2005

A New Milky Way Companion: Unusual Globular Cluster or Extreme Dwarf Satellite?

Beth Willman
Haverford College

Repository Citation

Willman, B., Blanton, M., West, A., Dalcanton, J.J., Hogg, D.W., Schneider, D., Wherry, N., Yanny, B., Brinkmann, J., 2005, A New Milky Way Companion: Unusual Globular Cluster or Extreme Dwarf Satellite?, AJ, 129, 2692

The Astronomical Journal, 129:2692–2700, 2005 June

A NEW MILKY WAY COMPANION: UNUSUAL GLOBULAR CLUSTER OR EXTREME DWARF SATELLITE?

Beth Willman,[1] Michael R. Blanton,[1] Andrew A. West,[2] Julianne J. Dalcanton,[2,3] David W. Hogg,[1] Donald P. Schneider,[4] Nicholas Wherry,[1] Brian Yanny,[5] and Jon Brinkmann[6]
Received 2004 October 12; accepted 2005 February 23

ABSTRACT

We report the discovery of SDSS J1049+5103, an overdensity of resolved blue stars at $(\alpha_{2000},\ \delta_{2000}) = (162\fdg343,\ 51\fdg051)$. This object appears to be an old, metal-poor stellar system at a distance of 45 ± 10 kpc, with a half-light radius of 23 ± 10 pc and an absolute magnitude of $M_V = -3.0^{+2.0}_{-0.7}$. One star that is likely associated with this Milky Way companion has an SDSS spectrum confirming it as a blue horizontal-branch star at 48 kpc. The color-magnitude diagram of SDSS J1049+5103 contains few, if any, horizontal or red giant branch stars, similar to the anomalously faint globular cluster AM 4. The size and luminosity of SDSS J1049+5103 places it at the intersection of the size-luminosity relationships followed by known globular clusters and by Milky Way dwarf spheroidal galaxies. If SDSS J1049+5103 is a globular cluster, then its properties are consistent with the established trend that the largest radius Galactic globular clusters are all in the outer halo. However, the five known globular clusters with similarly faint absolute magnitudes all have half-mass radii that are smaller than SDSS J1049+5103 by a factor of $\gtrsim 5$. If it is a dwarf spheroidal galaxy, then it is the faintest yet known by 2 orders of magnitude and is the first example of the ultrafaint dwarfs predicted by some theories. The uncertain nature of this new system underscores the sometimes ambiguous distinction between globular clusters and dwarf spheroidal galaxies. A simple friends-of-friends search for similar, blue, small scale length star clusters detected all known globular clusters and dwarfs closer than 50 kpc in the SDSS area but yielded no other candidates as robust as SDSS J1049+5103.

Key words: galaxies: dwarf — galaxies: formation — globular clusters: general — Local Group — surveys

Online material: color figures

1. INTRODUCTION

Milky Way globular clusters (GCs) are invaluable pieces in the puzzle of galaxy formation. At present, their properties support a general picture of Galactic halo formation as a combination of accretion and dissipative collapse (see review in Mackey & Gilmore 2004). However, the detailed interpretation of GC properties in the context of galaxy formation is complex. One outstanding problem is the sometimes ambiguous distinction between GCs and dwarf spheroidal galaxies (dSphs). For example, a few Milky Way GCs, such as ω Cen, have a spread in stellar age and metallicity similar to that seen in many dwarf galaxies (Ashman & Zepf 1998) and have absolute magnitudes that overlap those of known dSphs. A small number of faint GCs have radial profiles that are well fitted by a Navarro-Frenk-White (NFW) profile (e.g., Palomar 13 [Pal 13]; Côté et al. 2002) or have central densities similar to those of dSphs (e.g., Pal 14; Harris 1996) and thus may be the remnants of a stripped dSph.

The relationship between GCs and dSphs is particularly interesting in light of recent predictions for low-mass substructure around the Milky Way (Klypin et al. 1999; Moore et al. 1999; Bullock et al. 2000; Benson et al. 2002; Susa & Umemura 2004; Kravtsov et al. 2004, among others). It is difficult to determine whether GCs ever contained a substantial amount of nonbaryonic dark matter (Ashman & Zepf 1998), which would arguably put them in the category of ultrafaint dwarf galaxies. If some GCs are embedded in extended dark matter halos, the dark matter may not be dynamically important within the extent of the observable stellar distribution.

There are ~150 known GCs and nine known dSphs orbiting the Milky Way. The total number of known clusters has increased by just a few percent over the last 25 years (Harris et al. 1997; Harris 1996; Ortolani et al. 1993, 2000; Hurt et al. 2000; Irwin et al. 1995), and nearly all the new GCs lie at low Galactic latitude. Only one Milky Way dSph has been discovered since 1990. The lack of new GCs or dSphs at $|b| > 30°$ could lead some to believe that all high-latitude systems have been discovered. However, one anomalously faint GC (AM 4; $M_V = +0.2$) was discovered serendipitously more than 20 years ago (Madore & Arp 1982), suggesting that other ultrafaint star clusters may still reside undetected in our halo. Furthermore, the advent of the Sloan Digital Sky Survey (SDSS; York et al. 2000) could lead to the discovery of similar systems, should they exist (Willman et al. 2002). In this paper we report the discovery of SDSS J1049+5103, a new ultrafaint stellar system in the outer halo of the Milky Way. We estimate and discuss some properties of SDSS J1049+5103 in comparison to both GCs and Milky Way dSphs.

2. PHOTOMETRIC DATA

2.1. *Sloan Digital Sky Survey and Object Discovery*

The SDSS (York et al. 2000) is a spectroscopic and photometric survey in five passbands (u, g, r, i, and z; Fukugita et al. 1996; Gunn et al. 1998; Hogg et al. 2001; Smith et al. 2002) that has thus far imaged thousands of square degrees of the sky. Data are reduced with an automatic pipeline consisting of astrometry

[1] Center for Cosmology and Particle Physics, New York University, 4 Washington Place, New York, NY 10003.
[2] Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195.
[3] Alfred P. Sloan Research Fellow.
[4] Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802.
[5] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510.
[6] Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349.

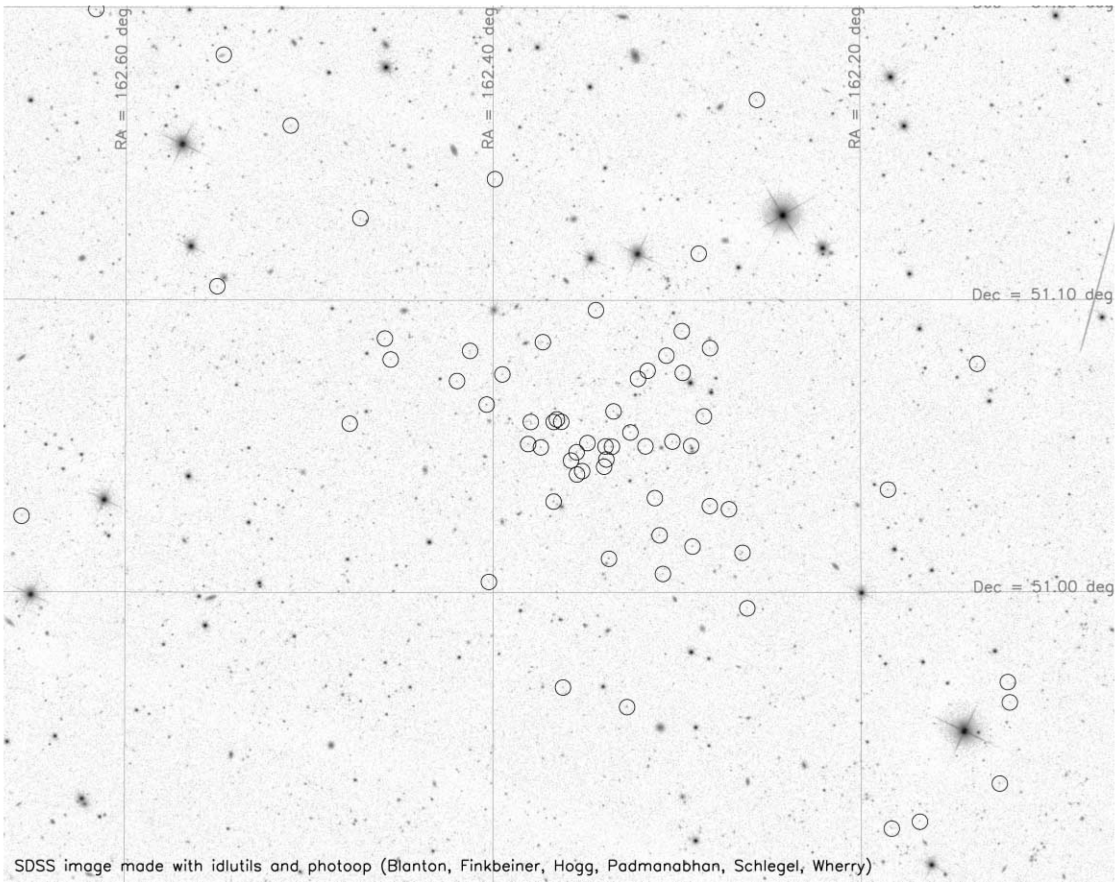

Fig. 1.—SDSS true-color g, r, i image of $0\overset{\circ}{.}57 \times 0\overset{\circ}{.}42$ centered on the detection. Stellar sources with colors consistent with blue horizontal-branch and main-sequence turnoff stars ($g - r < 0.3$) are circled. The image is made with color-preserving nonlinear stretches (Lupton et al. 2004). [*See the electronic edition of the Journal for a color version of this figure.*]

(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).

We discovered SDSS J1049+5103 as part of an ongoing SDSS survey for Milky Way satellite galaxies (Willman et al. 2002). This object was detected at $(\alpha_{2000}, \delta_{2000}) = (162\overset{\circ}{.}35, 51\overset{\circ}{.}05)$ as a 12 σ fluctuation over the average spatially smoothed density of stellar sources with $21.0 < r < 22.5$. (See Willman et al. [2002] and B. Willman et al. [2005, in preparation] for details of the survey analysis technique.) Although we have analyzed $\sim$5000 deg^2 of available photometric data thus far, the data relevant for this discovery are included in Data Release 2 (DR2) of the SDSS (Abazajian et al. 2004).

Figure 1 is a $0\overset{\circ}{.}57 \times 0\overset{\circ}{.}42$ g, r, i image centered on the detection. Because SDSS J1049+5103 is so sparse, it is difficult to see in the image alone. However, the stellar overdensity is readily visible in the overplotted spatial distribution of faint blue stars ($g - r < 0.3$). To more clearly illustrate the strength of the overdensity, we show a spatially smoothed density map of stars with $g - r < 0.65$ covering $0\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$ around the detection in Figure 2. This figure shows that the center of the cluster is detected at more than 20 σ over the foreground when only blue stars are included in the analysis. The density contours do not exhibit obvious evidence of tidal stripping, such as that seen around Pal 5 (Rockosi et al. 2002; Odenkirchen et al. 2003) and numerous other Milky Way GCs (Leon et al. 2000). However, a lack of obvious tidal features in the SDSS data is unsurprising, because the surface brightness of SDSS J1049+5103 is so faint. Therefore, deeper observations may reveal tidal distortion in the stellar distribution.

Our algorithm for detecting satellite galaxies is not optimized for the discovery of small scale length blue stellar overdensities such as SDSS J1049+5103. Therefore, to investigate whether numerous such systems remain undetected in the Milky Way's halo, we performed a friends-of-friends search for groups of stars with $g - r < 0.3$ and $r > 23$. We used a linking length of $0\overset{\prime}{.}8$ and examined groups with as few as five stars. Although this simple search recovered both SDSS J1049+5103 and all the known GCs and dSphs closer than 50 kpc in the area searched, no obvious new candidates were found. Unfortunately, AM 4, the lowest luminosity of the known clusters, is not in the SDSS area. It is thus unclear whether a comparably faint GC would have been detected with a simple friends-of-friends approach. Furthermore, the method we used is only sensitive to very blue star clusters closer than $\sim$50 kpc. It was nevertheless surprising that there appeared to be no other systems similar to SDSS J1049+5103 in the $\sim$5000 deg^2 currently covered in our search. However, if the Milky Way GC luminosity function (GCLF) at ultrafaint magnitudes does not deviate from that observed in the range $-4.0 < M_V < -7.4$, one would not expect to discover many additional GCs. Extrapolating the known GCLF (McLaughlin 1994; McLaughlin & Pudritz 1996) to faint magnitudes predicts a total of only a few undiscovered GCs fainter than $M_V = -4.0$ over the whole sky.

2.2. *Follow-up Observations*

On 2004 June 10 we obtained follow-up imaging of SDSS J1049+5103 on the 3.5 m telescope at Apache Point Observatory

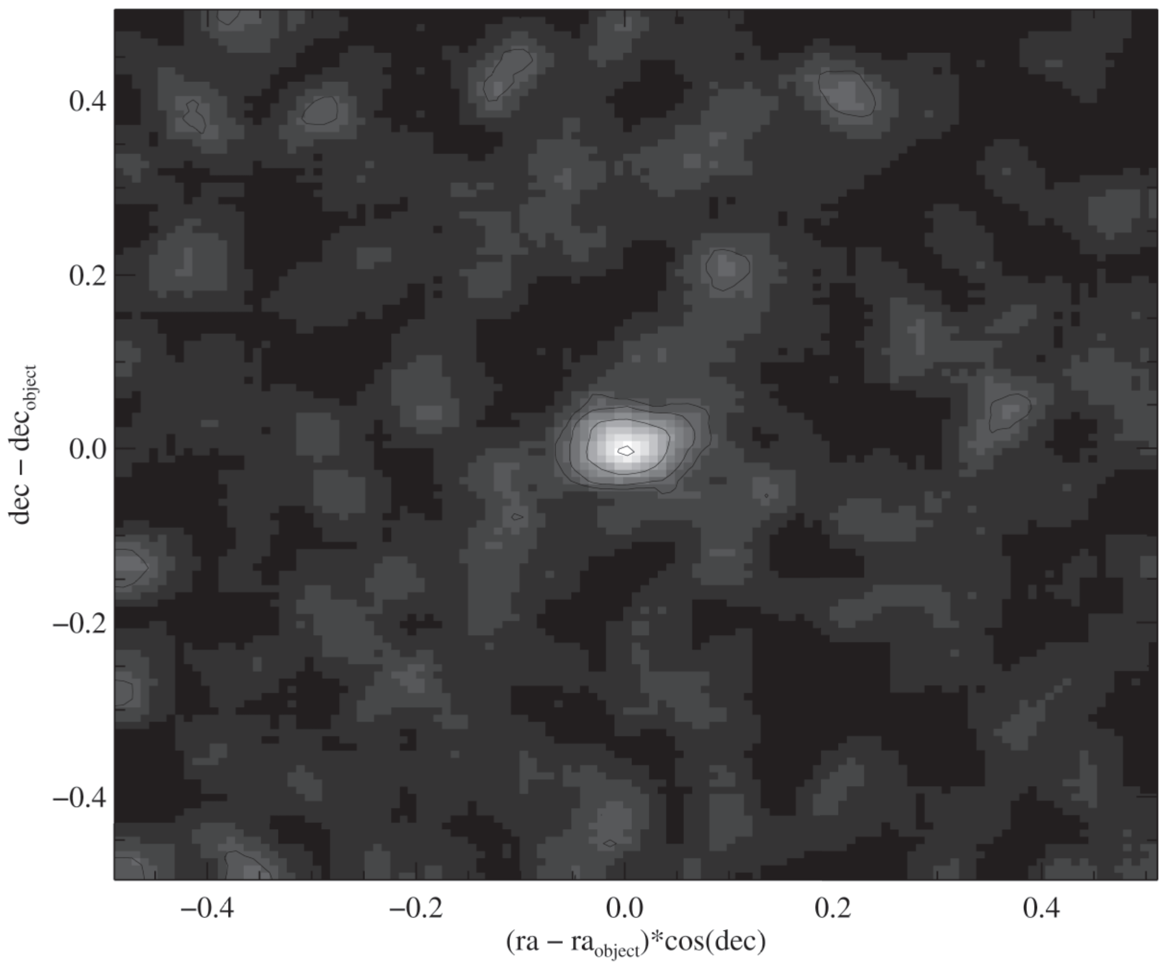

FIG. 2.—Smoothed image of stars with $g - r < 0.65$ and in a $0\overset{\circ}{.}5 \times 0\overset{\circ}{.}5$ field centered on the detection. The contours represent smoothed stellar densities of 3, 5, 10, and 20 σ above the foreground.

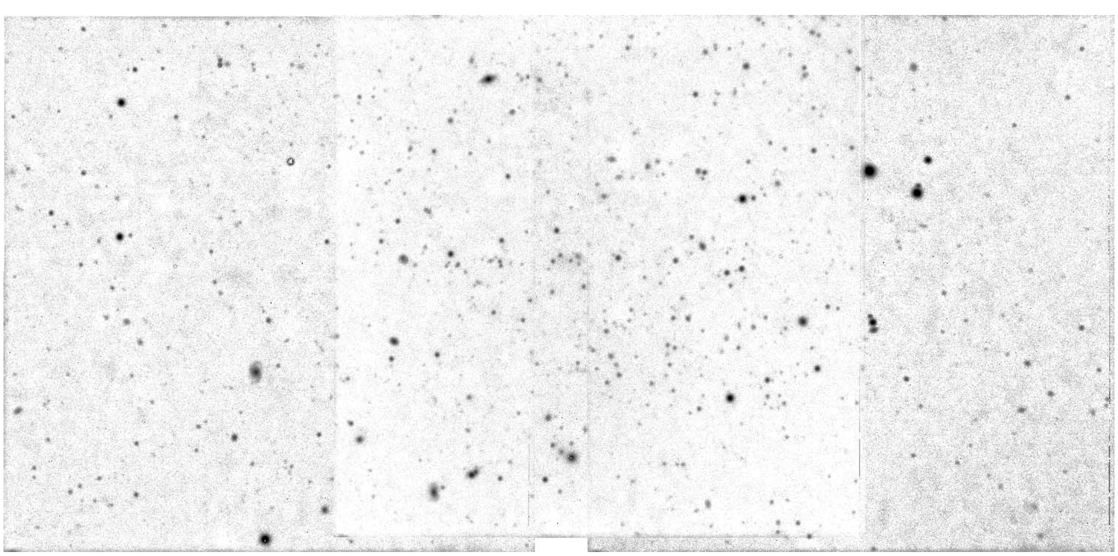

FIG. 3.—APO true-color g, r image of $0\overset{\circ}{.}2 \times 0\overset{\circ}{.}075$ centered on the detection. [*See the electronic edition of the Journal for a color version of this figure.*]

(APO). We used the SpiCAM 2048 × 2048 CCD, which has a resolution of 0″282 pixel^{-1}. Three 900 s exposures and one 600 s exposure were taken in the SDSS g filter, and 1200, 900, and 600 s exposures were taken in the SDSS r filter. Seeing was ∼1′6 in g and 1′4 in r, and observations were taken at high air mass. Thus, these combined observations are only sufficient to resolve stars as faint as $r \sim 23$. The total sky coverage of these data is ∼60 arcmin^2. These data were photometrically calibrated by comparison with SDSS observations of the same field.

Figure 3 is a 0°2 × 0°075 g, r image of the APO data. An overdensity of faint stars is visible near the center.

3. RESULTS

3.1. *Color-Magnitude Diagrams*

Figure 4 shows the color-magnitude diagram (CMD) of SDSS J1049+5103 and of the surrounding field as observed by SDSS. The stars in the "source" CMDs include all those within the central 1′75, which roughly corresponds to the half-light radius of the source (see § 3.2). The SDSS imaging data become incomplete near $r = 21.5$, because star-galaxy separation is unreliable at fainter magnitudes (Ivezić et al. 2000). These data have been corrected for reddening using the maps of Schlegel et al. (1998).

The CMD of SDSS J1049+5103 contains an overabundance of stars bluer than $g - r = 0.5$ relative to the field. We consider three broad possibilities for the nature of these blue stars:

1. A young, metal-rich stellar population with a main-sequence turnoff around $g - r = 0.3$.
2. An old, metal-poor stellar population with a main-sequence turnoff around $g - r = 0.3$.
3. A horizontal branch plus a few red giant branch stars.

Both a young, metal-rich and an old, metal-poor stellar population could have a main-sequence turnoff with $g - r \sim 0.3$. If the stars in SDSS J1049+5103 with $g - r \sim 0.3$ are indeed main-sequence turnoff stars, then the stars with $g - r = 0.45$ and $20 < r < 21$ are subgiant branch stars. However, those stars are bluer relative to the detected turnoff than subgiant stars of a young (<10 Gyr) stellar population (see isochrones in Girardi et al. 2004). We therefore consider it unlikely that SDSS J1049+5103 is a young, metal-rich stellar population.

To distinguish between the second and third possibilities, we compare the CMD of SDSS J1049+5103 to those of several low-luminosity GCs. We compare to empirical rather than theoretical isochrones because the main-sequence colors of theoretical isochrones in Sloan filters may be offset from those of actual old stellar populations (Girardi et al. 2004). Figure 5 shows the CMDs of Pal 5, Pal 15, and Pal 3 as observed by SDSS, with the empirically derived stellar locus of Pal 5 projected to the correct solar distance and overplotted on each CMD. The data in these plots have been corrected for reddening using the maps of Schlegel et al. (1998). The Pal 5 stellar locus does provide a reasonable match to both Pal 3's and Pal 15's stars but with a slight shift in color due to metallicity differences. Although Pal 5's stellar population has been shown to display mass segregation (Koch et al. 2004), it is nonetheless an acceptable basis for comparison because it is the most nearby, and thus the most well measured, of the sparse GCs in the SDSS area.

We overplotted the stellar locus of Pal 5 on the CMD of SDSS J1049+5103 in Figure 4. Considering the substantial photometric errors on stars fainter than $r = 21.5$ in the SDSS, the Pal 5 stellar locus projected to 45 and 170 kpc (plus an offset in color) both provide reasonable matches to the data. If the nearby distance is correct, then the blue stars are turnoff stars. If the far distance is correct, then they are horizontal-branch stars. The star at $(g - r,\ r) = (-0.32,\ 19.8)$, $(\alpha_{2000},\ \delta_{2000}) = (162°3048,\ 51°0424)$ has an SDSS spectrum (plate-MJD-fiber 876-52669-375) that shows it is a blue horizontal-branch star at a distance of 48 kpc, supporting the hypothesis that SDSS J1049+5103 is an old stellar system near $d = 45$ kpc.

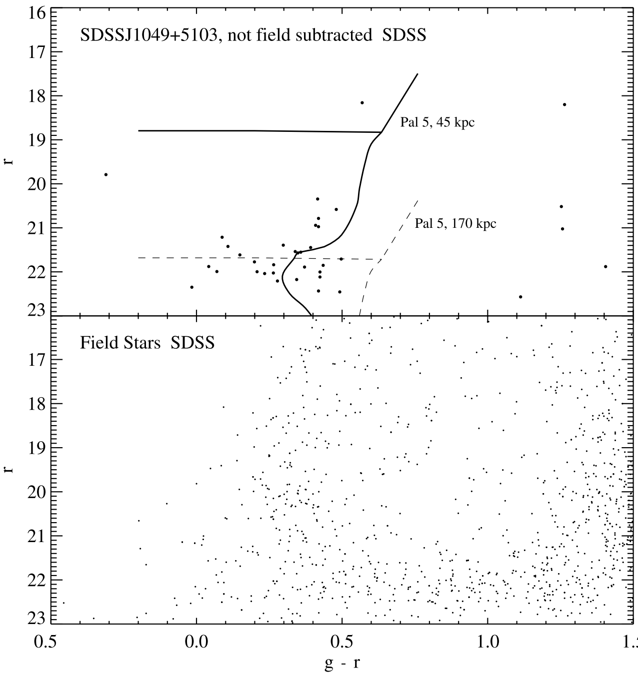

FIG. 4.—CMDs of the source and the surrounding field stars, as observed by SDSS. The source CMD includes all stars within 1′75 of the center and has not been field-subtracted. The field CMD includes all stars within 0°5 of the center. The stellar locus of Pal 5 stars that we empirically measured with SDSS data and projected to 45 and 170 kpc is overplotted. These data have been corrected for reddening (Schlegel et al. 1998).

The deeper CMD based on the APO data, shown in Figure 6, provides even more compelling evidence that the detected stellar overdensity is a turnoff at 45 kpc rather than a horizontal branch at 170 kpc. Pal 5 has an age of 11–12 Gyr (Martell et al. 2002) and an [Fe/H] $= -1.38$ (Harris 1996). The main-sequence turnoff of SDSS J1049+5103 is bluer than that of Pal 5. The bluer turnoff color may mean that this new companion is more metal-poor than Pal 5, although the small number of resolved stars in the existing data makes the metallicity difficult to estimate. We assign a generous uncertainty of ±10 kpc to the distance estimate to account for the fact that SDSS J1049+5103's turnoff may be intrinsically more or less luminous than that of Pal 5 (e.g., it would be intrinsically brighter if its stars were more metal-poor than and of a similar age to Pal 5's).

A few blue straggler candidates are visible in the CMD bluer than $g - r = 0.15$ and brighter than $r = 21.5$. Assuming that we are seeing the turnoff of an old, metal-poor population, SDSS J1049+5103 contains very few stars brighter than the subgiant branch. One known GC, AM 4, also appears to be devoid of any horizontal-branch or red giant branch stars. In § 3.3 we evaluate the significance of the dearth of evolved stars in SDSS J1049+5103.

Figure 7 shows the $(X,\ Z)$ distribution of the known Milky Way GCs and dSphs with the new detection overplotted. Our estimated distance of 45 kpc from the Sun places SDSS J1049+5103

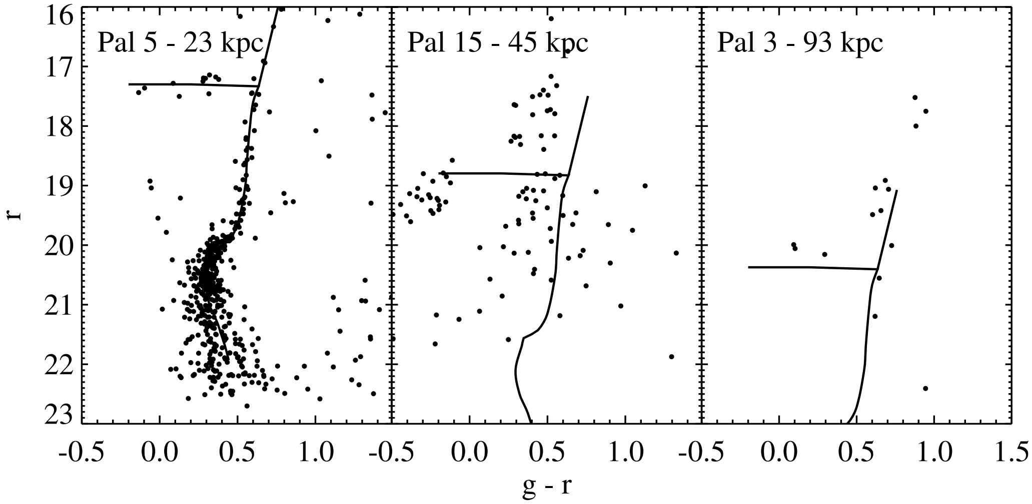

FIG. 5.—CMDs of the known GCs Pal 5, Pal 15, and Pal 3. All stars within their published half-mass radii (Harris 1996) are included in the CMDs. Pal 5's empirically derived stellar locus is projected to the distance of each cluster and overplotted for reference. These data have been corrected for reddening (Schlegel et al. 1998). Cluster distances are from Harris (1996).

at 50 kpc from the center of the Galaxy. If SDSS J1049+5103 is indeed a GC, it will add to the small number of GCs known to have galactocentric distances greater than 35 kpc.

3.2. *Radial Profile*

Figure 8 shows the azimuthally averaged radial profile of SDSS J1049+5103. Because our APO observations do not have sufficient area to properly subtract the foreground, we used a cut of $g - r < 0.65$ and $r < 22.5$ to eliminate the majority of foreground field stars from both the APO and the SDSS observations. Figure 8 shows that the SDSS stars satisfying these criteria approach a field density of $\sim$0.22 stars arcmin^{-1} by 4$'$.5 from the detection center. The dotted line denotes this adopted foreground level. The profile is consistent with a power law, with a possible break near 2$'$, and shows no evidence of a core at the center. However, the central radial bin in this plot has a radius of 1$'$.0 (13 pc at a distance of 45 kpc), so any core would likely be unresolved by the current data. The small number of stars also prevents us from measuring a reliable central surface brightness.

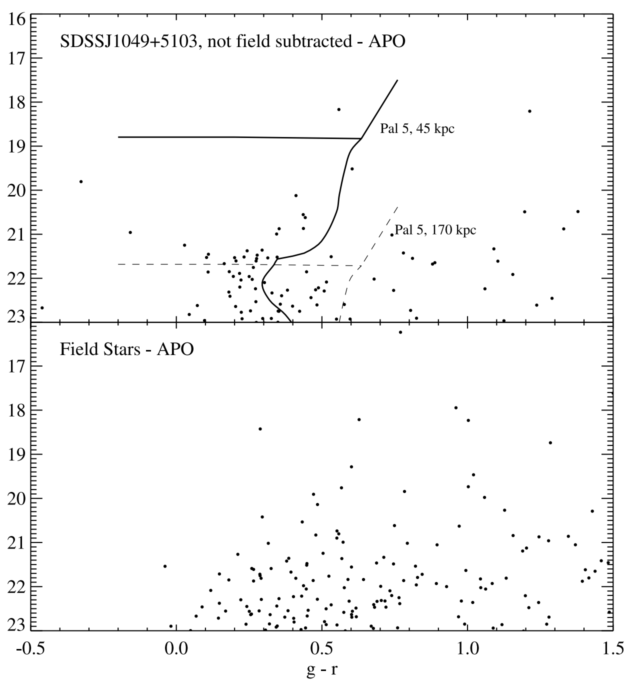

FIG. 6.—CMDs of the source and the surrounding field stars, as observed in follow-up observations at APO. As in Fig. 4, the source CMD includes all stars within 1$'$.75 of the center and is not field-subtracted. Seeing was $\sim$1$'$.6 in g and 1$'$.4 in r, and observations were taken at high air mass. The field CMD includes all other stars in the entire $\sim$60 arcmin^2 follow-up area. The stellar locus of Pal 5 stars, empirically measured with SDSS data and projected to 45 and 170 kpc, is overplotted. These data have been corrected for reddening (Schlegel et al. 1998).

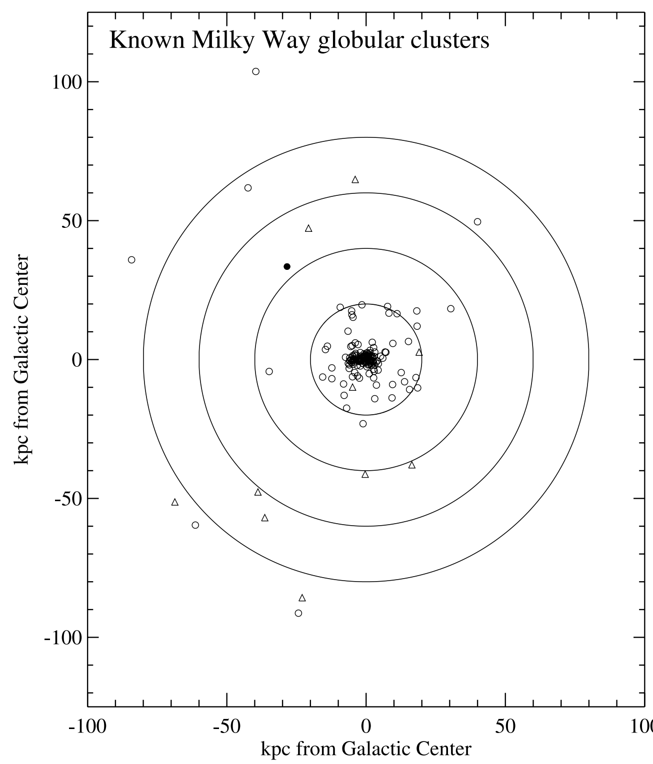

FIG. 7.—Spatial distribution of the (X, Z) positions of 150 known GCs (*open circles*; Harris 1996), 10 known nearby dwarfs (*triangles*; Mateo 1998), and the new companion (*filled circle*). The large circles show projected galactocentric distances of 20, 40, 60, and 80 kpc. The Galactic disk is oriented perpendicular to the y-axis.

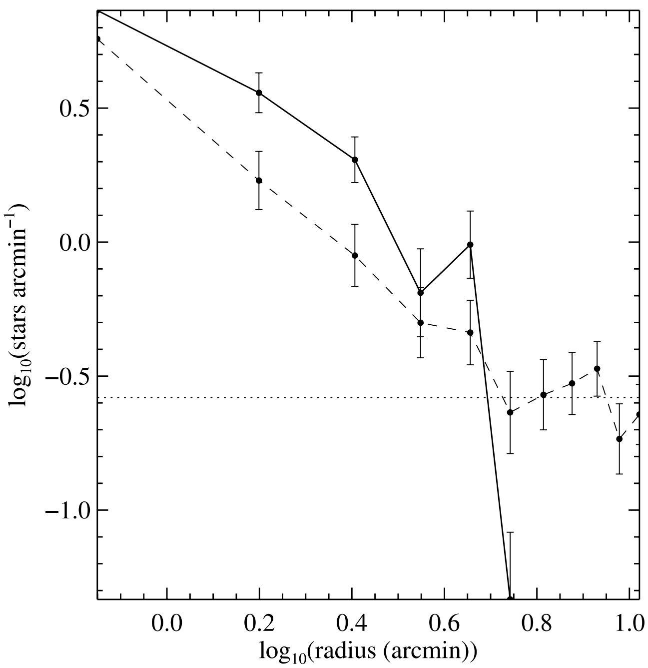

FIG. 8.—Radial profile of the stellar number density observed for the detection. The dotted line shows the adopted foreground stellar density of stars bluer than $g - r = 0.65$ and brighter than $r = 22.5$. Error bars were calculated assuming Poisson statistics.

We corrected the radial stellar counts for the foreground level overplotted on Figure 8 and estimated the half-light radius from the resulting cumulative radial profile shown in Figure 9. This estimate assumes that the stellar population is roughly constant with radius. The half-light radius, $r_{1/2}$, is a good way to characterize the initial size of stellar systems, because it changes slowly with their dynamical evolution (Murphy et al. 1990, among others). Both the SDSS data and the APO data yield $r_{1/2} \sim 1'.75$, which corresponds to a physical size of 23 pc at a distance of 45 kpc. Allowing for a generous uncertainty in $r_{1/2}$ of $\pm 0'.5$ and including a distance uncertainty of ± 10 kpc, we estimate a plausible range of physical half-mass radii of 13–36 pc.

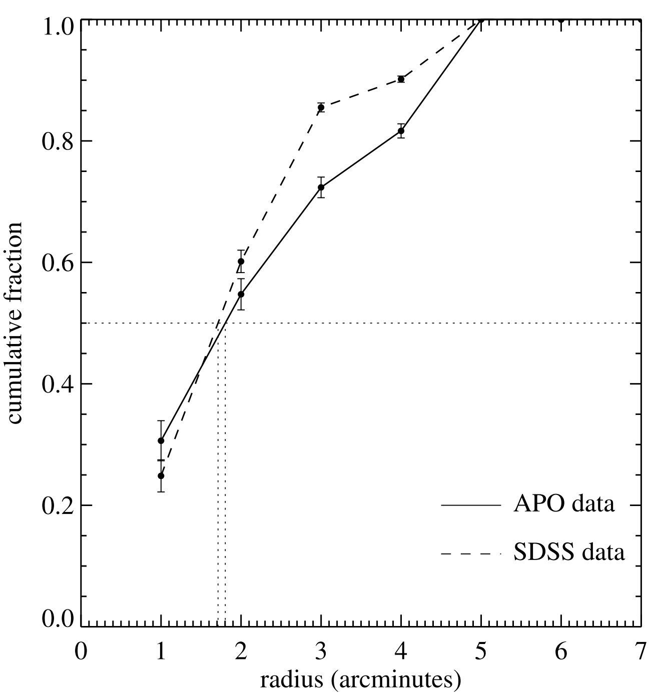

FIG. 9.—Cumulative radial distribution of stars in the detection that are bluer than $g - r = 0.65$ and brighter than $r = 22.5$. The cumulative fraction is corrected for the foreground stellar density overplotted in Fig. 8 and forced to be 1.0 at the radius beyond which observed stellar density reaches the foreground level. The dotted lines show the half-mass radii found with the SDSS and the APO data, assuming a constant stellar population with radius. Error bars were calculated assuming Poisson statistics.

If it is a GC, then SDSS J1049+5103 follows the well-known trend that all large-size GCs are in the outer Galactic halo (van den Bergh 2003). Pal 14 is the only known GC with a half-mass radius larger than 20 pc.

3.3. *Stellar Luminosity Function and Total Luminosity*

We use three approaches to estimate the total luminosity of SDSS J1049+5103. First, we estimate a lower limit by summing the luminosity of likely cluster stars within the half-light radius and then doubling the summed luminosity to account for stars outside the half-light radius. Taking all stars with $g - r < 0.65$ and $20.3 < r < 23.0$, and accounting for the liberal distance uncertainty stated above, this approach yields $M_{V,\,\mathrm{faint}} = -1.5 \pm 0.5$.

Second, we compare the observed stellar luminosity function of the new object to that of Pal 5. Table 1 shows the stellar luminosity functions of SDSS J1049+5103, as observed by both SDSS and APO, and of Pal 5 projected to 45 kpc. We include all stars bluer than $g - r = 0.65$ in the luminosity function of SDSS J1049+5103. The sharp increase at faint magnitudes in the ratio of SDSS J1049+5103 stars observed at APO to Pal 5 stars observed by SDSS is due to the fact that SDSS does not resolve stars as faint as those in the APO observation. The numbers in this table show that SDSS J1049+5103 has $\lesssim \frac{1}{5}$ the number of Pal 5 stars in each of the magnitude bins bright enough to be well resolved by SDSS. We thus divided Pal 5's luminosity by the conservatively small factor of 5 to yield $M_{V,\,\mathrm{bright}} = -3.3$. However, Table 1 shows that SDSS J1049+5103 has few, if any, stars brighter than $r \sim 20.5$, which means that it has few, if any, horizontal-branch or red giant branch stars. We thus crudely correct $M_{V,\,\mathrm{bright}}$ for the fact that ~30% of Pal 5's luminosity comes from stars brighter than the subgiant branch and find $M_{V,\,\mathrm{corr}} = -3.0$, which we adopt as the absolute magnitude of SDSS J1049+5103 for the rest of this paper. Accounting for distance uncertainty, we derive a maximum plausible luminosity of $M_V = -3.7$ with this technique, resulting in a total range of $-1 < M_V < -3.7$.

TABLE 1
STELLAR LUMINOSITY FUNCTION OF SDSS J1049+5103

m_r	N (SDSS)[a,b]	N (APO)[a,b]	N (Pal 5)[a,c]
<20.0	1	3	29
20.0–20.5	1	1	8
20.5–21.0	4	6	20
21.0–21.5	4	5	53
21.5–22.0	12	17	103
22.0–22.5	9	16	114
22.5–23.0	0	21	78
23.0–23.5	0	31	81
23.5–24.0	0	18	57

[a] The number of stars within the half-light radius, 1'.75 for SDSS J1049+5103 and 2'.9 for Pal 5, from Harris (1996).
[b] These numbers only include stars that are bluer than $g - r = 0.65$.
[c] These numbers have been properly corrected for field stars, and the luminosity function has been projected to 45 kpc.

Similar to SDSS J1049+5103, the GC AM 4 has no stars brighter than its main-sequence turnoff. By comparison with M3, Inman & Carney (1987) estimated that AM 4 should have 9 ± 1 stars brighter than its turnoff; however, it only has one. SDSS J1049+5103 is not as anomalous as AM 4 in that respect. By comparison with Pal 5, we estimate that there should be approximately seven stars in SDSS J1049+5103 with an apparent magnitude brighter than 20.5. The APO observations contain four candidates for such stars: $(g-r,\ r) = (0.41,\ 20.12)$, $(-0.33,\ 19.81)$ (the BHB star), (0.60, 19.52), and (0.56, 18.17). It is plausible that the dearth of bright red stars in SDSS J1049+5103 is simply due to its low stellar surface density. Furthermore, Pal 5 has been shown to exhibit radial mass segregation. This segregation causes stars at the bright end of Pal 5's luminosity function to be overrepresented in its central region, relative to what one would expect for an unrelaxed system. This bias could result in an overestimate of the expected number of horizontal and red giant branch stars for SDSS J1049+5103.

4. COMPARISON WITH THE PROPERTIES OF KNOWN STELLAR SYSTEMS

We now compare the properties estimated above to those of known GCs and dSphs.

4.1. M_V and $r_{1/2}$

We compare the estimated half-light radius, $r_{1/2}$, and absolute magnitude of SDSS J1049+5103 to those of the known Milky Way GCs and the Milky Way dSphs (except for Sagittarius) in Figure 10. We estimate the half-light radii of the dSphs using data from Mateo (1998) to determine the geometric mean of each core and tidal radius along the semimajor and semiminor axes and then integrate the corresponding King model. We shade the empirical size-luminosity locus followed by both the GCs and the dSphs. Because there are so few known Milky Way dSphs, their locus is not robustly known. We thus overplot the red galaxies from the SDSS low-luminosity galaxy catalog of Blanton et al. (2005). The Milky Way dSphs follow nearly the same size-luminosity relation followed by other red low-luminosity galaxies.

SDSS J1049+5103's combination of size and luminosity places it at the intersection of the relationships followed by GCs and by the nearby dSphs. Although SDSS J1049+5103 is 6 mag fainter than the faintest known Milky Way dwarf, its low surface brightness reraises the timely question, What is the difference between globular clusters and dwarf galaxies? The presence of dark matter is the apparent physical, and perhaps the fundamental, distinction between the two sets of objects. The fact that GCs are much more compact than dwarfs is the most easily measured and most reliable observational criterion for classification. However, Figure 10 shows that the size-luminosity relationships of GCs and of Milky Way dSphs overlap at low luminosities, highlighting the vague distinction between these two classes of objects. Furthermore, the 6 mag separating the faintest Milky Way dwarfs and SDSS J1049+5103 have not yet been uniformly searched for dwarfs. New surveys may uncover additional nearby faint galaxies, and then SDSS J1049+5103 would not be such an outlier from other dwarfs.

Indeed, Benson et al. (2002) predict the existence of Milky Way dwarf satellite galaxies as faint as the faintest GCs and with half-mass radii that roughly follow the same size-luminosity relation as the known dSphs. Three known GCs also fall within the overlapping size-luminosity region: AM 1, Pal 5, and Pal 14. Pal 5 is well known to currently be undergoing massive disruption by the Milky Way (Rockosi et al. 2002; Odenkirchen et al. 2003). Pal 14 is a young GC known to have the lowest central concentration of any known GC, and AM 1 is the most distant Milky Way GC ($d = 120$ kpc; Harris 1996). Pal 14 and AM 1 are obvious candidates to search for dark matter in nearby GCs.

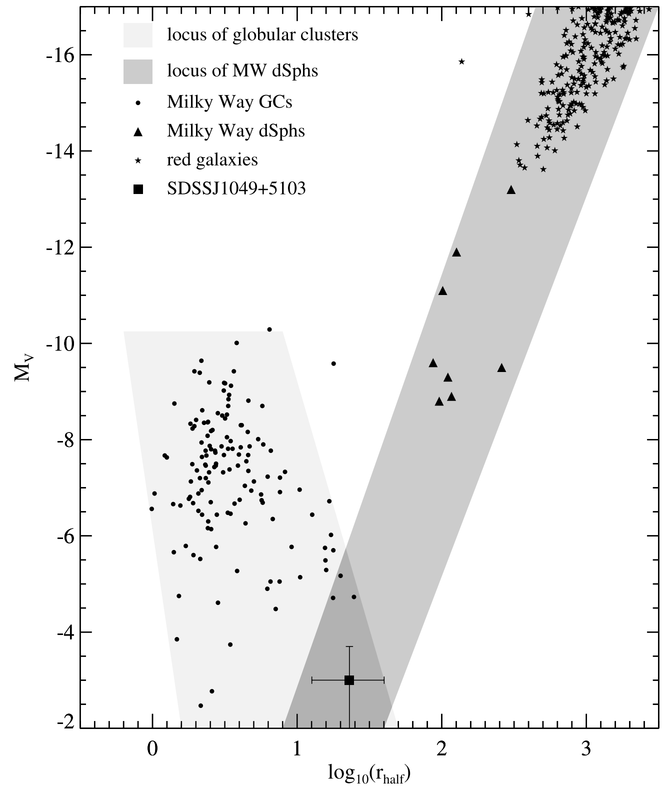

FIG. 10.—Absolute magnitudes and half-light radii of Milky Way GCs (*circles*), dSphs (*triangles*), faint red galaxies in the SDSS (*stars*; Blanton et al. 2005), and SDSS J1049+5103 (*square*). AM 4 is too faint ($M_V = +0.2$) to be included on this plot. The approximate loci of the GC and dSph data are shaded. The Milky Way dSphs appear to follow a similar size-luminosity relation to that of other faint red galaxies. Data are from Harris (1996) and Mateo (1998).

Figure 10 also shows that SDSS J1049+5103 is $\gtrsim 5$ times the physical size of other faint GCs. However, the fact that SDSS J1049+5103 is an apparent outlier in size from other faint GCs could be due to observational bias. A GC with a larger scale size than a cluster of the same total luminosity is more difficult to detect than the more compact cluster. Furthermore, all known large scale length GCs are in the outer halo (van den Bergh 2003). It is thus possible that other ultrafaint, large scale length GCs exist but are not detectable because they lie at outer halo distances where far fewer of their stars are resolved than if they were more nearby. The lack of other candidates identified by our friends-of-friends search may argue against this possibility.

4.2. *Mass*

If SDSS J1049+5103 is a GC, Figure 10 suggests that it has an anomalously large half-light radius. This raises the possibility that it is a GC undergoing tidal disruption. In this section we do a crude calculation of cluster mass and tidal radius to investigate whether the present data are consistent with this interpretation.

Mandushev et al. (1991) used the dynamical masses of 32 GCs to derive an empirical relationship between cluster mass and absolute magnitude:

$$\log(M_{GC}/M_\odot) = -0.456 M_V + 1.64. \qquad (1)$$

Given the result from § 3.3 that $-3.7 < M_V < -1.0$, this equation yields $10^{2.1}\ M_\odot < M < 10^{3.3}\ M_\odot$ for SDSS J1049+5103. We note that all the clusters used in their study were brighter than $M_V = -5.6$, so the reliability of the extrapolation to $M_V \sim -3.0$ is quite uncertain.

We estimate the tidal radii corresponding to this range of satellite masses using the equation

$$r_{\rm tidal} \sim R_{\rm GC}\left(\frac{M_{\rm GC}}{3M_{\rm MW}}\right)^{1/3} \quad (2)$$

from Binney & Tremaine (1987). In this equation, R is the satellite's galactocentric distance, and $M_{\rm MW}$ is the total mass of the Milky Way within that distance. We calculated $r_{\rm tidal}$ assuming $R_{\rm GC} = 50$ kpc and $v_c = 220$ km s^{-1} at that distance (as recently shown to be the case by Bellazzini 2004). The mass range estimated above yields 22 pc $< r_{\rm tidal} <$ 40 pc ($1'.7$–$3'.0$ at a solar distance of 45 kpc). This range of tidal radii is an upper limit on $r_{\rm tidal}$ for SDSS J1049+5103, if it is truly a low mass-to-light ratio system such as a GC. The satellite's pericentric distance could be much smaller than its present galactocentric distance, which would result in smaller derived tidal radii. Its radial profile does not exhibit a break until $r \sim 3'.5$, and it reaches the foreground stellar density at $r \sim 6'$. If the tidal radius of SDSS J1049+5103 is actually $\lesssim 1'.7$–$3'.0$, one may expect the stellar profile to exhibit a break characteristic of tidal stripping at $r < 3'.5$. However, the data are not yet deep enough to produce a robust measurement of the stellar distribution. The existing data thus allow the possibilities that SDSS J1049+5103 is a low mass-to-light ratio system that might be tidally stripped or that the stars are embedded in a more extended, higher mass-to-light ratio system.

5. SUMMARY AND FUTURE WORK

In this paper we report the discovery of SDSS J1049+5103, a new stellar system that is likely in the outer halo of the Milky Way. Based on comparison with Palomar 5, this new system appears to be ~50 kpc from the Galactic center and have a half-light radius of 23 pc and $M_V = -3.0^{+2.0}_{-0.7}$. SDSS J1049+5103 has a size and luminosity that places it at the intersection of the size-luminosity locus followed by Milky Way GCs and that followed by Milky Way dSphs and nearby faint red galaxies. Both the fundamentally ambiguous distinction between some GCs and dSph galaxies and the fact that SDSS J1049+5103 is unusual relative to the vast majority of GCs leave open the possibility that it is an extreme dwarf galaxy nearly 2 orders of magnitude fainter than Ursa Minor, the faintest known Milky Way dSph. Furthermore, some theories predict the presence of low central surface density, ultrafaint dSphs (e.g., Benson et al. 2002) such as SDSS J1049+5103. If SDSS J1049+5103 is a GC, then its properties are consistent with undergoing tidal disruption.

Neither the Willman et al. (2002) survey nor a friends-of-friends search revealed additional companions similar to, or even a bit fainter than, SDSS J1049+5103 in the 5000 deg^2 analyzed thus far. This suggests that there is not a substantial unknown population of similar companions closer than ~50 kpc.

We are in the process of obtaining both deep, wide-field imaging to accurately measure the spatial distribution of SDSS J1049+5103 and spectra of individual stars to measure ages, metallicities, and line-of-sight velocities. Specifically, deeper imaging may distinguish between a King and an NFW surface brightness profile and may also reveal tidal features, which would provide strong constraints on its current mass (Moore 1996).

B. W. and J. J. D. were partially supported by the Alfred P. Sloan Foundation. M. R. B., D. W. H., and N. W. were partially supported by NASA (grant NAG5-11669) and the NSF (grants PHY-0101738 and AST 04-28465). D. P. S. acknowledges support from NSF grant AST 03-07582. We thank David Martínez-Delgado, David Schlegel, and Douglas Finkbeiner for useful discussions and data analysis software. We also thank the anonymous referee for comments that improved this paper.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the University of Chicago, the US Department of Energy's Fermi National Accelerator Laboratory, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Korean Scientist Group, Los Alamos National Laboratory, the Max Planck Institute for Astronomy, the Max Planck Institute for Astrophysics, New Mexico State University, the University of Pittsburgh, Princeton University, the US Naval Observatory, and the University of Washington.

Funding for the project has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, NASA, the NSF, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society.

REFERENCES

Abazajian, K., et al. 2004, AJ, 128, 502
Ashman, K. M., & Zepf, S. E. 1998, Globular Cluster Systems (Cambridge: Cambridge Univ. Press)
Bellazzini, M. 2004, MNRAS, 347, 119
Benson, A. J., Frenk, C. S., Lacey, C. G., Baugh, C. M., & Cole, S. 2002, MNRAS, 333, 177
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)
Blanton, M. R., et al. 2005, AJ, submitted
Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2000, ApJ, 539, 517
Côté, P., Djorgovski, S. G., Meylan, G., Castro, S., & McCarthy, J. K. 2002, ApJ, 574, 783
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Girardi, L., Grebel, E. K., Odenkirchen, M., & Chiosi, C. 2004, A&A, 422, 205
Gunn, J. E., et al. 1998, AJ, 116, 3040
Harris, W. E. 1996, AJ, 112, 1487
Harris, W. E., Phelps, R. L., Madore, B. F., Pevunova, O., & Skiff, B. A. 1997, AJ, 113, 688
Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., & Gunn, J. E. 2001, AJ, 122, 2129
Hurt, R. L., Jarrett, T. H., Kirkpatrick, J. D., Cutri, R. M., Schneider, S. E., Skrutskie, M., & van Driel, W. 2000, AJ, 120, 1876
Inman, R. T., & Carney, B. W. 1987, AJ, 93, 1166
Irwin, M. J., Demers, S., & Kunkel, W. E. 1995, ApJ, 453, L21
Ivezić, Ž., et al. 2000, AJ, 120, 963
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Koch, A., Grebel, E. K., Odenkirchen, M., Martínez-Delgado, D., & Caldwell, J. A. R. 2004, AJ, 128, 2274
Kravtsov, A. V., Gnedin, O. Y., & Klypin, A. A. 2004, ApJ, 609, 482
Leon, S., Meylan, G., & Combes, F. 2000, A&A, 359, 907
Lupton, R., Blanton, M. R., Fekete, G., Hogg, D. W., O'Mullane, W., Szalay, A., & Wherry, N. 2004, PASP, 116, 133
Lupton, R. H., Gunn, J. E., Ivezić, Ž., Knapp, G. R., Kent, S., & Yasuda, N. 2001, in ASP Conf. Ser. 238, Astronomical Data Analysis Software and Systems X, ed. F. R. Harnden, Jr., F. A. Primini, & H. E. Payne (San Francisco: ASP), 269
Mackey, A. D., & Gilmore, G. F. 2004, MNRAS, 355, 504
Madore, B. F., & Arp, H. C. 1982, PASP, 94, 40
Mandushev, G., Staneva, A., & Spasova, N. 1991, A&A, 252, 94
Martell, S. L., Smith, G. H., & Grillmair, C. J. 2002, BAAS, 34, 1103
Mateo, M. L. 1998, ARA&A, 36, 435

McLaughlin, D. E. 1994, PASP, 106, 47
McLaughlin, D. E., & Pudritz, R. E. 1996, ApJ, 457, 578
Moore, B. 1996, ApJ, 461, L13
Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. 1999, ApJ, 524, L19
Murphy, B. W., Cohn, H. N., & Hut, P. 1990, MNRAS, 245, 335
Odenkirchen, M., et al. 2003, AJ, 126, 2385
Ortolani, S., Bica, E., & Barbuy, B. 1993, A&A, 273, 415
———. 2000, A&A, 361, L57
Pier, J. R., Munn, J. A., Hindsley, R. B., Hennessy, G. S., Kent, S. M., Lupton, R. H., & Ivezić, Ž. 2003, AJ, 125, 1559
Rockosi, C. M., et al. 2002, AJ, 124, 349
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Smith, J. A., et al. 2002, AJ, 123, 2121
Stoughton, C., et al. 2002, AJ, 123, 485
Susa, H., & Umemura, M. 2004, ApJ, 610, L5
van den Bergh, S. 2003, ApJ, 590, 797
Willman, B., Dalcanton, J., Ivezić, Ž., Jackson, T., Lupton, R., Brinkmann, J., Hennessy, G., & Hindsley, R. 2002, AJ, 123, 848
York, D. G., et al. 2000, AJ, 120, 1579