the 14 ultra-faints discovered in SDSS I data could have been found outside of the SDSS footprint. Within the SDSS footprint, the most extensive calculation of the limitations of the ultra-faint dwarf census is that of WWJ. WWJ simulated the detectability of nearly 4 million artificial galaxies with a range of luminosity, scale size, distance, and Galactic latitude [61]. They estimate that the SDSS MW dwarf census is more than 99% complete within 300 kpc to dwarfs brighter than $M_V = -6.5$ with scale sizes up to 1 kpc. Although this is a tremendous improvement, only four of the 14 new MW satellites are brighter than this limit. d_{90}, the distance *at* which 90% of dwarfs with some set of properties can be detected, is independent of the distribution of objects. d_{90} is ∼35, 60, and 100 kpc for dwarfs with $M_V \sim -2, -3$, and -4 with scale sizes similar to those of the known ultra-faints at like absolute magnitude. (This is smaller than the distance *within* which 90% of dwarfs with some set of properties can be detected.) Larger scale length (lower surface brightness) systems are less detectable. For example, systems with $M_v = -2$ and a scale size of 100 pc or with $M_v = -4$ and a scale size of 500 pc would have been undetectable in SDSS. Koposov et al. [14] derived quantitative detection limits for their SDSS search for ultra-faint dwarfs and found similar results.

The luminosity bias still present in the MW dwarf census as a function of distance has several major implications. First, the unknown underlying radial distribution of MW dwarfs prevents assumption-free predictions of their total number or luminosity function. Second, assumption-free comparisons between the observed and predicted spatial distribution of MW dwarfs are still not possible. However, studies of the spatial distribution that only include the brighter MW dwarfs ($M_V < -5.5$) would provide initial insight into models. Finally, four of the MW ultra-faint companions (Willman 1, Boötes II, Segue 1 and 2) have $L < 10^3 L_\odot$ ($M_V \gtrsim -2.5$). At present, only ∼1/200 of the volume within the SDSS footprint has been mined for such ultra-faints. Are there pristine dwarfs in other environments with such low luminosities? Answering this question will be critical for determining whether they have extremely low luminosities because of nature (they formed that way) or nurture (e.g., the tidal field of the Milky Way removed previously bound stars). Preliminary morphological studies suggest that the properties of the nearest ultra-faints may have been affected by the MW's tidal field.

These limitations and achievements do not substantively vary across most of the SDSS footprint. ∼50% of the SDSS DR6 footprint resides at $b > 50°$ and only ∼10% at $b < 30°$. d_{90} is almost identical for dwarfs with $b = 53°$ and $b = 73°$ and is up to ∼25% less for $b \sim 30°$, depending on $M_{V,\rm dwarf}$. The relatively weak variation with latitude is owing to the CM filter (Figure 1) that does not include stars with $g - r > 1.0$, cutting the majority of thin disk stars from analysis. Although the spatial variation is weak *on average*, regions of lower Galactic latitude plus longitude or regions containing substantial Sagittarius stream debris do have a lower sensitivity for dwarfs. For searches extending to $b \lesssim 30°$, careful attention must be paid to the dependence of detectability on Galactic direction.

5. Mining for Ultra-Faint Dwarfs Post-SDSS

To move from the excitement of discovery to more concrete comparisons between observations and predictions will require progress on the observational limitations described in Section 4. Here we highlight several new and upcoming wide-field optical surveys that contain the qualities necessary to make this progress.

The Southern Sky Survey (SSS) [22] and PanSTARRs (PS1) are optical surveys of the entire Southern and Northern skies, respectively. The SSS is anticipated to begin survey operations at the end of 2009, and PS1 has already begun obtaining survey data. The SDSS filter set [66] plus a Strömgren u filter will be used for the SSS, while SDSS $griz$ plus a y filter at 1 micron is being used for PS1. These surveys are both conducted on small aperture telescopes (1.3 m for SSS, 1.8 m for PS1), with images of the sky obtained repeatedly over a period of about 5 years. The coadded point source catalogs anticipated from these surveys will be 0.5 (SSS) to 1 (PS1) magnitude deeper than the SDSS catalog.

Searches for resolved dwarf galaxies in the SSS will be led by H. Jerjen and the *Stromlo Missing Satellites* team and in PS1 will be lead by N. Martin at MPIA. Between the SSS and PS1, a full digital picture of the sky at optical wavelengths will be obtained, nearly 75% of it for the very first time. The region of sky at $b < -20^\circ$ to be observed by the SSS should contain many discoverable ultra-faint galaxies – perhaps a dozen by comparison with those already known in the North. These new surveys will also substantially progress our understanding of the distribution of dwarfs close to the disk. However, mining for dwarfs at low b will require careful adjustments to the search techniques applied to SDSS data owing to severe Galactic contamination and obscuration at low Galactic latitudes. For example, it has been common to use a $1^\circ \times 1^\circ$ running windows to measure the local density of the foreground [14, 61]. The steep spatial gradient in the number density of disk stars at low b will demand a more careful characterization of the average point source counts when searching for localized overdensities.

These imminent surveys will also reveal ultra-faint dwarfs throughout a greater fraction of the Milky Way's virial volume. A naive extrapolation from the detectability of dwarfs in the SDSS yields $d_{\mathrm{max,PS1}}/d_{\mathrm{max,SDSS}} = (f_{\mathrm{lim,PS1}}/f_{\mathrm{lim,SDSS}})^{0.5}$. In this approximation, analyzing the PS1 star catalog with methods analogous to those applied to SDSS data will reveal dwarfs (at $|b| > 20^\circ$) to distances ~1.6 times farther, which is a factor of 4 in volume. Despite this anticipated improvement, these surveys will not provide an unbiased measurement of the ultra-faint dwarf galaxy population all the way out to the virial radius of the Milky Way (~300 kpc).

Only a survey such as the planned Large Synoptic Survey Telescope (LSST (http://www.lsst.org/)) project, currently scheduled to begin survey operations in 2016, will potentially yield a measurement of the ultra-faint dwarf galaxy population that truly satisfies all of the observational requirements needed to fully exploit these objects for dark matter and galaxy formation science. LSST's primary mode will be the planned "deep-wide-fast" survey that will observe 20 000 deg^2 of sky at $\delta < 34^\circ$ roughly 1000 times over 6 bands (SDSS $ugriz$ plus y). Single 15-second exposures have an anticipated 5σ limit of $r = 24.5$, and the final 10-year co-added catalog has an anticipated limit of $r = 27.5$ [24].

Using the same naive extrapolation of the detectability of dwarfs in SDSS applied above to the PS1 survey, Tollerud et al. [15] showed that an SDSS-like analysis of a 10-year LSST-like catalog of stars would reveal $M_V = -2.0$ dwarfs to distances of at least 400 kpc. More luminous ultra-faints would be detectable throughout the entire Local Group, and even beyond, based on this sort of extrapolation. Such a calculation assumes that the number density of contaminating point sources passing color-magnitude filtering (such as shown in Figure 1) does not substantially vary with distance. However, the landscape of the point source population at magnitudes fainter than $r \sim 24$ does differ greatly from that in the SDSS-depth data shown in Figure 1.

Figure 1 showed that thick disk and halo main sequence and main sequence turnoff stars in the Milky Way were the primary noise in SDSS searches. At fainter apparent magnitudes, the number density of unresolved galaxies, galaxies at high redshift that cannot be distinguished from individual stars by morphology alone, rapidly increases. Figure 3 shows the $(V - I, V)$ color-magnitude diagram of galaxies in the 9 arcmin^2 Hubble Ultra Deep Field (HUDF) with an angular full-width half-max size smaller than $0.8''$, the expected average image quality of LSST. Overplotted in red are the stellar sources in the HUDF; they are outnumbered by galaxies by a factor of 75.

The CMDs in Figure 4 illustrate in more detail the point source contamination expected in deep searches for resolved ultra-faint dwarfs. Figure 4(a) displays a TRILEGAL (http://stev.oapd.inaf.it/cgi-bin/trilegal) [68] simulation of Milky Way stars in a one square deg field at $(l, b) = (45,40)$. Figure 4(b) displays a simulation of the galaxy population as it will be observed by LSST. The LSST image simulation project (led by A. Connolly at UW) was based on a mock catalog generated from the Millennium simulation [69]. The isochrone of an old and metal-poor stellar population overplotted on Figure 4(a) shows that red giant branch stars belonging to a system ~300 kpc away will be contaminated by MW halo dwarf and subdwarf stars (the plume at $g - r \sim 1.0$). In multicolor survey data of sufficient depth and photometric precision, colors can be used to select stars based on temperature, metallicity, and surface gravity [70]. For example, it has been shown that $g-r$ combined with $u-g$ separates metal-poor red giants at halo distances from red dwarf stars in the disk of the Milky Way, but only to $r \sim 17$ in SDSS-depth data [71]. SDSS was not deep enough in all filters to utilize photometric stellar classification to distances beyond 25 kpc. LSST will have small enough photometric errors to photometrically select red giant stars at outer halo distances. Therefore, color-color selection of red giant stars at outer halo distance may reveal both bound and unbound structure at MW halo distances to unprecedentedly low surface brightnesses.

The overploted isochrone on Figure 4(b) shows that the main sequence turnoff of stars in an old and metal-poor stellar population in the MW's outer halo will be

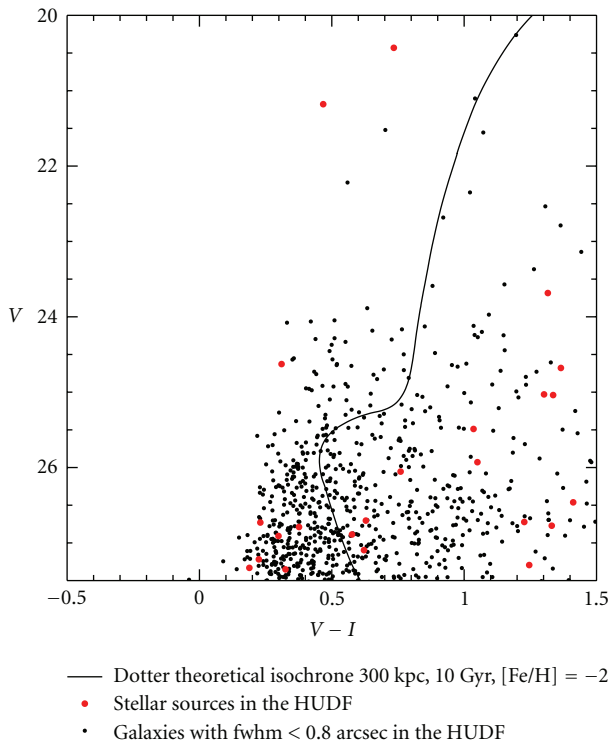

Figure 3: Color-magnitude diagram of galaxies with small angular sizes and stellar sources in the Hubble Ultra Deep Field [67]. Galaxies outnumber stellar objects by a factor of 75 in this figure, suggesting that unresolved galaxies will be the primary source of contamination in searches for ultra-faint dwarfs in deep survey data. Objects designated "stellar" in this image are those with *type* > 0.3 in the HUDF catalog.

severely contaminated by unresolved galaxies. The mock galaxy catalog predicts ∼700 000 galaxies per deg^2 with $r < 27.5$ and $g - r < 1.5$. By contrast, the Trilegal model predicts ∼35 000 stars per deg^2 with those same colors and magnitudes. Based on the HUDF catalog, roughly half of the galaxies at the faint magnitudes to be accessible by LSST have angular sizes smaller than the expected median image quality of 0.8″. Unresolved galaxies thus outnumber stars by a factor of 100 in observations down to $r = 27.5$ when only angular size is used to morphologically classify objects, consistent with the results obtained from the small HUDF field-of-view.

The very least luminous ($M_V \gtrsim -3$) systems can only be discovered by their MSTO and main sequence stars, because they have few, if any, red giant branch stars. The contamination by unresolved galaxies could therefore be catastrophic for discoveries of such systems at large distances, particularly because galaxies themselves are clustered and thus do not provide a smooth background that can easily be removed. However, a combination of careful morphological classification and color-color-magnitude filtering can be used to drastically reduce the noise from unresolved galaxies. In reality, star-galaxy separation is not performed by a simple measurement of angular size; the extended shapes of the light profiles of sources are often used to discriminate between stars and galaxies. For example, [72] describes a method to use the curve-of-growth of the light profile of individual objects to yield a morphological star-galaxy classification. This type of classification will still yield a star catalog that is dominated by faint galaxies. Galaxies also have colors that differ from those of stars. For example, color-color information has been used to distinguish Milky Way stars from unresolved galaxies at very faint magnitudes in the Deep Lens Survey, a deep, ground-based, survey in multiple optical filters [73].

An important consideration for dwarf searches in LSST-depth data is prospects for meaningful follow-up observations. Follow-up imaging to obtain deep CMDs has been needed to confirm many of the 14 known ultra-faint dwarfs. However, color-magnitude diagrams deeper than the expected LSST limiting r-magnitude of 27.5 could likely not be obtained from the ground. Space-based follow-up to confirm new dwarfs with JWST will probably also not be feasible, because the number of dwarfs may be in the hundreds (with a higher number of candidates) and because the fields-of-view of the cameras on JWST (∼2.2′ × 2.2′) are smaller than the angular sizes expected for all but the smallest scale size dwarfs. With a half-degree field-of-view, the camera on the Supernova Acceleration Probe (SNAP) could provide the imaging needed to confirm the presence of relatively distant dwarfs tentatively detected in LSST data. There are not currently plans for SNAP to be a pointed tool for such science. Therefore the number of resolved stars required for a certain ultra-faint detection in very deep survey data will necessarily be higher than in SDSS-depth data. The spectroscopic resources now being used to measure the masses of new ultra-faint objects (e.g., DEIMOS on Keck II, Hectochelle on the MMT) are also already being pushed to their limits with the dwarfs discovered in SDSS. Much fainter or more distant dwarfs could not be effectively studied with these resources but instead will require next generation 30 m class telescopes (such as a Giant Magellan Telescope or Thirty Meter Telescope) and/or instrumentation.

A final consideration for searches is based on resolved stars in an LSST-depth dataset—the possible crowding of stars belonging to more distant satellites. Although fewer stars are resolved in more distant galaxies, the apparent angular separation of resolved stars decreases with increasing distance. If the average star separation is small relative to the average full-width half-max of stars in the image, then an object may be confusion limited and its individual stars not identified in a standard photometric pipeline. Could ultra-faint dwarf galaxies become confusion limited before they are, in theory, too distant to detect as overdensities of resolved stars? Using the Dotter stellar luminosity functions (http://stellar.dartmouth.edu/) [74] and assuming a star catalog as deep as the LSST 10-year coadd, the average spacing between resolved stars in a 10 Gyr, [Fe/H] = −2.0 stellar population is roughly constant with distance for 100 kpc—$d_{\rm lim}$. $d_{\rm lim}$ is the optimistic limiting detection distance for dwarfs with $-2.5 > M_V > -7.5$. For ultra-faint Milky Way satellites with scales sizes ∼50% smaller (and thus smaller angular separation between stars) than those of ultra-faints

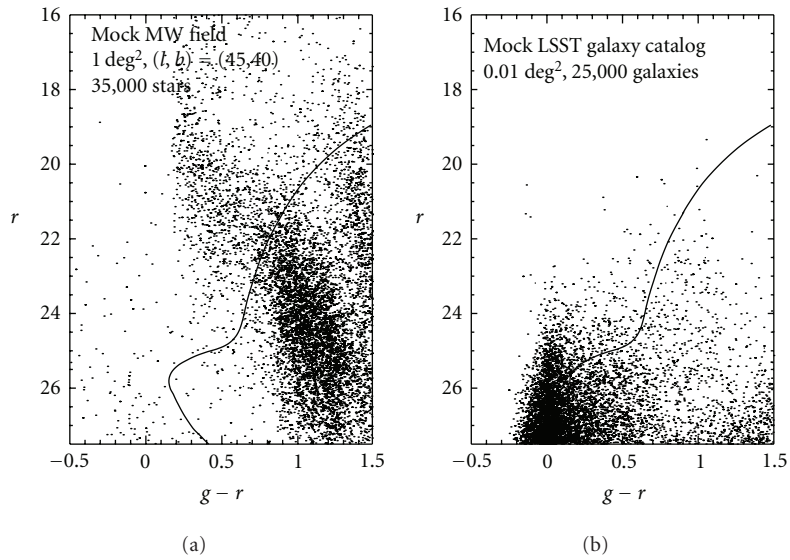

Figure 4: Simulated observations of Milky Way stars and galaxies in an LSST-like survey. (a) TRILEGAL simulated observation of Milky Way stars in a one deg^2 field at $(l, b) = (45,40)$. (b) Simulated observation of galaxies in a 0.01 deg^2 field based on [69] (A. Connolly, private communication). A Dotter isochrone for a 10 Gyr, [Fe/H] $= -2.0$ stellar population at a distance of 300 kpc ($m - M \sim 22$) is overplotted on both panels. For clarity, only 1/4 of sources in each panel are plotted. LSST-like photometric uncertainties have not been added to the simulated data.

with similar magnitudes, this average separation is expected to range between 1″ and 2″. Because this separation is larger than the average image quality expected for LSST and because LSST will likely reach its coadded depths by simultaneous photometering of numerous exposures, rather than photometering a single stacked image, crowding should not be a technical issue that will inhibit future dwarf searches.

6. Conclusion

The next 15 years will be an exciting time for near-field dwarf galaxy cosmology. A lot hinges on the new class of ultra-faint galaxies that was only discovered in the last 5 years but that may be the most numerous and cosmologically important class of galaxies. However, to effectively exploit these dwarfs as cosmological barometers will require improvements on many observational limitations. Several wide-field, optical surveys are planned that may finally reveal the true nature of the MW's satellite population and the true nature of ultra-faint dwarfs. Careful statistical analyses of star counts will continue to be a primary method to identify ultra-faints, which are known to have surface brightnesses as low as $\sim$27.5 mag arcsec^{-2}. Future surveys could possibly reveal such objects at Mpc and greater distances by their diffuse light, rather than just by individual stars. Planned and current surveys at infrared wavelengths will at minimum complement searches for dwarf galaxies done with optical datasets and will provide important support for dwarf searches near the Galactic plane. The upcoming Vista Hemisphere Survey (PI Richard McMahon) will image the entire Southern Sky in J and K_S 4 magnitudes deeper than 2MASS. UKIDSS is in the middle of survey operations and is obtaining 7000 deg^2 of IR imaging in the North to a depth of $K \sim 18$, including part of the Galactic plane. These surveys have the promise to open up enough new dwarf discovery space to reveal systems not yet accessible in optical datasets.

Pointed surveys will also reveal low luminosity galaxies in other systems, although they cannot yet reveal objects as low luminosity as many of the MW's ultra-faints. Recently, [75] identified 22 dwarf galaxy candidates as faint as $r = -10$ around M81. They used both eyeball evaluation and automated analysis of resolved stars in 65 square degrees of deep imaging. The on-going PAndAS survey (PI A. McConnachie) of 350 square degrees around M31 and M33 is expected to reveal diffuse objects around these galaxies as faint as 32 magnitudes per square arcsecond.

The future will reveal whether we have yet seen the ultimate limit of galaxy formation. The possibilities remain that either (1) the low luminosities of the ultra-faint dwarfs are an artifact of nature, rather than nurture, and/or (2) the present survey data are not deep enough to reveal the very least luminous systems and a vast population of ultra-faint dwarfs lie just beyond our fingertips. Regardless, at least dozens of ultra-faint satellites will be discovered in the near future, with the possibility of hundreds or more.

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References

[1] M. Mateo, "Dwarf galaxies of the local group," *Annual Review of Astronomy and Astrophysics*, vol. 36, no. 1, pp. 435–506, 1998.

[2] S. G. van den Bergh, "The local group of galaxies," *The Astronomy and Astrophysics Review*, vol. 9, pp. 273–318, 1999.

[3] M. Geha, B. Willman, J. D. Simon, et al., "The least-Luminous galaxy: spectroscopy of the Milky Way satellite segue 1," *Astrophysical Journal*, vol. 692, pp. 1464–1475, 2009.

[4] A. E. Dolphin, D. R. Weisz, E. D. Skillman, and J. A. Holtzman, "Star formation histories of local group dwarf galaxies," in *Proceedings of the International Conference on Resolved Stellar Populations*, Cancun, Mexico, April-June 2005.

[5] H. T. MacGillivray, R. K. Bhatia, S. M. Beard, and R. J. Dodd, "An automated search for halo star clusters and Local Group dwarf galaxies," in *Proceedings of the European Southern Observatory Astrophysics Symposia*, M. Azzopardi and F. Matteucci, Eds., vol. 27 of *European Southern Observatory Astrophysics Symposia*, pp. 477–479, 1987.

[6] A. Klypin, A. V. Kravtsov, O. Valenzuela, and F. Prada, "Where are the missing galactic satellites?" *Astrophysical Journal*, vol. 522, no. 1, pp. 82–92, 1999.

[7] B. Moore, S. Ghigna, F. Governato, et al., "Dark matter substructure within galactic halos," *Astrophysical Journal*, vol. 524, no. 1, pp. L19–L22, 1999.

[8] J. Diemand, M. Kuhlen, P. Madau, et al., "Clumps and streams in the local dark matter distribution," *Nature*, vol. 454, no. 7205, pp. 735–738, 2008.

[9] V. Springel, J. Wang, M. Vogelsberger, et al., "The aquarius project: the subhaloes of galactic haloes," *Monthly Notices of the Royal Astronomical Society*, vol. 391, no. 4, pp. 1685–1711, 2008.

[10] J. S. Bullock, A. V. Kravtsov, and D. H. Weinberg, "Reionization and the abundance of galactic satellites," *Astrophysical Journal*, vol. 539, no. 2, pp. 517–521, 2000.

[11] A. J. Benson, C. S. Frenk, C. G. Lacey, C. M. Baugh, and S. Cole, "The effects of photoionization on galaxy formation—II: satellite galaxies in the local group," *Monthly Notices of the Royal Astronomical Society*, vol. 333, no. 1, pp. 177–190, 2002.

[12] A. V. Kravtsov, O. Y. Gnedin, and A. A. Klypin, "The tumultuous lives of galactic dwarfs and the missing satellites problem," *Astrophysical Journal*, vol. 609, no. 2, pp. 482–497, 2004.

[13] J. D. Simon and M. Geha, "The kinematics of the ultra-faint Milky Way satellites: solving the missing satellite problem," *Astrophysical Journal*, vol. 670, no. 1, pp. 313–331, 2007.

[14] S. Koposov, V. Belokurov, N. W. Evans, et al., "The luminosity function of the Milky Way satellites," *Astrophysical Journal*, vol. 686, no. 1, pp. 279–291, 2008.

[15] E. J. Tollerud, J. S. Bullock, L. E. Strigari, and B. Willman, "Hundreds of Milky Way satellites? Luminosity bias in the satellite luminosity function," *Astrophysical Journal*, vol. 688, no. 1, pp. 277–289, 2008.

[16] B. Willman, F. Governato, J. J. Dalcanton, D. Reed, and T. Quinn, "The observed and predicted spatial distribution of Milky Way satellite galaxies," *Monthly Notices of the Royal Astronomical Society*, vol. 353, no. 2, pp. 639–646, 2004.

[17] M. T. Busha, M. A. Alvarez, R. H. Wechsler, T. Abel, and L. E. Strigari, "The impact of inhomogeneous reionization on the satellite galaxy population of the Milky Way," submitted to *Astrophysical Journal*.

[18] L. E. Strigari, J. S. Bullock, M. Kaplinghat, J. Diemand, M. Kuhlen, and P. Madau, "Redefining the missing satellites problem," *Astrophysical Journal*, vol. 669, no. 2, pp. 676–683, 2007.

[19] P. Kroupa, C. Theis, and C. M. Boily, "The great disk of Milky-Way satellites and cosmological sub-structures," *Astronomy and Astrophysics*, vol. 431, no. 2, pp. 517–521, 2005.

[20] M. Metz, P. Kroupa, and N. I. Libeskind, "The orbital poles of Milky Way satellite galaxies: a rotationally supported disk of satellites," *Astrophysical Journal*, vol. 680, no. 1, pp. 287–294, 2008.

[21] J. Wang and S. D. M. White, "Discreteness effects in simulations of hot/warm dark matter," *Monthly Notices of the Royal Astronomical Society*, vol. 380, no. 1, pp. 93–103, 2007.

[22] S. C. Keller, B. P. Schmidt, M. S. Bessell, et al., "The SkyMapper telescope and the southern sky survey," *Publications of the Astronomical Society of Australia*, vol. 24, no. 1, pp. 1–12, 2007.

[23] The Dark Energy Survey Collaboration, "The dark energy survey," White Paper submitted to *Dark Energy Task Force*, http://arxiv.org/abs/astro-ph/0510346.

[24] Z. Ivezic, J. A. Tyson, R. Allsman, et al., "LSST: from science drivers to reference design and anticipated data products," submitted, http://arxiv.org/abs/0805.2366, http://www.lsst.org/overview.

[25] H. Shapley, "A stellar system of a new type," *Harvard College Observatory Bulletin*, vol. 908, pp. 1–11, 1938.

[26] H. Shapley, "Two stellar systems of a new kind," *Nature*, vol. 142, no. 3598, pp. 715–716, 1938.

[27] R. G. Harrington and A. G. Wilson, "Two new stellar systems in Leo," *Publications of the Astronomical Society of the Pacific*, vol. 62, pp. 118–120, 1950.

[28] A. G. Wilson, "Sculptor-type systems in the local group of galaxies," *Publications of the Astronomical Society of the Pacific*, vol. 67, pp. 27–29, 1955.

[29] R. D. Cannon, T. G. Hawarden, and S. B. Tritton, "A new sculptor-type dwarf elliptical galaxy in Carina," *Monthly Notices of the Royal Astronomical Society*, vol. 180, pp. 81P–82P, 1977.

[30] E. K. Grebel, J. S. Gallagher III, and D. Harbeck, "The progenitors of dwarf spheroidal galaxies," *The Astronomical Journal*, vol. 125, no. 4, pp. 1926–1939, 2003.

[31] M. J. Irwin, P. S. Bunclark, M. T. Bridgeland, and R. G. McMahon, "A new satellite galaxy of the Milky Way in the constellation of Sextans," *Monthly Notices of the Royal Astronomical Society*, vol. 244, pp. 16P–19P, 1990.

[32] M. J. Irwin, "Searches for galactic dwarf spheroidal satellites," in *Proceedings of the European Southern Observatory Astrophysics Symposia*, G. Meylan and P. Prugniel, Eds., vol. 49 of *European Southern Observatory Astrophysics Symposia*, p. 27, January 1994.

[33] R. A. Ibata, G. Gilmore, and M. J. Irwin, "A dwarf satellite galaxy in Sagittarius," *Nature*, vol. 370, no. 6486, pp. 194–196, 1994.

[34] J. T. Kleyna, M. J. Geller, S. J. Kenyon, and M. J. Kurtz, "An adaptive kernel approach to finding DSPH galaxies around the Milky Way," *The Astronomical Journal*, vol. 113, no. 2, pp. 624–633, 1997.

[35] A. B. Whiting, G. K. T. Hau, M. Irwin, and M. Verdugo, "An observational limit on the dwarf galaxy population of the local group," *The Astronomical Journal*, vol. 133, no. 2, pp. 715–733, 2007.

[36] D. G. York, J. Adelman, J. E. Anderson Jr., et al., "The sloan digital sky survey: technical summary," *The Astronomical Journal*, vol. 120, pp. 1579–1587, 2000.

[37] B. Willman, M. R. Blanton, A. A. West, et al., "A new Milky Way companion: unusual globular cluster or extreme dwarf satellite?" *The Astronomical Journal*, vol. 129, no. 6, pp. 2692–2700, 2005.

[38] B. Willman, J. J. Dalcanton, D. Martinez-Delgado, et al., "A new Milky Way dwarf galaxy in URSA major," *Astrophysical Journal*, vol. 626, no. 2, pp. L85–L88, 2005.

[39] V. Belokurov, D. B. Zucker, N. W. Evans, et al., "A faint new Milky Way satellite in bootes," *Astrophysical Journal*, vol. 647, no. 2, pp. L111–L114, 2006.

[40] D. B. Zucker, V. Belokurov, N. W. Evans, et al., "A curious Milky Way satellite in Ursa Major," *Astrophysical Journal*, vol. 650, no. 1, pp. L41–L44, 2006.

[41] D. B. Zucker, V. Belokurov, N. W. Evans, et al., "A new Milky Way dwarf satellite in canes venatici," *Astrophysical Journal*, vol. 643, no. 2, pp. L103–L106, 2006.

[42] V. Belokurov, D. B. Zucker, N. W. Evans, et al., "Cats and dogs, hair and a hero: a quintet of new Milky Way companions," *Astrophysical Journal*, vol. 654, no. 2, pp. 897–906, 2007.

[43] M. J. Irwin, V. Belokurov, N. W. Evans, et al., "Discovery of an unusual dwarf galaxy in the outskirts of the Milky Way," *Astrophysical Journal*, vol. 656, no. 1, pp. L13–L16, 2007.

[44] S. M. Walsh, H. Jerjen, and B. Willman, "A pair of boötes: a new Milky Way satellite," *Astrophysical Journal*, vol. 662, no. 2, pp. L83–L86, 2007.

[45] V. Belokurov, M. G. Walker, N. W. Evans, et al., "Leo V: a companion of a companion of the Milky Way galaxy?" *Astrophysical Journal*, vol. 686, no. 2, part 2, pp. L83–L86, 2008.

[46] V. Belokurov, M. G. Walker, N. W. Evans, et al., "The discovery of segue 2: a prototype of the population of satellites of satellites," *Monthly Notices of the Royal Astronomical Society*, p. 903, 2009.

[47] N. F. Martin, J. T. A. de Jong, and H.-W. Rix, "A comprehensive maximum likelihood analysis of the structural properties of faint Milky Way satellites," *Astrophysical Journal*, vol. 684, no. 2, pp. 1075–1092, 2008.

[48] E. N. Kirby, J. D. Simon, M. Geha, P. Guhathakurta, and A. Frebel, "Uncovering extremely metal-poor stars in the Milky Way's ultrafaint dwarf spheroidal satellite galaxies," *Astrophysical Journal*, vol. 685, no. 1, pp. L43–L46, 2008.

[49] A. Frebel, J. D. Simon, M. Geha, and B. Willman, "High-resolution spectroscopy of extremely metal-poor stars in the least evolved galaxies: Ursa major II and coma berenices," submitted to *The Astrophysical Journal*, http://arxiv.org/abs/0902.2395.

[50] G. D. Martinez, J. S. Bullock, M. Kaplinghat, L. E. Strigari, and R. Trotta, "Indirect dark matter detection from dwarf satellites: joint expectations from astrophysics and supersymmetry," *Journal of Cosmology and Astro-Particle Physics*, vol. 6, p. 14, 2009.

[51] L. E. Strigari, S. M. Koushiappas, J. S. Bullock, et al., "The most dark-matter-dominated galaxies: predicted gamma-ray signals from the faintest Milky Way dwarfs," *Astrophysical Journal*, vol. 678, no. 2, pp. 614–620, 2008.

[52] D. B. Zucker, A. Y. Kniazev, E. F. Bell, et al., "Andromeda IX: a new dwarf spheroidal satellite of M31," *Astrophysical Journal*, vol. 612, no. 2, pp. L121–L124, 2004.

[53] N. F. Martin, R. A. Ibata, M. J. Irwin, et al., "Discovery and analysis of three faint dwarf galaxies and a globular cluster in the outer halo of the Andromeda galaxy," *Monthly Notices of the Royal Astronomical Society*, vol. 371, no. 4, pp. 1983–1991, 2006.

[54] S. R. Majewski, R. L. Beaton, R. J. Patterson, et al., "Discovery of andromeda XIV: a dwarf spheroidal dynamical rogue in the local group?" *Astrophysical Journal*, vol. 670, no. 1, pp. L9–L12, 2007.

[55] D. B. Zucker, A. Y. Kniazev, D. Martínez-Delgado, et al., "Andromeda X, a new dwarf spheroidal satellite of M31: photometry," *Astrophysical Journal*, vol. 659, no. 1, pp. L21–L24, 2007.

[56] R. Ibata, N. F. Martin, M. Irwin, et al., "The haunted halos of andromeda and triangulum: a panorama of galaxy formation in action," *Astrophysical Journal*, vol. 671, no. 2, pp. 1591–1623, 2007.

[57] M. J. Irwin, A. M. N. Ferguson, A. P. Huxor, N. R. Tanvir, R. A. Ibata, and G. F. Lewis, "Andromeda XVII: a new low-luminosity satellite of M31," *Astrophysical Journal*, vol. 676, no. 1, pp. L17–L20, 2008.

[58] A. W. McConnachie, A. Huxor, N. F. Martin, et al., "A trio of new local group galaxies with extreme properties," *Astrophysical Journal*, vol. 688, no. 2, pp. 1009–1020, 2008.

[59] K. N. Abazajian, J. K. Adelman-Mccarthy, M. A. Agüeros, et al., "The seventh data release of the sloan digital sky survey," *Astrophysical Journal, Supplement Series*, vol. 182, no. 2, pp. 543–558, 2009.

[60] B. Willman, J. Dalcanton, Ž. Ivezić, et al., "An SDSS survey for resolved Milky Way satellite galaxies. I. Detection limits," *The Astronomical Journal*, vol. 123, no. 2, pp. 848–854, 2002.

[61] S. M. Walsh, B. Willman, and H. Jerjen, "The invisibles: a detection algorithm to trace the faintest Milky Way satellites," *The Astronomical Journal*, vol. 137, no. 1, pp. 450–469, 2009.

[62] C. M. Rockosi, M. Odenkirchen, E. K. Grebel, et al., "A matched-filter analysis of the tidal tails of the globular cluster palomar 5," *The Astronomical Journal*, vol. 124, no. 1, pp. 349–363, 2002.

[63] N. F. Martin, M. G. Coleman, J. T. A. de Jong, et al., "A deep large binocular telescope view of the Canes Venatici I dwarf galaxy," *Astrophysical Journal*, vol. 672, no. 1, pp. L13–L16, 2008.

[64] F. J. Lockman, "High-velocity cloud complex H: a satellite of the Milky Way in a retrograde orbit?" *Astrophysical Journal*, vol. 591, no. 1, pp. L33–L36, 2003.

[65] N. F. Martin, R. A. Ibata, M. Bellazzini, M. J. Irwin, G. F. Lewis, and W. Dehnen, "A dwarf galaxy remnant in Canis Major: the fossil of an in-plane accretion on to the Milky Way," *Monthly Notices of the Royal Astronomical Society*, vol. 348, no. 1, pp. 12–23, 2004.

[66] T. X. Thuan and J. E. Gunn, "A new four-color intermediate-band photometric system," *Publications of the Astronomical Society of the Pacific*, vol. 88, pp. 543–547, 1976.

[67] S. V. W. Beckwith, M. Stiavelli, A. M. Koekemoer, et al., "The hubble ultra deep field," *The Astronomical Journal*, vol. 132, no. 5, pp. 1729–1755, 2006.

[68] L. Girardi, M. A. T. Groenewegen, E. Hatziminaoglou, and L. da Costa, "Star counts in the galaxy simulating from very deep to very shallow photometric surveys with the TRILEGAL code," *Astronomy and Astrophysics*, vol. 436, no. 3, pp. 895–915, 2005.

[69] M. G. Kitzbichler and S. D. M. White, "The high-redshift galaxy population in hierarchical galaxy formation models," *Monthly Notices of the Royal Astronomical Society*, vol. 376, no. 1, pp. 2–12, 2007.

[70] D. D. Lenz, J. Newberg, R. Rosner, G. T. Richards, and C. Stoughton, "Photometric separation of stellar properties using SDSS filters," *Astrophysical Journal, Supplement Series*, vol. 119, no. 2, pp. 121–140, 1998.

[71] A. Helmi, Ž. Ivezić, F. Prada, et al., "Selection of metal-poor giant stars using the sloan digital sky survey photometric system," *Astrophysical Journal*, vol. 586, no. 1, pp. 195–200, 2003.

[72] H. K. C. Yee, "A faint-galaxy photometry and image-analysis system," *Publications of the Astronomical Society of the Pacific*, vol. 103, pp. 396–411, 1991.

[73] P. C. Boeshaar, V. Margoniner, and The Deep Lens Survey Team, "Ground-based optical deep pencil beam surveys," in *Brown Dwarfs*, E. Martín, Ed., vol. 211 of *IAU Symposium*, p. 203, 2003.

[74] A. Dotter, B. Chaboyer, D. Jevremovic, V. Kostov, E. Baron, and J. W. Ferguson, "The dartmouth stellar evolution database," *Astrophysical Journal, Supplement Series*, vol. 178, no. 1, pp. 89–101, 2008.

[75] K. Chiboucas, I. D. Karachentsev, and R. B. Tully, "Discovery of new dwarf galaxies in the M81 group," *The Astronomical Journal*, vol. 137, no. 2, pp. 3009–3037, 2009.