

HOROLOGIIUM II: A SECOND ULTRA-FAINT MILKY WAY SATELLITE IN THE HOROLOGIIUM CONSTELLATION

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ABSTRACT

We report the discovery of a new ultra-faint Milky Way satellite candidate, Horologium II (Hor II), detected in the Dark Energy Survey Y1A1 public data. Hor II features a half-light radius of $r_h = 47 \pm 10$ pc and a total luminosity of $M_V = -2.6_{-0.3}^{+0.2}$ that place it in the realm of ultra-faint dwarf galaxies on the size–luminosity plane. The stellar population of the new satellite is consistent with an old (~ 13.5 Gyr) and metal-poor ($[\text{Fe}/\text{H}] \sim -2.1$) isochrone at a distance modulus of $(m - M) = 19.46 \pm 0.20$, or a heliocentric distance of 78 ± 8 kpc, in the color–magnitude diagram. Hor II has a distance similar to the Sculptor dwarf spheroidal galaxy (~ 82 kpc) and the recently reported ultra-faint satellites Eridanus III (87 ± 8 kpc) and Horologium I (79 ± 8 kpc). All four satellites are well aligned on the sky, which suggests a possible common origin. As Sculptor is moving on a retrograde orbit within the Vast Polar Structure when compared to the other classical MW satellite galaxies including the Magellanic Clouds, this hypothesis can be tested once proper motion measurements become available.

Key words: galaxies: dwarf – galaxies: individual (Horologium II) – galaxies: stellar content – Galaxy: halo – Local Group

1. INTRODUCTION

Over the past few decades, wide-field imaging surveys have systematically revealed new satellite companions to the Milky Way (MW). The Sloan Digital Sky Survey (SDSS; York et al. 2000) was especially instrumental in establishing a new class of stellar systems, the ultra-faint dwarf (UFD) galaxies (e.g., Willman et al. 2005; Belokurov et al. 2006; Zucker et al. 2006; Irwin et al. 2007; Walsh et al. 2007; Grillmair 2009), thereby more than doubling the number of known MW satellite galaxies over half the northern hemisphere. Deep imaging follow-ups and spectroscopic studies suggest that the UFDs typically hold old (e.g., Muñoz et al. 2010; Sand et al. 2012; Brown et al. 2014) and metal-poor (e.g., Kirby et al. 2008; Frebel et al. 2010; Norris et al. 2010) stellar populations. The high mass-to-light ratios of the UFDs ($M/L_V > 100$) inferred from internal kinematics (e.g., Martin et al. 2007; Simon & Geha 2007; Simon et al. 2011) are one of properties that differentiate them from star clusters (Willman & Strader 2012). The efforts to find new MW satellites over a larger area of sky continued with the VST ATLAS (Shanks et al. 2015) and Pan-STARRS 3 π (K. Chambers et al. 2015, in preparation) surveys, both of which have delivered a couple of discoveries to date (Belokurov et al. 2014; Laevens et al. 2014, 2015). Most recently, systematic searches based on the first data release (Y1A1) of the Dark Energy Survey (DES; The Dark Energy Survey Collaboration 2005) have continued the success of its predecessor the SDSS, reporting nine objects over ~ 1800 deg² in the southern sky (Bechtol et al. 2015; Koposov et al. 2015a),¹ some of which have been already confirmed as UFDs by spectroscopic investigations (Koposov et al. 2015b; Simon et al. 2015; Walker et al. 2015). Other independent surveys, such as the Stromlo Missing Satellite Survey (Jerjen 2010) and the Survey of the Magellanic Stellar History (D. Nidever et al.

2015, in preparation), also took advantage of the power of the Dark Energy Camera (DECam) to boost the census of MW companions in the southern sky (Kim et al. 2015b; Martin et al. 2015).

The use of different detection algorithms also contributed significantly to the increase in the number of known MW satellites (Koposov et al. 2008; Walsh et al. 2009). Due to their extremely low surface brightness (Martin et al. 2008), UFDs would be difficult to characterize without the help of such specialized data mining techniques. Further improvements to the detection sensitivity even led to new discoveries of stellar systems hiding in the preexisting SDSS data (e.g., Kim & Jerjen 2015; Kim et al. 2015a).

Here, we announce the discovery of a new ultra-faint MW satellite galaxy candidate found in the DES Y1A1 data. We note that this object, Horologium II (Hor II), does not correspond to any object in the previous studies by Koposov et al. (2015a) and Bechtol et al. (2015) or in catalogs including the NASA/IPAC Extragalactic Database and SIMBAD.

2. DATA REDUCTION AND DISCOVERY

DES is a deep photometric survey using the wide-field (~ 3 deg²) DECam imager that consists of 62 $2k \times 4k$ CCD chips installed at the 4 m Blanco Telescope located at CTIO. DES started operation in 2013 August and will cover ~ 5000 deg² of the Southern Sky in the vicinity of the Magellanic Clouds in five photometric bands (*grizY*) over five years. The data used in this paper are its first-year public data set, DESDM Y1A1, collected between 2013 August and 2014 February over approximately 1800 deg² and released to the public by the NOAO Science archive after a one-year proprietary period. This data set includes individual images and corresponding weight-maps processed by the DES data management (DESDM) pipeline. Each image is a 90 s single exposure. The instCal images we used for our analysis are bias, dark, and flat-field corrected and contain the world coordinate system

¹ We note that the satellite reported as Indus I by Koposov et al. (2015a) and as DES J2108.8-5109 by Bechtol et al. (2015) is identical to Kim 2 that was discovered earlier by Kim et al. (2015b).

provided by the DESDM image processing pipeline (see Desai et al. 2012 and Mohr et al. 2012 for more details).

We downloaded all of the Y1A1 instCal images and corresponding weight-maps for the g and r bands from the NOAO Science archive using its SQL interface. Cross-matching the central coordinates of the images within $1''.0$ radius yielded 1980 image pairs between the two photometric bands. To produce photometric catalogs, we performed point-spread function photometry over the images using SExtractor/PSFEx (Bertin & Arnouts 1996; Bertin 2011) on a local 16 node/128 core computer cluster. We carried out star/galaxy separation based on the threshold $|\text{SPREAD_MODEL}| < 0.003 + \text{SPREADERR_MODEL}$ as described in Koposov et al. (2015a). The catalogs, which contained the instrumental magnitudes of the star-like objects, were cross-matched between g and r bands by employing STILTS (Taylor 2005) with a $1''$ tolerance. We then calibrated the instrumental magnitudes of the star-like point sources with respect to the APASS DR 8 stars by means of 500 bootstrap samples with 3σ clipping. On average, we found ~ 370 cross-matches between the instrumental and APASS catalogs on each frame, which yielded photometric zero points with uncertainties ~ 0.003 mag in both the g and r bands. The calibrated magnitudes were finally corrected for Galactic extinction using the reddening map by Schlegel et al. (1998) and the correction coefficients from Schlafly & Finkbeiner (2011).

We then applied our overdensity detection algorithm to the star catalogs to search for MW satellites. Briefly, this algorithm, following the approach by Walsh et al. (2009), involves a photometric filtering process in which an isochrone mask is applied to select a single age/metallicity stellar population at a fixed distance modulus. The density map generated from the selected stars is then convolved with a Gaussian kernel. The significance of local stellar overdensities is measured by comparing their signal-to-noise ratios to the smoothed density map. These steps are repeated shifting the isochrone mask over a range of distance moduli. The detection process is described in more detail in Kim & Jerjen (2015). As part of this photometric analysis of the entire 1800 deg^2 of gr images of the Y1A1 data set, we successfully recovered all the UFD candidates reported by Koposov et al. (2015a) and Bechtol et al. (2015), e.g., Phoenix II (17σ), Pictoris I (13σ), Tucana II (11σ), Eridanus III (10σ), and Grus I (9σ). We also found one additional MW satellite candidate in the constellation of Horologium. This new object, Hor II, was initially detected at the $7\text{--}8\sigma$ significance levels in two separate, but overlapping, DECam images. To fill the CCD chip gaps, we combined the photometric catalogs of the two frames and removed duplicates with $1''$ tolerance. Hor II was then recovered with a significance of 10σ .

The upper panel of Figure 1 presents the density contour map of Hor II, made from stars passing the isochrone filter. Hor II appears elongated but well defined by high level density contours ($>3\sigma$). The lower panel shows the corresponding contour map of non-stellar objects in the same field of view.

3. CANDIDATE PROPERTIES

The left panel of Figure 2 shows the distribution of all stellar objects in our photometric catalogs within a $25' \times 25'$ window centered on Hor II. The small red rectangles indicate the six locations of residual CCD chip gaps where the two DES images provided no data. In the middle panel, we present the

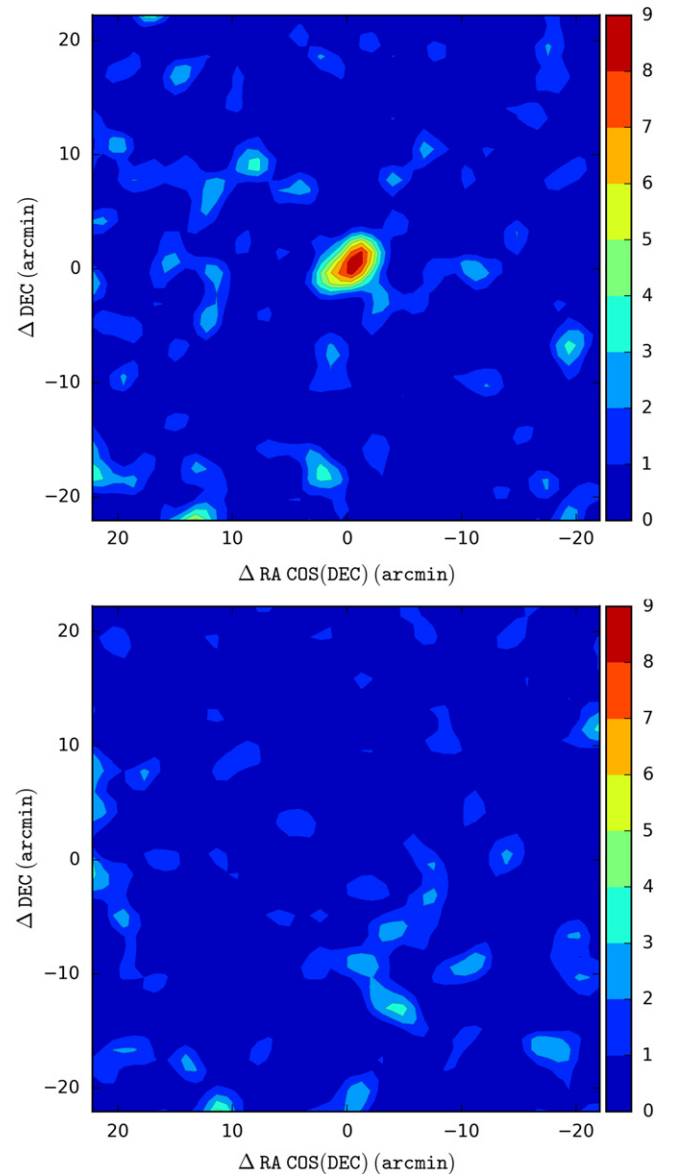


Figure 1. Upper panel: smoothed density contour map of candidate stars, selected by the photometric filter with a PARSEC isochrone of 13.5 Gyr and $[\text{Fe}/\text{H}] = -2.1$ (Bressan et al. 2012) shifted to the distance modulus $(m - M) = 21.56$ mag, centered on Hor II in the $45 \times 45 \text{ arcmin}^2$ window. The contours represent the stellar density in units of the standard deviation above the background level. Lower panel: same as the upper panel, but for non-stellar objects, showing no overdensity consistent with Hor II in the upper panel.

color-magnitude diagram (CMD) for the stars in the inner circle shown in the left panel, equal to the dashed circle in the upper panel of Figure 1. Overplotted is the PARSEC isochrone (Bressan et al. 2012) of 13.5 Gyr and $[\text{Fe}/\text{H}] = -2.1$ shifted to the distance modulus of $(m - M) = 19.46 \pm 0.20$ or a heliocentric distance of 78 ± 8 kpc. Compared to the control CMD established in the same manner as in Belokurov et al. (2006) shown in the right panel, the stars in the vicinity of Hor II consistently trace the old and metal-poor stellar population from the red giant branch (RGB) down to the main-sequence turn off. Hor II also hosts two potential blue horizontal branch (BHB) stars.

We derived the structural parameters of Hor II using a maximum likelihood (ML) algorithm similar to the one

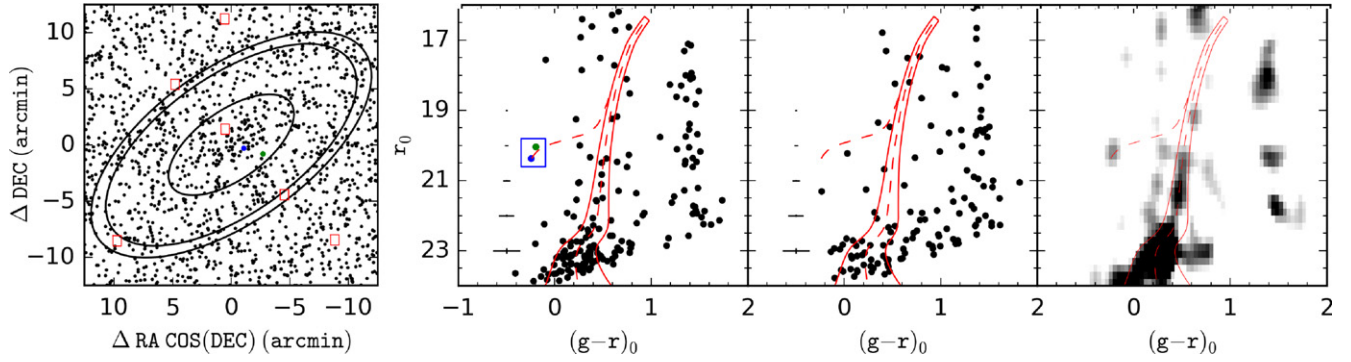


Figure 2. DECam view of Hor II. Left panel: distribution of all stars in a $25' \times 25'$ field centered on Hor II. The blue and green dots mark the two BHB candidates falling into the blue box in the next panel. The ellipses mark elliptical radii of $6'3$ ($\sim 3r_h$), $12'6$ ($\sim 6r_h$), and $14'1$, respectively. The red rectangles mark the locations of stars in the inner circle. Middle left panel: CMD of stars lying in the inner circle. Overplotted is the best-fitting PARSEC (red dashed lines) isochrone of age 13.5 Gyr and $[\text{Fe}/\text{H}] = -2.1$ shifted to the distance modulus of $(m - M) = 19.46$. Within the isochrone mask (red solid lines) based on photometric uncertainties, there are candidate stars consistently aligned with the isochrone from the RGB to the main-sequence turn off. The two BHB candidates are colored and correspond to those in the left panel. Middle right panel: control CMD of stars falling in the annulus between the two outer circles but covering the same on-sky area as in the middle panel. Right panel: differential Hess diagram, the inner CMD minus the control CMD, which exhibits a clear excess of stars in the RGB and the main-sequence turn-off regions.

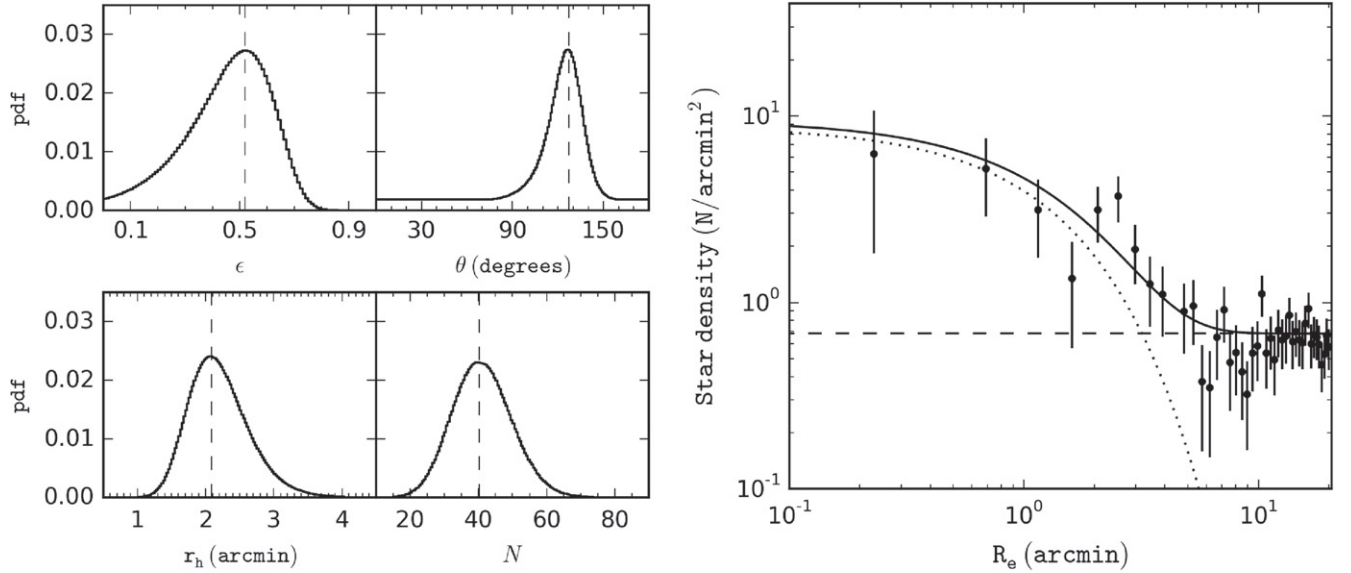


Figure 3. Left panels: marginalized probability distribution functions for the ellipticity (ϵ), the position angle (θ), the half-light radius (r_h), and the number of stars in the system for our photometric selection (N). The dashed lines mark the modes of the distributions. Right panel: radial density profile of Hor II, constructed on the mode values of each parameter as a function of elliptical radius R_e . The error of each data point is based on Poisson statistics. The dotted line marks the best-fit exponential model, the dashed line the foreground level, and the solid line the combined fit.

described in Martin et al. (2008). The resulting marginalized pdfs for the structural parameters are presented in the left panels of Figure 3. The right panel shows the radial density profile with the best-fit exponential profile based on the best parameters: an ellipticity of $\epsilon = 0.52$, a position angle of $\theta = 127^\circ$ and a half-light radius of $r_h = 2'.09$. Adopting the heliocentric distance of 78 kpc, the ML-estimated physical size of Hor II is $r_h = 47 \pm 10$ pc.

The total luminosity of Hor II is estimated as follows. Briefly, we use the total number of member stars N above the photometric threshold ($r_0 \sim 23.5$ mag) and its associated uncertainty derived from the ML algorithm run. We then integrate a normalized theoretical luminosity function as a probability density function of magnitude by the same magnitude limit and use the ratio of the number N to the probability density to scale the luminosity function up to the observed level. Integrating the scaled luminosity function

inclusive of the missing flux below the threshold gives the absolute luminosity of Hor II. Using the PARSEC isochrone of 13.5 Gyr and $[\text{Fe}/\text{H}] = -2.1$ based on the initial mass function by Kroupa (2001), we obtain $M_r \sim -2.74$ or $M_V \sim -2.57$ by the luminosity-weighted mean color $V - r = 0.17$ of the isochrone. We adopt a total luminosity of $M_V = -2.6^{+0.2}_{-0.3}$ as our final estimate, where its uncertainty is derived from the star counts N . All of the resulting parameters are summarized in Table 1. We note that a heliocentric distance of 78 kpc was adopted in the calculations of the physical size and total luminosity, to which the distance uncertainty was not propagated.

4. DISCUSSION AND CONCLUSION

We analyzed the first installment (Y1A1) of the DES gr imaging data to search for MW satellites, where we recovered all the previously reported systems and also found a new

Table 1
Properties of Hor II

Parameter	Value	Unit
α_{J2000}	3 16 32.1 \pm 5.0	h m s
δ_{J2000}	-50 01 05 \pm 5	° ' "
l	262.472	deg
b	-54.137	deg
$(m - M)$	19.46 \pm 0.20	mag
d_{\odot}	78 \pm 8	kpc
r_h	2.09 $^{+0.44}_{-0.41}$	'
	47 \pm 10 ^a	pc
ϵ	0.52 $^{+0.13}_{-0.17}$...
θ	127 \pm 11	deg
M_V	-2.6 $^{+0.2}_{-0.3}$ ^a	mag

Note.

^a Adopting a distance of 78 kpc.

satellite candidate in the constellation of Horologium. The new MW satellite candidate Hor II appears faint ($M_V = -2.6^{+0.2}_{-0.3}$), elongated ($\epsilon = 0.52^{+0.13}_{-0.17}$), and rather extended ($r_h = 47 \pm 10$ pc). On the size–luminosity plane, Hor II is placed in the realm of UFDs close to Boötes II. It also features a typically old (~ 13.5 Gyr) and metal-poor ($[\text{Fe}/\text{H}] \sim -2.1$) stellar population. The best isochrone fit yields a heliocentric distance of 78 ± 8 kpc, which is the same as that of a recently discovered neighbor in the DES Y1A1 coverage, Hor I. Compared to the new satellite candidate, Hor I is about twice as luminous ($M_V = -3.4 \pm 0.3$), smaller ($r_h = 30^{+4.4}_{-3.3}$ pc), and more circular ($\epsilon < 0.28$), consequently being placed in the somewhat ambiguous region on the size–luminosity plane where UFDs and extended globular clusters overlap (Koposov et al. 2015a). A recent spectroscopic study by Koposov et al. (2015b) has revealed that the dynamical mass-to-light ratio of Hor I reaches $M/L_V = 570^{+1154}_{-112}$ and confirmed that that system is indeed a UFD, possibly (once) associated with the LMC. The pair of UFDs, Hor I and II, are only $\sim 7^\circ$ away from each other on the sky, have identical distances, and are well aligned with the Vast Polar Structure (Pawlowski et al. 2015). Such UFD pairs have been reported for quite some time, e.g., Boötes I–II (Walsh et al. 2007), Leo IV–V (Belokurov et al. 2008), and Pisces II–Pegasus III (Kim et al. 2015a). The tentative link between Hor I and II can be extended further to the Sculptor dwarf spheroidal ($d_{\odot} \sim 82$ kpc; Weisz et al. 2014) and the UFD Eridanus III ($d_{\odot} = 87 \pm 8$ kpc). As Sculptor is moving on a retrograde orbit within the Vast Polar Structure when compared to the other classical MW satellite galaxies in the vicinity, including the Magellanic Clouds, the hypothesis of a common origin can be tested once proper motion measurements become available. Nevertheless, this alignment is already suggestive of a “layer” of outer halo UFDs parallel to the Magellanic Clouds, possibly associated with the most luminous Sculptor dwarf. Indeed, there is one more object nearby, namely, Phe II, that also shares the same distance.

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