A PAIR OF BOÖTÉS: A NEW MILKY WAY SATELLITE

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ABSTRACT

As part of preparations for a southern sky search for faint Milky Way dwarf galaxy satellites, we report the discovery of a stellar overdensity in the Sloan Digital Sky Survey Data Release 5, lying at an angular distance of only 1.5° from the recently discovered Boötes dwarf. The overdensity was detected well above statistical noise by employing a sophisticated data-mining algorithm and does not correspond to any cataloged object. Overlaid isochrones using stellar population synthesis models show that the color-magnitude diagram of that region has the signature of an old (12 Gyr), metal-poor (Fe/H ≈ −2.0) stellar population at a tentative distance of 60 kpc, evidently the same heliocentric distance as the Boötes dwarf. We estimate the new object to have a total magnitude of $M_V \sim -3.1 \pm 1.1$ mag and a half-light radius of $r_h = 4.1' \pm 1.6'$ (72 ± 28 pc), placing it in an apparent 40 pc $< r_h < 100$ pc void between globular clusters and dwarf galaxies, occupied only by another recently discovered Milky Way satellite, Coma Berenices.

Subject headings: galaxies: dwarf — Local Group

1. INTRODUCTION

The last 3 years have seen a torrent of new Milky Way (MW) satellites being discovered in the northern hemisphere, almost doubling the number known prior to 2005: Boötes (Belokurov et al. 2006a), Canes Venatici (Zucker et al. 2006a), Willman 1 (Willman et al. 2005a), Ursa Major (Willman et al. 2005b), Ursa Major II (Zucker et al. 2006b), Hercules, Coma Berenices, SEGUE 1, Canes Venatici II, Leo IV (Belokurov et al. 2006b), and Leo T (Irwin et al. 2007). Eight of these new objects are consistent in size and luminosity with dwarf spheroidal satellites, while Willman 1 and Segue 1 straddle the intersection of dwarfs and globular clusters. Coma Berenices falls in an apparent void of objects spanning the 40–100 pc range (see Fig. 1 in Gilmore et al. 2007).

These objects were all initially detected as overdensities of resolved stars in the photometric data of the Sloan Digital Sky Survey (SDSS; York et al. 2000) and, with the exception of Leo IV, subsequently confirmed with follow-up observations. The numerous discoveries of extremely low surface brightness dwarf spheroids (dSphs) in the $\frac{1}{4}$ of the sky covered by SDSS strongly suggests that there are many more yet undiscovered. A significant new population of dwarf satellite galaxies would go a long way toward reconciling the current discrepancy between LCDM theory predictions (Klypin et al. 1999; Moore et al. 1999) and actual observed dSph numbers.

The next few years will see the advent of digital surveys that will enable all-sky searches for Milky Way satellites (e.g., PanSTARRS; Kaiser et al. 2005). We intend to blindly scan the entire southern sky (20,000 deg$^2$) for new MW dwarf satellites with the upcoming Southern Sky Survey performed with the 1.3 m ANU SkyMapper telescope at Siding Spring (Keller et al. 2007). The final combined ∼25 TB catalog of the survey is estimated to reach a signal-to-noise ratio of 5 at $r = 22.6$, 1.0 mag deeper than SDSS. In preparation for this survey, we are testing sensitive data-mining algorithms and search strategies using the freely available SDSS Data Release 5 (DR5; Adelman-McCarthy et al. 2006). A full overview, results, and a detailed discussion will be presented in a subsequent paper (S. Walsh et al. 2007, in preparation). Our software test on SDSS data has yielded several promising candidates, the most prominent of which we present here. While follow-up observations will reveal the candidate’s true nature in more detail, its size and luminosity are consistent with those of the other recent detections that have been labeled dwarf spheriodals. We thus follow convention and designate it Boötes II.

2. DATA AND DISCOVERY

DR5 includes a five-color photometric catalog covering 8000 deg$^2$ around the north Galactic pole (Adelman-McCarthy et al. 2006). We have searched this publicly available data for concentrations of old stars at various distance intervals out to the Galactic virial radius of 250 kpc. We use a method similar to that described in Willman et al. (2002) and Willman (2003), and described in full in S. Walsh et al. (2007, in preparation). We use a complicated set of cuts to identify all stellar sources in fields of 3° height in declination and of arbitrary width in right ascension that are consistent in $(g - r, r)$ parameter space with that of a dSph at a desired distance (red giant branch, blue horizontal branch, and main-sequence turnover). We then convolve the binned spatial positions of these sources with an exponential surface brightness profile and subtract the 0.9° × 0.9° running mean from each 0.02° × 0.02° pixel. A density threshold in standard deviations above the local mean is defined as a function of the background stellar density for each pixel, allowing us to search over fields with stellar density gradients. The process is repeated for different magnitude bins to change sensitivity with distance.

Applying this method to DR5, we recovered all of the recently reported dSphs, as well as many previously known objects such as globular clusters (GCs) and background galaxy clusters. The detection significance of the faintest dwarfs, quantified by the parameter $P$ (maximum level above threshold density times area above threshold), are shown in Figure 1, along with the result for the new object. The solid curve shows the number of “detections” in 39 1000 deg$^2$ randomized stellar fields, each of varying stellar density to determine foreground contamination from random clustering. The newly discovered satellites (minus SEGUE 1, which fell outside the analyzed...
area) as well as the Boötes II overdensity are all well above the threshold \( P = 85 \) above which our detection algorithm statistically yields less than one false-positve detection over the entire area of DR5. The Boötes II overdensity is not associated with any known Galactic or extragalactic object and is consistent in \((g - r)\) and size-luminosity space with a new dwarf. Figure 2 shows the position of Boötes II relative to Boötes.

Figure 3 shows our detections of Coma Berenices, Boötes II, and Boötes. The contours represent the level above the threshold density, which is then multiplied by the detection area to give \( P \). Coma Berenices and Boötes II peak at higher densities because they are more concentrated than Boötes, but the latter’s spatial extent means that it is still a stronger detection. The detection of Boötes II is consistent in all respects with the detections of the other Galactic satellites, albeit much fainter.

3. CANDIDATE PROPERTIES

We use SDSS data to extract as much information as possible and to estimate preliminary parameters for Boötes II (Table 1). The overdensity is visible even before smoothing, and the lack of a concentration of background galaxies (Fig. 4) allows us to exclude a galaxy cluster as an origin. The color-magnitude diagram (CMD) in Figure 3 reveals a weak red giant branch and blue horizontal branch (or red clump) at a distance modulus apparently identical to that of Boötes, and similar to the Coma Berenices dwarf \((m - M = 18.2;\) Belokurov et al. 2006b). The CMD features become even more prominent in the associated area-normalized field-subtracted Hess diagram. Overplotted is the isochrone of a metal-poor ([Fe/H] = −2.0), old (12 Gyr) stellar population (Girardi et al. 2004) to illustrate the consistency of our object with an old stellar population. Using the assumed distance modulus of \((m - M) = 18.9 (60 \text{ kpc})\), which is the same heliocentric distance of the Boötes dwarf, Boötes II would lie at a spatial distance of only \(~1.6 \text{ kpc}\) from Boötes. This hints at a physical connection between the two systems, although a further discussion of this idea is beyond the scope of this Letter.

Figure 5 presents the azimuthally averaged stellar density profile generated from all stars with \((g - r) < 0.65\) and \(17.0 < r < 22.5\) centered on Boötes II. These data were then fitted with a Plummer profile (dotted line) plus a constant (dashed line), the latter to account for the foreground screen of Galactic stars. The best-fitting profile has a half-light radius of \(4.1' \pm 1.6'\), approximately one-third of the physical size of Boötes. Alternatively, fitting an exponential profile to the data gives a half-light radius of \(4.0' \pm 1.9'\).

We use two methods to empirically derive the total magnitude of our object. First, we use SDSS coverage of the Draco dSph to calculate the flux ratio of the integrated luminosity functions. We derive a flux ratio \( f_{\text{Draco}} / f_{\text{Boo II}} \approx 172 \pm 38\). This converts into a magnitude difference of \(2.1 \pm 0.3 \text{ mag}\) and a total absolute magnitude of \(M_v = \sim -3.8 \pm 0.6 \text{ mag}\) for Boötes II, adopting \(M_v = -9.4 \text{ mag}\) for Draco (Grebel et al. 2003). The same analysis yields \(M_v = \sim -6.0 \pm 0.6 \text{ for Boötes II}\), adopting \(M_v = -5.3 \pm 0.6 \text{ given by Belokurov et al. (2006a)}\). Second, we use the integrated surface brightness profiles of Boötes and Boötes II. The flux ratio from this method gives \( f_{\text{Boo}} / f_{\text{Boo II}} \approx 15\). Using \(M_v = \sim -5.3 \pm 0.6 \text{ for Boötes gives } M_v = \sim -2.4 \pm 0.6\). We therefore adopt a result of \(M_v = \sim -3.1 \pm 1.1\).

4. DISCUSSION AND CONCLUSION

We report a new Galactic satellite called Boötes II, only \(~1.5^\circ\) away from the Boötes dwarf. This object was discovered as a resolved stellar overdensity in an automated search of SDSS DR5. Any object that is detected by our algorithm will fall in one of the following categories: random foreground clustering, galaxy clusters, stellar associations of partially resolved nearby galaxies, globular clusters, or Galactic dwarf
spheroidals. Random clustering at this level is extremely unlikely with ~0.008 such false objects occurring in the entire DR5 area (Fig. 1). The CMD shows an apparent main-sequence turnoff and red giant branch structure that is unlikely to be associated with a distant galaxy cluster, and no evidence is found of a suspicious accumulation of background galaxies (Fig. 4).

The combined evidences from CMD and surface brightness profile and the good agreement with the size-luminosity relationship of other MW satellites lead us to conclude that this object is a previously undiscovered companion to the Milky Way at a tentative distance of 60 kpc. But is it a GC or a dSph? Traditionally, these objects are distinguished by their differing physical size; dark matter–dominated dSphs are more extended than a purely stellar system of equal luminosity. Equipped with the two parameters $\log (r_{e}/\text{pc}) = 1.8^{+0.2}_{-0.3}$ and $M_{V} = -3.1 \pm 1.1$ mag for Boötes II, we add our object to the other recently discovered dwarfs in the size-luminosity plot (Fig. 6). The distinction between dSphs and GCs is blurred in the low-luminosity regime as was emphasized by the discovery of Willman 1 (Willman et al. 2005a). Boötes II falls alongside Coma Berenices in

**TABLE 1**

| Parameter | Value |
|-----------|-------|
| R.A.      | 13°58'00" |
| Decl.     | +12°51'00" |
| $(i, b)$  | (353.7°, 68.9°) |
| $(m - M)$ | 18.9 ± 0.5 |
| Distance  | 60 ± 10 kpc |
| $M_{V}$   | $-3.1 \pm 1.1$ mag |
| [Fe/H]    | $-2.0$ |
| Age       | 12 Gyr |
| $\mu_{g}$ (Plummer) | $29.8 \pm 0.8$ |
| $r_{e}$ (Plummer)    | $4.1' \pm 1.6'$ |
| $\mu_{g}$ (exponential) | $29.6 \pm 0.8$ |
| $r_{e}$ (exponential) | $4.0' \pm 1.9'$ |

**Fig. 3.—** From top to bottom: Coma Berenices, Boötes II, and Boötes. Left panels: Positions of SDSS stars passing the photometric selection criteria. Middle left panel: Smoothed positions with contours at 0.5, 0.75, 1.0 (thick line), 1.2, 1.4, 1.6, and 1.8 multiples of threshold density. Middle right panel: CMD of region within the 1.0 contour. Right panels: Field-subtracted Hess diagrams of same regions with stellar isochrone overlaid.

**Fig. 4.—** SDSS image (15' × 15') centered on the detection of Boötes II with SDSS galaxies overlaid (triangles). Left is east, and up is north.
the 40–100 pc region devoid of other objects, between globular clusters and dwarfs. Boötes II is of comparable luminosity to SEGUE 1 but is a factor of ~2 larger.

With a physical half-light size that is an order of magnitude larger than most GCs but similar to those of dSphs, we are inclined to designate Boötes II a galaxy. However, without kinematic data, it is not possible to say for certain whether or not Boötes II formed inside of a dark matter halo, which would confirm it as such. It is also not possible with the current data to determine the extent to which tidal effects may have shaped the observed size and luminosity of Boötes II. A combination of follow-up spectroscopy and deep imaging will not only enable a more robust evaluation of the dark matter content of this object but will also enable an evaluation of a possible physical relationship between Boötes and Boötes II.

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