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A FAINT NEW MILKY WAY SATELLITE IN BOOTES

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ABSTRACT

We announce the discovery of a new satellite of the Milky Way in the constellation of Bootes at a distance of ~60 kpc. It was found in a systematic search for stellar overdensities in the north Galactic cap using Sloan Digital Sky Survey Data Release 5. The color-magnitude diagram shows a well-defined turnoff, red giant branch, and extended horizontal branch. Its absolute magnitude is $M_V \sim -5.8$ mag, which makes it one of the faintest galaxies known. The half-light radius is ~220 pc. The isodensity contours are elongated and have an irregular shape, suggesting that Boo may be a disrupted dwarf spheroidal galaxy.

Subject headings: galaxies: dwarf — galaxies: individual (Bootes) — Local Group

1. INTRODUCTION

The last few years have seen a number of discoveries of new satellite companions to the Milky Way. Willman (2006) systematically surveyed ~5800 deg^2 of the Sloan Digital Sky Survey (SDSS; York et al. 2000) and identified two strong candidates. The first, now called Willman 1, is an unusually extended object with properties intermediate between those of globular clusters and dwarf galaxies (Willman et al. 2005a). The second proved to be a new dwarf spheroidal (dSph) companion to the Milky Way, located in the constellation of Ursa Major (Willman et al. 2005b; Kleyna et al. 2005).

Very recently, Zucker et al. (2006) serendipitously discovered a stellar overdensity in the "Field of Streams" (Belokurov et al. 2006), a plot of the halo substructure in the Galactic northern hemisphere derived from SDSS Data Release 5 (DR5; Adelman-McCarthy et al. 2006). Closer analysis revealed that this was a new dwarf spheroidal galaxy, Canes Venatici, at a distance of ~200 kpc. All this suggests that there remain unknown Milky Way companions and that further systematic surveys to find them are warranted. Here we describe a simple algorithm to carry this out in SDSS DR5 and present another strong candidate for a Milky Way satellite, lying in the constellation of Bootes. The properties of this object are somewhat unusual.

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2. DATA AND DISCOVERY

SDSS imaging data are produced in five photometric bands, namely *u*, *g*, *r*, *i*, and *z* (Fukugita et al. 1996; Gunn et al. 1998, 2006; Hogg et al. 2001). Thanks to the efforts of many people, the data are automatically processed through pipelines to measure photometric and astrometric properties (Lupton et al. 1999; Stoughton et al. 2002; Smith et al. 2002; Pier et al. 2003; Ivezić et al. 2004).

To carry out a systematic survey, the stars with $16 \leq r \leq 22$ are first binned into $10' \times 10'$ regions in right ascension and declination. Then, a running window of size $1° \times 1°$ is used to compute the background. All bins that are more than 3 σ away from the background are selected. Known satellite galaxies and globular clusters are removed using the list of van den Bergh (2000a). Visual inspection is used to discard a few obvious contaminants, such as resolved stellar associations in background galaxies. All the candidates are ranked according to signal-to-noise ratio. The two strongest candidates that remain are the Canes Venatici dSph (Zucker et al. 2006) and the object studied in this Letter, which is named Boo after the constellation of Bootes in which it lies.

The top left panel of Figure 1 shows a gray-scale SDSS image of the sky centered on Boo. There is no obvious object. However, on plotting the density of all objects classified by the SDSS pipeline as stars, a curiously shaped overdensity is readily visible (*top middle and top right panels*). Plotting these stars in a color-magnitude diagram (CMD) reveals a clear red giant branch and horizontal branch (*bottom panels*). This evidence of a localized overdensity of stars with a distinct CMD suggests that this is a new satellite—possibly a dwarf galaxy.

3. PHYSICAL PROPERTIES AND STELLAR POPULATION

Follow-up observations of Boo were made on 2006 February 25 and 2006 March 7 (UT) with the 4 m Blanco telescope at Cerro Tololo Inter-American Observatory in Chile, using the MOSAIC-II CCD camera. This comprises eight 2K × 4K pixel

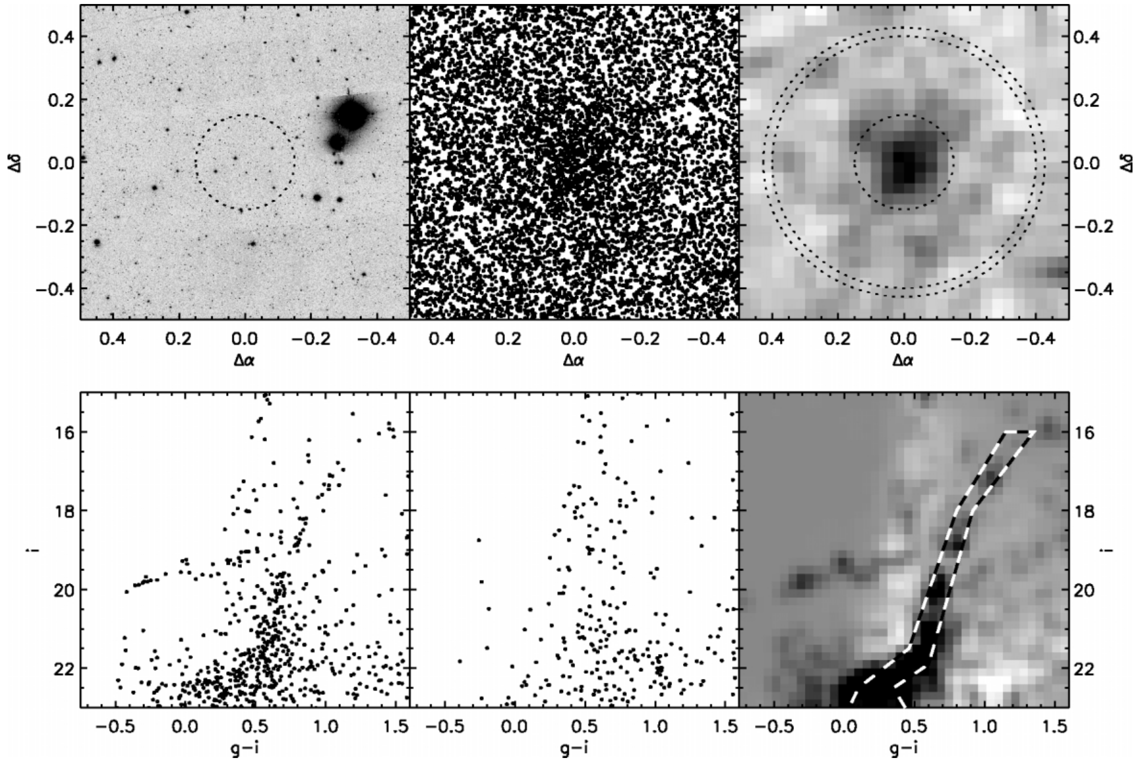

FIG. 1.—Bootes satellite. *Top left*: Combined SDSS *g*, *r*, *i* images of a 1° × 1° field centered on the overdensity; $\Delta\alpha$ and $\Delta\delta$ are the relative offsets in right ascension and declination, measured in degrees; the dotted circle indicates a radius of 0°.15. *Top middle*: Spatial distribution of all objects classified as stars in the same area. *Top right*: Binned spatial density of all stellar objects. The inner dotted circle marks a radius of 0°.15 and encloses the same area as the two outer circles, which have radii of 0°.4 and 0°.43. Bins are 0°.033 × 0°.033, smoothed with a Gaussian with a FWHM of 0°.1. *Bottom left*: CMD of all stellar objects within the inner 0°.15 radius circle. There is a clear red giant and horizontal branch, even without removal of field contamination. *Bottom middle*: Control CMD, showing all stellar objects in the annulus between 0°.4 and 0°.45 of the center. *Bottom right*: Color-magnitude density plot (Hess diagram) showing the inner CMD minus the control CMD, normalized to the number of stars in each CMD. A mask is shown around the satellite's sequence.

SITe CDDs, with a field of view 36′ × 36′ and a scale of 0″.27 pixel^{-1} at the image center. Boo was observed in the *g* and *i* bands, with exposure times of 3 × 360 s in each filter on the first night and 3 × 600 s in each filter on the second night, for a total exposure of 2880 s in each filter. The telescope was offset (≈30″) between exposures.

Data were processed in Cambridge using a general purpose pipeline for processing wide-field optical CCD data (Irwin & Lewis 2001). Images were debiased and trimmed, and then flat-fielded and gain-corrected to a common internal system using clipped median stacks of nightly twilight flats. The *i*-band images, which suffer from an additive fringing component, were also corrected using a fringe frame computed from a series of long *i*-band exposures taken during the night.

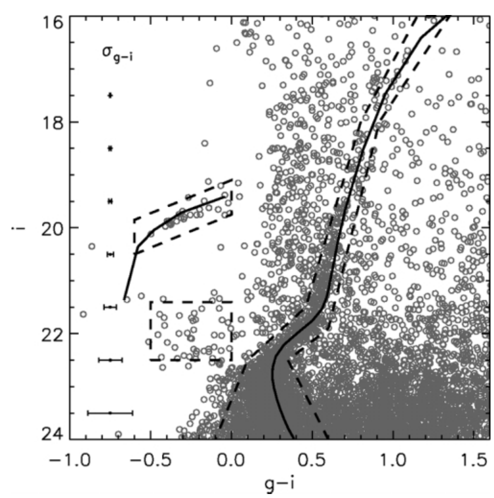

FIG. 2.—CMD of Boo derived from CTIO data. Overplotted is the ridge line for the old, metal-poor globular cluster M92. The dashed lines are used to select stars belonging to the main sequence, giant branch, and horizontal branch of the satellite. For each magnitude bin, the mean color error is shown on the left-hand side.

For each image frame, an object catalog was generated using the object detection and parameterization procedure discussed in Irwin et al. (2004). Astrometric calibration of the individual frames is based on a simple zenithal polynomical model derived from linear fits between catalog pixel-based coordinates and standard astrometric stars derived from online APM plate catalogs. The astrometric solution was used to register the frames prior to creating a deep stacked image in each passband. Object catalogs were created from these stellar images and objects morphologically classified as stellar or nonstellar (or noiselike). The detected objects in each passband were merged by positional coincidence (within 1″) to form a *g*, *i* combined catalog. This catalog was photometrically calibrated onto the SDSS system using the overlap with the SDSS catalogs.

Figure 2 shows a CMD constructed from the CTIO data. The fiducial ridgeline of the metal-poor globular cluster M92 ([Fe/H] ∼ −2.3) from Clem (2005) is overplotted on the CMD. The horizontal branch is well matched, although Boo's giant branch and main-sequence turnoff are slightly blueward of the M92 isochrone. This is consistent with Boo being somewhat younger and slightly more metal-poor than M92. Note in particular the narrowness of the giant branch of the CMD in Figure 2, as evidenced by the mean color error bar shown on the left-hand side. This is characteristic of single-epoch stellar populations,

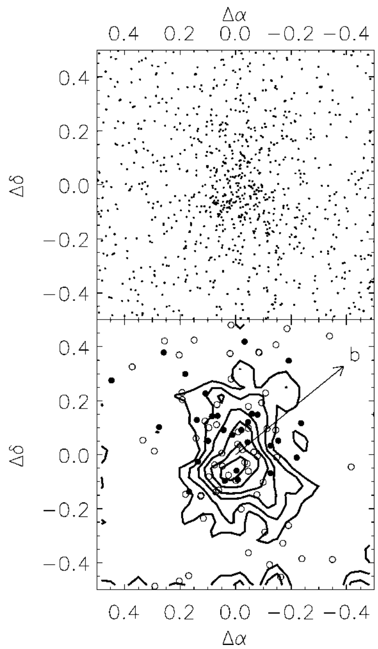

FIG. 3.—Morphology of Boo. *Top*: Spatial distribution of SDSS stars selected from CMD regions marked with dashed lines in Fig. 1. *Bottom*: Contour plot of the spatial distribution of Boo's stars; candidate blue horizontal branch stars and blue stragglers (from the boxes in the CMD) are overplotted with black dots and open circles. The contours are 1.5, 3, 5, 7, 10, and 13 σ above the background level. The direction of increasing Galactic latitude is marked by an arrow.

TABLE 1
Properties of the Bootes Satellite

Parameter[a]	Value
Coordinates (J2000)	$14^h00^m06^s$, $+14°30'00'' \pm 15''$
Galactic coordinates (l, b)	358°.1, 69°.6
Position angle	$10° \pm 10°$
Ellipticity	0.33
r_h (Plummer)	$13'.0 \pm 0'.7$
r_h (exponential)	$12'.6 \pm 0'.7$
A_V	0.06 mag
$\mu_{0,V}$ (Plummer)	28.3 ± 0.5 mag
$\mu_{0,V}$ (exponential)	27.8 ± 0.5 mag
V_{tot}	13.6 ± 0.5 mag
$(m - M)_0$	18.9 ± 0.20 mag
$M_{tot,V}$	-5.8 ± 0.5 mag

[a] Surface brightnesses and integrated magnitudes are corrected for the mean Galactic foreground reddenings A_V (shown).

which are normally associated with globular clusters. However, although most dSph galaxies show evidence of multiple stellar populations, a few are known whose CMDs possess narrow red giant branches, such as Ursa Minor and Carina (van den Bergh 2000b). In both cases, the narrow red giant branch is nonetheless consistent with a number of epochs of star formation (see, e.g., Shetrone et al. 2001; Koch et al. 2006). From the fact that the horizontal branch of M92 provides a good fit, we can estimate the distance of Boo. The distance modulus is $(m - M)_0 \sim 18.9 \pm 0.2$, corresponding to ~$60 \pm 6$ kpc, where the error bar includes the uncertainty based on differences in stellar populations of Boo and M92, as well as the uncertainty in the distance of M92. Note also that there is a prominent clump in the CMD below the horizontal branch, where Boo's blue straggler population resides.

Even though the CMD resembles that of a globular cluster, this is emphatically not the case for the object's morphology and size. To select candidate stars, we use the boundaries marked by the dashed lines on the CMD, which wrap around the satellite sequence. SDSS data are used here, as the CTIO data are largely confined to the inner parts of Boo. The locations of SDSS stars with $r < 23$ lying within the boundaries are plotted in the top panel of Figure 3. These objects are binned into 30×30 bins, each 0°.033 × 0°.033, and smoothed with a Gaussian with FWHM of 0°.067 to yield the plot in the bottom panel. The density contours, representing 1.5, 3, 5, 7, 10, and 13 σ above the background level, are elongated and irregular—more so than even the most irregular of the Galactic dSphs, Ursa Minor (see, e.g., Palma et al. 2003). The black dots are candidate blue horizontal branch stars, and open circles are blue stragglers. The spatial distribution of both populations is roughly consistent with the underlying density contours and shows the same tail-like extensions. There are hints that Boo could be a much larger object, as the blue horizontal branch and straggler population extend beyond the outermost contours.

To estimate the properties listed in Table 1, we use the SDSS data shown in Figure 3 to derive the centroid from the density-weighted first moment of the distribution, and the average ellipticity and position angle using the three density-weighted second moments (e.g., Stobie 1980). The radial profile shown in Figure 4 is derived by computing the average density within elliptical annuli after first subtracting a constant asymptotic background level (0.2 arcmin^{-2}) reached at large radii. We then fit the radial profile with standard Plummer and exponential laws (Fig. 4; see also Irwin & Hatzidimitriou 1995). The best-fitting position angle, ellipticity, and half-light radius are listed in Table 1. At a distance of ~60 kpc, the half-light radius of 13'.0 corresponds to ~220 pc. This is the typical scale length of the Galactic dSph galaxies, and a factor of ~10 times larger than the scale length of the largest Galactic globular clusters. Note that neither the Plummer nor the exponential laws provide exceptional fits to the data; in particular, the center of the object is not well fitted and appears to lack a clearly defined core. Although Boo appears superficially somewhat similar to Willman 1, it is substantially larger and more luminous. Willman 1 has a characteristic scale length of only ~20 pc and an absolute magnitude of $M_{tot,V} \sim -2.5$ mag. The stellar populations are also different; for example, Willman 1 has no red-giant or horizontal-branch stars (Willman et al. 2006).

The overall luminosity is computed by masking the stellar

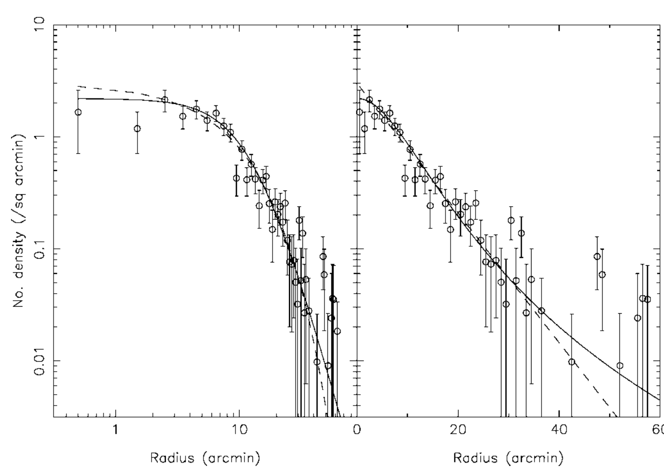

FIG. 4.—Profile of Boo, showing the stellar density in elliptical annuli as a function of mean radius. The left panel is logarithmic in both axes, and the right panel is linear in radius. The overplotted lines are fitted Plummer (*solid line*) and exponential (*dashed line*) profiles.

locus of Boo in the CMD in Figure 1 and computing the total flux within the mask and within the elliptical half-light radius. A similar mask, but covering a larger area to minimize shot noise, well outside the main body of Boo is scaled by relative area and used to compute the foreground contamination within the half-light radius. After correcting for this contamination, the remaining flux is scaled to the total, assuming the fitted profiles are a fair representation of the overall flux distribution. We also apply a correction of 0.3 mag for unresolved/faint stars, based on the stellar luminosity functions of other low-metallicity, low surface brightness dSphs. The resulting luminosity estimate is $M_{\rm tot,\,V} \sim -5.8$ mag. Applying our procedure to the Ursa Major dSph, discovered by Willman et al. (2005a), gives $M_{\rm tot,\,V} \sim -5.5$ mag. We conclude that Boo is, within the uncertainties, comparable in faintness to Ursa Major.

We argue that Boo is not a tidally disrupted globular cluster as follows. First, it is much too extended. If a globular cluster is tidally disrupted, its half-light radius may increase somewhat, but it does not grow to such an immense radius as ∼220 pc. Second, for it to be a destroyed globular cluster, Boo would have to be on a plunging radial orbit. Then the outermost isodensity contours, which should be aligned with the direction of the proper motion, should point toward the Galactic center. This is not the case, as judged from Figure 3. Third, globular clusters often show evidence for mass segregation driven by internal dynamical evolution (see, e.g., Koch et al. 2004). Accordingly, Figure 5 shows normalized luminosity functions for the inner and outer parts of Boo constructed with the CTIO data. There is no evidence for substantial mass segregation in Boo with the present data. However, these data are largely restricted to stars of similar mass, and deeper data are required to give a conclusive result.

4. CONCLUSIONS

We have discovered a new companion to the Milky Way in the constellation of Bootes. The object has a globular-cluster-like CMD, dominated by an old, metal-poor stellar population. With a characteristic scale length of 220 pc, the size of the object is typical of the Galactic dwarf spheroidal satellites. The irregular nature of the density contours suggests that it may be undergoing tidal disruption. If, as seems likely, it is a dwarf galaxy, then Boo is one of the faintest ($M_V \sim -5.8$ mag) so far discovered.

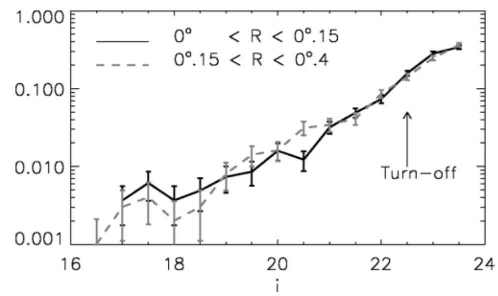

FIG. 5.—Normalized luminosity functions of the inner (*solid line*) and outer (*dashed line*) parts of Boo, constructed with the CTIO data. The main-sequence turnoff is indicated by the arrow.

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