Two New Milky Way Companions

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Abstract.

We discuss the detection limits and current status of a uniform survey of SDSS I for ultra-faint Milky Way dwarf galaxies. We present the properties of two new, low surface brightness Milky Way companions discovered as a result of this survey. One of these companions is the Ursa Major dwarf, the newest dwarf spheroidal companion to the Milky Way and the lowest luminosity galaxy yet known. Ursa Major is about 100 kpc away and is similar to Sextans, but with roughly an order of magnitude fewer stars. The other companion, SDSSJ1049+5103, lies ~50 kpc away. Its stellar distribution suggests that it may be undergoing tidal stripping. This companion is extremely faint (M_V ~ -3) but has a large half-light size for its luminosity. It is therefore unclear whether it is a globular cluster or a dwarf galaxy.

1. Introduction

Of all galaxies that have survived until the present epoch, the lowest mass dwarf galaxies inhabit the dark matter halos with the shallowest potential wells and have been the most limited in their ability to cool gas. As such, their properties are the most sensitive to physical processes that control galaxy formation. Most of the least massive dwarfs currently cataloged have been found near the Milky Way. Milky Way dwarfs are also special because they are close enough to allow precise measurements of their star formation histories, detailed spatial and kinematic structures, and to measure the metallicities and ages of individual stars.

Over the past few years, theoretical and observational studies of Milky Way dwarf galaxies have flourished as a result of new interest motivated by the 'missing galaxy' and the 'cusp/core' problems with CDM cosmologies, as well as improvements in observational and computational resources. The Milky Way satellites are now being studied with unprecedented detail (Palma et al. 2003; Tolstoy et al. 2004; Wilkinson et al. 2004; Babusiaux et al. 2005; Mayer et al. 2005; Munoz et al. 2005, among many others), and new satellites and remnants thereof are being discovered around both the Milky Way and M31 (Newberg et al. 2002; Yanny et al. 2003; Ibata et al. 2003; Rocha-Pinto et al. 2004; Majewski et al. 2003; Martin et al. 2004; Zucker et al. 2004, among many others).

Although systematic searches have successfully identified some of the Milky Way dwarfs, there currently aren’t well-defined, quantitative limits on the faint end of the local galaxy luminosity function. The possibility also remains that existing survey data has not yet been searched to the faintest possible depths for new dwarf galaxies. This lack of a well-defined sample of dwarfs currently
undermines our understanding of the “substructure problem”: that cold dark matter (CDM) cosmologies predict more than an order of magnitude more low mass dark matter halos than the number of dwarfs observed around galaxies such as the Milky Way (Klypin et al. 1999; Moore et al. 1999). Models that implement baryonic physical processes into CDM models of galaxy formation have made new predictions for the observable population of dwarfs around the Milky Way and M31 (Benson et al. 2002; Kravtsov et al. 2004). However any comparison between the observed dwarf populations and these predictions is rendered less meaningful by the uncertain completeness of the local dwarf galaxy population (Willman et al. 2004).

To create a well-defined census of Milky Way dwarfs to fainter limits than previously possible, we have been conducting a uniform, automated search for new Milky Way companions (Willman et al. 2002). Two companions have been discovered as a result of this search thus far.

2. An SDSS Survey For Milky Way Companions

To identify candidates for Milky Way companions, we search for statistical fluctuations in star counts in the Sloan Digital Sky Survey catalog (SDSS; York et al. 2000). SDSS data is reduced with an automatic pipeline consisting of: astrometry (Pier et al. 2003); source identification, deblending and photometry (Lupton et al. 2001); photometricity determination (Hogg et al. 2001); calibration (Fukugita et al. 1996; Smith et al. 2002); and spectroscopic data processing (Stoughton et al. 2002).

Our search algorithm enhances the apparent overdensity of an extragalactic stellar system over the foreground of the Milky Way by combining color and magnitude cuts on resolved stars with spatial smoothing. Candidates can be identified either with or without a color-cut designed to select stars with $g - r$, $r - i$ colors consistent with those of metal-poor red giant branch stars. Although it is somewhat crude, this technique is sensitive to dwarfs many times fainter than those known. Our primary survey only includes stars brighter than $r = 21.5$ so that star-galaxy separation is uniform enough to produce well-defined detection limits. However, we also extend our analysis to stars with fainter magnitudes to maximize the possibility of finding new companions.

The detection limits of the primary survey are a function of: i) the density of the stellar foreground due to the Milky Way and ii) the stellar surface density as a function of color and magnitude of a candidate dwarf (which is a function of the dwarf’s central surface brightness, scale size, distance, star formation history, and metallicity). First, we determine the detection thresholds that produce only $\sim 1$-2 spurious detections in 1000 deg$^2$ of randomly distributed stars. We then use those adopted thresholds to calculate the survey’s detection limits. We simulate the stellar surface densities of metal-poor, old population dwarf spheroidal galaxies with a range of sizes and distances, based on a template stellar luminosity function created with SDSS observations of Palomar 5. The simulated galaxies are embedded in SDSS data at a range of stellar foreground densities and the resulting detection efficiencies determine the detection limits. See Willman et al. (2002) and Willman et al (2005, in prep) for a detailed description of the survey technique and detection limits.
Figure 1 shows the limiting absolute magnitude for a fiducial direction of $(l,b) = (0.50)$. These limits are updated from the preliminary results published in Willman et al. (2002). Each line in this Figure corresponds to the absolute magnitude corresponding to a 50% detection efficiency for a galaxy of a different physical size. The magnitudes and scale sizes of the known Milky Way dwarf spheroidals are overplotted. This Figure shows that the survey is sensitive to galaxies much fainter than any yet known (not including Ursa Major) to distances beyond the Milky Way’s virial radius. We have verified that all of the Milky Way dwarfs imaged by SDSS are detected at many $\sigma$ over the search’s detection threshold. The (very uncertain) magnitude and scale size of the Ursa Major dwarf galaxy (UMa), the first new companion produced by the primary survey, is also overplotted.

Figure 1. Absolute magnitude limits of our survey for a fiducial direction as a function of dwarf size and distance. These limits were calculated using the stellar luminosity function of Palomar 5 and assuming a purely old stellar population (see Willman et al. 2002 and Willman et al. 2005, in prep for details). The physical scale lengths and absolute magnitudes of the known Milky Way dSph companions are overplotted (from Grebel et al. 2003 and Willman et al. 2005b), although the plotted values for Ursa Major are quite uncertain. Dwarf galaxies several times fainter than any known (not including Ursa Major) are detectable within 350 kpc.
3. The Ursa Major Dwarf

Our primary survey has included \( \sim 4700 \) deg\(^2\) of sky thus far and has produced 17 candidates, not including all of the previously known Milky Way companions that were detected. The first candidate we obtained follow-up imaging of was detected as an 8.5\(\sigma\) fluctuation in the number of red stars with \(19.0 < r < 20.5\) and is located in the Ursa Major constellation at \((\alpha_{2000}, \delta_{2000}) = (158.72, 51.92)\). The distribution of stellar densities produced by our algorithm is not quite Gaussian, so 8.5\(\sigma\) is actually only 0.3\(\sigma\) above our detection threshold.

Figure 2 shows the SDSS color-magnitude diagram of Ursa Major alongside the SDSS color-magnitude diagram (CMD) of Sextans, one of the two lowest surface brightness galaxies known prior to Ursa Major. Sextans is an old and metal-poor ([Fe/H] = -2.1 \pm 0.3; Lee et al. 2003) Milky Way dSph at a distance of 86 kpc. The stellar population of Ursa Major (UMa) is strikingly similar to that of Sextans, including the morphologies of their horizontal and red giant branches, suggesting they may have similar ages and metallicities. UMa also has roughly an order of magnitude fewer stars than Sextans, which is remarkable given that the surface brightness of Sextans is only \(\mu_V = 26.2\).

Follow-up imaging obtained at the Isaac Newton Telescope in March 2005 in B and r revealed that this detected overdensity truly is a dwarf galaxy composed of an old stellar population at a distance of \(\sim 100\) kpc. We used the DAOPHOT II/ALLSTAR package (Stetson 1994) to obtain photometry of the resolved stars. Figure 3, from Willman et al. (2005b), shows that an [Fe/H] = -1.7, 13 Gyr isochrone projected to 100 kpc provides a good match to Ursa Major’s INT color-magnitude diagram.
In Willman et al. (2005b), we estimated some of Ursa Major’s properties and compared them to other known systems. By a comparison with the stellar luminosity functions of Sextans and Palomar 5, we estimated the absolute magnitude of Ursa Major to be $M_V \sim -6.75$, which is several times fainter than the faintest dwarf previously known. Based on the spatial distribution of red giant branch stars in the Ursa Major dwarf, and assuming a distance of 100 kpc, we estimated $r_{\text{half-light,UMa}} \sim 250$ pc, which is similar to the half-light radius of Sextans (200 pc). This absolute magnitude and size are currently quite uncertain, but do give a sense of UMa’s properties relative to other known systems. Both its combination of a faint total luminosity with a relatively large half-light radius and the fact that UMa is more distant than all but one of the Milky Way’s 150+ globular clusters, cause us to conclude that Ursa Major is the tenth confirmed dwarf spheroidal companion to the Milky Way (see below for some additional discussion).

4. SDSSJ1049+5103

An extended survey analysis including stars as faint as $r = 23.0$ produced numerous candidates, many of which appear to be cluster galaxies misclassified as stars or globular clusters around nearby galaxies that get classified as stars. However one system, SDSSJ1049+5103, stood out as a strong candidate for a new Milky Way companion. In Willman et al. (2005a), we used SDSS data to determine that this companion is an old, metal-poor stellar population at $d \sim 50$ kpc, with $M_V \sim -3$, and $r_{\text{half-light}} \sim 25$ pc.

We then obtained follow-up deep, wide-field imaging of SDSSJ1049+5103 at the INT in March 2005 and again used the DAOPHOTII/ALLSTAR package to obtain photometry of stellar sources. The right panel of Figure 4 shows the CMD of stars from chip 4 of the WFC that lie within $3.5''$ ($2r_{\text{half}}$) of the center of SDSSJ1049+5103, with boxes outlining the main-sequence turnoff and the sub-giant branch. This CMD extends almost two magnitudes fainter than the main sequence turnoff. When extended to brighter magnitudes, this CMD shows few possible horizontal branch or red giant branch stars (see Willman et al. 2005a). Despite SDSSJ1049+5103 having an ultra-low luminosity, its stellar population clearly dominates the stars in this CMD. However, the CMD of field stars observed on chips 1, 2, and 3 and shown in the left panel of Figure 4 is dominated by field stars. These adjacent chips do not display a clear signature of object stars, but there is a hint that some SDSSJ1049+5103 stars may be found in these chips. This hint suggests that SDSSJ1049+5103 may be more extended than originally thought or may be getting tidally stripped.

Figure 5 also suggests the possibility of tidal stripping. The spatial distribution of stars in the main-sequence turnoff and sub-giant branch boxes is not symmetric and clearly displays a “tail” extending to the west of the primary object. The entire area of this figure is covered by chip 4 of the INT observation. We will present a more detailed analyses of these data in an upcoming paper.
5. **SDSSJ1049+5103 and Ursa Major: globular clusters or dwarf galaxies?**

We have shown that Ursa Major and SDSSJ1049+5103 are newly discovered Milky Way companions. The fact that their luminosities overlap those of known globular clusters more than those of known dwarf galaxies raises the question: Are they star clusters or dwarf galaxies? The likely fundamental difference between globular clusters and dwarf galaxies is that a dwarf galaxy forms inside of its own dark matter halo and a globular cluster does not. However, the most reliable way to observationally classify such objects has been the fact that globular clusters are much more compact than dwarfs at a given luminosity.
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Figure 4. **Right Panel:** CMD of stars within 3.5' of the center of SDSSJ1049+5103 (from chip 4 of the WFC on the INT). The main-sequence turnoff and sub-giant branch are outlined. **Left Panel:** CMD of stars in surrounding fields (a total of $\sim 800^2$; all stars on chips 1, 2 and 3).

Figure 5. The spatial distribution of stars centered on SDSSJ1049+5103. This figure includes all stars that fall in the main-sequence turnoff and sub-giant branch boxes plotted on the color-magnitude diagrams of Figure 4.

Figure 6 displays the absolute magnitude vs. half light size of: 1) Milky Way globular clusters, 2) Milky Way dwarf spheroidals, 3) faint red galaxies.
And IX and Ursa Major both fall close to the size-magnitude relationship followed by dwarf galaxies, but quite far from that followed by GCs. It is possible that they lie to the right of the current dwarf locus simply because dwarfs in that region of size-magnitude space are too low surface brightness to have been detected previously. The dashed line shows a fiducial line of constant $\mu_{50}$ for comparison.

Unlike Ursa Major, SDSSJ1049+5103 lies at the intersection of the globular clusters and the dwarf galaxies. Although many times fainter than the faintest dwarf, SDSSJ1049+5103 is also $\geq 5$ times larger in physical size than similarly faint GCs. It thus remains unclear whether it is a globular cluster or a dwarf galaxy. It may be possible to use tidal features around SDSSJ1049+5103 to constrain its current dark matter content (Moore 1996), which may or may not reflect the conditions under which it formed.

6. Summary and Future Directions

The discoveries of at least one new Milky Way satellite and at least one other ambiguous companion in $< 1/8$ of the sky suggests that many more ultra-faint Milky Way satellites may yet to be discovered. These discoveries also raise a number of interesting questions whose answers could impact our global understanding of galaxy formation: Do these systems have few stars as a result of nature or nurture? What is the lower limit of galaxy formation? What is the relationship between globular clusters and dwarf galaxies?

We are in the process of obtaining and analyzing follow-up imaging for the remaining 16 candidates produced by our survey. We are also currently performing a more detailed analysis of deep imaging of both Ursa Major and SDSSJ1049+5103, as well as of HIRES spectra of some Ursa Major stars.

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Figure 6. The absolute magnitudes and half-light radii of Milky Way globular clusters (circles), MW dwarf spheroidal galaxies (triangles), faint red galaxies in the SDSS (stars; Blanton et al. 2004), And IX (Zucker et al. 2004), Ursa Major dSph (Willman et al. 2005b), and SDSSJ1049+5103 (square). The globular cluster AM 4 is too faint ($M_V = +0.2$) to be included on this plot. The approximate loci of the globular cluster and the dwarf spheroidal data are shaded. The Milky Way dSphs appear to follow a similar size-luminosity relation as other faint red galaxies. A fiducial line of constant $\mu_50$ is also overplotted for reference. GC and MW dSph data are from Harris (1996), Mateo (1998), and Grebel et al. (2003).

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