DISCOVERY OF A CLOSE PAIR OF FAINT DWARF GALAXIES IN THE HALO OF CENTAURUS A

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ABSTRACT

As part of the Panoramic Imaging Survey of Centaurus and Sculptor (PISCeS), we report the discovery of a pair of faint dwarf galaxies (CenA-MM-Dw1 and CenA-MM-Dw2) at a projected distance of ~90 kpc from the nearby elliptical galaxy NGC 5128 (CenA). We measure a tip of the red giant branch distance to each dwarf, finding \( D = 3.63 \pm 0.41 \) Mpc for CenA-MM-Dw1 and \( D = 3.60 \pm 0.41 \) Mpc for CenA-MM-Dw2, both of which are consistent with the distance to NGC 5128. A qualitative analysis of the color–magnitude diagrams indicates stellar populations consisting of an old, metal-poor red giant branch \(( \geq 12 \) Gyr, \([	ext{Fe}/\text{H}] \sim -1.7 \) to \(-1.9 \)). In addition, CenA-MM-Dw1 seems to host an intermediate-age population as indicated by its candidate asymptotic giant branch stars. The derived luminosities \((M_V = -10.9 \pm 0.3 \) for CenA-MM-Dw1 and \(-8.4 \pm 0.6 \) for CenA-MM-Dw2\) and half-light radii \((r_h = 1.4 \pm 0.04 \) kpc for CenA-MM-Dw1 and \(0.36 \pm 0.08 \) kpc for CenA-MM-Dw2) are consistent with those of Local Group dwarfs. CenA-MM-Dw1’s low central surface brightness \((\mu_V = 27.3 \pm 0.1 \) mag arcsec\(^{-2}\)) places it among the faintest and most extended M31 satellites. Most intriguingly, CenA-MM-Dw1 and CenA-MM-Dw2 have a projected separation of only 3 arcmin \((\sim 3 \) kpc): we are possibly observing the first, faint satellite of a satellite in an external group of galaxies.

Key words: galaxies: dwarf – galaxies: halos – galaxies: groups: individual (CenA) – galaxies: photometry

Online-only material: color figures

1. INTRODUCTION

The relative number and astrophysical properties of dwarf galaxies represent one of the major challenges to the widely accepted \( \Lambda \)CDM cosmological model of structure formation. For instance, the predicted number of DM haloes around a Milky-Way-(MW)-sized halo exceeds the observed number by at least an order of magnitude (e.g., Klypin et al. 1999; Moore et al. 1999), and their central densities at a given mass are lower than inferred from simulations (e.g., Boylan-Kolchin et al. 2011, 2012).

Pioneering studies of faint satellite systems beyond the LG have begun. The M81 group of galaxies \((D \sim 3.6 \) Mpc\) has been the subject of a resolved stellar population search for satellites utilizing deep ground based imaging and Hubble Space Telescope (HST) follow-up (Chiboucas et al. 2009, 2013), finding satellites down to \(M_V = -10 \) and largely confirming the faint satellite deficit with respect to \( \Lambda \)CDM seen in the LG. Studies of unresolved low surface brightness satellites have additionally been undertaken for more distant groups (e.g., M101; Merritt et al. 2014), where dwarf galaxy distance measurements are still necessary to produce conclusive results.

We have begun the Panoramic Imaging Survey of Centaurus and Sculptor (PISCeS) to significantly increase the sample of massive galaxy halos with a complete census of satellites down to \(M_V \sim -8 \) mag. PISCeS is focused on two nearby massive galaxies—the spiral NGC 253 and the elliptical NGC 5128/ CentaurusA (CenA) that reside in a loose group of galaxies (Sculptor) and in a rich group (CenA), respectively (see Sand et al. 2014 for more details). PISCeS will identify faint satellites and streams from resolved stellar light out to \(R \sim 150 \) kpc in each system, allowing for direct comparison with the MW, the M31 Pan-Andromeda Archaeological Survey (PAndAS; McConnachie et al. 2009) and M81 (Chiboucas et al. 2013). Out of the planned survey area of \(\sim 17 \) deg\(^2\), we have already collected data over \(\sim 12 \) deg\(^2\) around CenA.

In this Letter, we present the first results of our survey around CenA: the discovery of a close pair of faint dwarf galaxies, likely associated with CenA. The dwarfs were immediately visible in our PISCeS survey data and are located near CenA’s major axis in the northeast direction, at a projected distance of 92 kpc and thus still within its extended halo (Crnojević et al. 2013). For the more luminous dwarf, a modest surface brightness enhancement can be recognized in archival Digital Sky Survey images.

In Section 2 we describe our data and reduction procedure, while in Section 3 we present the physical properties derived for the newly discovered dwarfs. In Section 4 we discuss the

\* This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.
possibility of these dwarfs constituting a pair of galaxies and draw our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

The data presented here were acquired on 2013 June 4 (UT), as part of the PISCes survey, with Megacam (McLeod et al. 2006) at the Magellan Clay 6.5 m telescope, which has a $\sim 24' \times 24'$ field of view and a binned pixel scale of $0'.16$. The seeing was excellent throughout the night, with a median of $\sim 0.55-0.6$, and the conditions were photometric. The final stacked images had a total exposure time of $5 \times 300$ s for the $r$ band and $6 \times 300$ s for the $g$ band. Initial data reduction (image detrending, astrometry, and stacking) was performed by the Smithsonian Astrophysical Observatory Telescope Data Center, using a code developed by M. Comroy, J. Roll, and B. McLeod.

We perform point-spread-function-(PSF)-fitting photometry on the final stacked images, adopting the suite of programs DAOPHOT and ALLFRAME (Stetson 1987, 1994). We construct a PSF for each band selecting $\sim 450$ bright stars across the image. We then fit the PSF to all objects $3\sigma$ above the background for each image, and compute the coordinate transformations between filters with DAOMATCH/DAOMASTER (Stetson 1993). Finally, we perform simultaneous photometry of all the objects detected in both filters in order to obtain deeper catalogs. We only keep those objects satisfying the criteria $|\delta| < 3$ and $\chi < 1.5$. The same night, several equatorial Sloan Digital Sky Survey fields were observed at different airmasses to obtain zeropoints, color terms, and extinction coefficients, and thus calibrate the instrumental magnitudes to the SDSS system. Stars have been individually corrected for Galactic extinction (Schlafly & Finkbeiner 2011), which has an average value of $E(B - V) \sim 0.15$.

The photometric errors and incompleteness of our data have been computed via artificial star experiments. We have injected $\sim 10^5$ fake stars with a uniform distribution on each of the stacked images, divided into 20 experiments in order not to increase the stellar crowding artificially. The fake stars cover the whole relevant range in color–magnitude space, and additionally reach $r \sim 29$ mag ($\sim 2$ mag fainter than the faintest real recovered stars). The same PSF-fitting photometry procedure used for the real data has been performed on the fake stars. We find the overall (color-averaged) $50\%$ completeness limit to be $r \sim 25.75$ and $g \sim 26.75$. Note that in the central $\sim 1$ arcmin of CenA-MM-Dw1 the crowding is higher than in the rest of the pointing, and the $50\%$ completeness limits correspond to $r \sim 25.5$ and $g \sim 26.5$.

Figure 1 shows our dereddened CMDs where stars within the half light radius are plotted. A background field CMD with the same area is shown for comparison (right panels, see Figure 2). The inset plot shows the Sobel filter response and derived TRGB magnitude (Section 3.2). Overplotted on the clearly visible RGB for each dwarf is a Dartmouth isochrone shifted to the dwarf’s distance, with an age of 12 Gyr and metallicity [Fe/H]$= -1.7$ for CenA-MM-Dw1 and $-2.0$ for CenA-MM-Dw2. The RGB selection box, utilized in Figure 2, is drawn in red. The dashed lines indicate the $50\%$ completeness level while photometric errors stemming from artificial star tests are shown on the left side of each CMD.

(A color version of this figure is available in the online journal.)

3. PROPERTIES OF CENa-MM-DW1 AND CENA-MM-DW2

We begin this section by broadly discussing the stellar populations of our newly found dwarfs, and visualizing these new systems via red giant branch (RGB) stellar maps. We then discuss the distance, structure, metallicity and luminosity of this faint pair of CenA dwarfs.

Figure 1 shows our dereddened CMDs where stars within the half light radius (calculated in Section 3.3) are plotted. The field CMDs (rescaled to the area of each dwarf) in the right panels are from three rectangular regions with an area of $\sim 0.01$ deg$^2$ each, as shown in Figure 2. The choice of the field regions is driven by the necessity of taking into account a possible density gradient and small-scale substructures in CenA’s halo. The field CMDs show the main contaminants, i.e., Galactic foreground (almost vertical) sequences at $(g - r) \sim 0.5$ and $\sim 1.3$, unresolved background galaxies centered at $(g - r) \sim 0$, and CenA RGB halo stars (sparingly populated but still detected out to these large projected galactocentric distances, $\sim 90-95$ kpc; Crnojević et al. 2013).
3.2. Distances to the New Dwarfs

We derive the distance to the new dwarfs using the tip of the RGB (TRGB) method, which utilizes the brightest, metal-poor RGB stars as a standard candle (e.g., Lee et al. 1993; Salaris et al. 2002; Rizzi et al. 2007). We employ a Sobel edge detection filter to identify a sharp transition in the r-band luminosity function, with a color cut of $0.8 < (g - r)_{0} < 1.2$ in order to minimize contamination from foreground Galactic stars (at red colors) and unresolved background galaxies (bluer than the RGB).

We find $r_{0,\text{TRGB}} = 24.79 \pm 0.22$ for CenA-MM-Dw1 and $r_{0,\text{TRGB}} = 24.77 \pm 0.22$ for CenA-MM-Dw2, where the errors mainly depend on photometric uncertainties rather than the number of stars. These values correspond to distance moduli of $(m - M)_{0} = 27.80 \pm 0.24$ and $(m - M)_{0} = 27.78 \pm 0.24$, respectively, once adopting a theoretically calibrated TRGB absolute value of $M_{r}^{\text{TRGB}} = -3.01 \pm 0.1$ (as computed in Sand et al. 2014 for SDSS bands). As a test, we derive TRGB distances for the adopted field regions, i.e., for stars belonging to CenA’s outer halo. We obtain $(m - M)_{0} = 27.85 \pm 0.28$, in excellent agreement with the average of literature values using several methodologies $(m - M)_{0} = 27.91 \pm 0.05$; Harris et al. 2010). The derived distances put the two dwarfs at roughly the same distance as CenA, thus suggesting they are its satellites. Follow-up HST data will be used to refine these distances and investigate the possibility that the two dwarfs form a physical pair (see discussion in Section 4).

3.3. Structural Parameters and Luminosities

To quantify the structure and luminosities of our new dwarf discoveries, we work with RGB stars from the selection boxes shown in Figure 1. First, the dwarf centers are determined via an
The uncontaminated profiles trace out to \( \sim 2 \) times the derived half-light radii for the dwarfs. We derive their luminosities by integrating the best-fit Sérsic profiles, and obtain \( M_V = -11.2 \pm 0.3 \) for CenA-MM-Dw1 and \( M_V = -8.9 \pm 0.6 \) for CenA-MM-Dw2 (uncertainties from error propagation). Using the transformation between SDSS and Johnson–Cousins filters reported by Jester et al. (2005), the \( V \)-band total magnitudes of the dwarfs are \( M_V = -10.9 \pm 0.3 \) for CenA-MM-Dw1 and \(-8.4 \pm 0.6 \) for CenA-MM-Dw2.

3.4. Metallicities

The two dwarfs host relatively metal-poor stellar populations, as can be seen from the isochrones overplotted on the CMDs in Figure 1. To quantify this, we use the standard method for computing photometric metallicities (e.g., Crnojević et al. 2010): we interpolate between solar-scaled isochrones with a fixed age of 12 Gyr and [Fe/H] varying from \(-2.5 \) to \(-1.1 \), adopting the Dartmouth stellar evolutionary database (Dotter et al. 2008). A metallicity value is obtained for each individual RGB star with magnitude \( r_0 < 25.5 \). The mean values we deduce are \([Fe/H] \sim -1.7 \) for CenA-MM-Dw1 and \([Fe/H] \sim -1.9 \) for CenA-MM-Dw2 (as plotted in Figure 1). The spread of the RGB is consistent with photometric errors, however, we cannot exclude an intrinsic range of metallicities for CenA-MM-Dw1 in particular. Follow-up data will be crucial to assess the metallicity content of these dwarfs more precisely.

4. DISCUSSION AND CONCLUSIONS

We have presented the discovery of a faint pair of (likely) satellites of the elliptical galaxy CenA, discovered within our PIScES survey. CenA-MM-Dw1 and CenA-MM-Dw2 are located at a projected distance of 92 kpc from the center of their parent galaxy and lie at its approximate distance (\( \sim 3.6 \pm 0.4 \) Mpc), although the uncertainties call for deeper photometric follow-up. Both dwarfs contain predominantly old (\( \sim 12 \) Gyr) and metal-poor stellar populations ([Fe/H] \( \sim -1.9 \)), while CenA-MM-Dw1 likely also contains intermediate age asymptotic giant branch stars. Neither CenA-MM-Dw1 or CenA-MM-Dw2 are detected in the H\( \alpha \) Parkes All Sky Survey (HIPASS; Barnes et al. 2001), with \( \sigma \) upper mass limits of \( M_{\text{HI}} \lesssim 4 \times 10^7 M_\odot \).

The derived structural and luminosity parameters of CenA-MM-Dw1 and CenA-MM-Dw2 (Table 1) place them within the main locus defined by MW and M31 dwarfs (Figure 4). Of some note is the low central surface brightness of CenA-MM-Dw1 (\( \mu_{V,0} = 27.3 \) mag arcsec\(^{-2} \)), which lies at the edge of the M31 satellites distribution in a surface brightness versus luminosity plot. Its properties are comparable to a few M31 satellites (AndXXIII, AndXIX, LacI and CasIII; McConnachie 2012; Martin et al. 2013) with large half light radii (\( \gtrsim 1 \) kpc) and unusually low central surface brightness (\( \mu_{V,0} \gtrsim 26–28 \) mag arcsec\(^{-2} \)). No MW satellite shows such a low central surface brightness and large half light radius at the same time. It has been suggested that M31 companions with \( V_Y > -9 \) have lower surface brightness and are more extended with respect to MW companions with similar luminosity (Kalirai et al. 2010), although the inclusion of the latest results for the M31 subgroup have substantially decreased this difference (Tollerud et al. 2012).

The new dwarfs’ distances are consistent with each other, and their very small angular separation (3 arcmin or 3.1 kpc at their distance) suggests we are looking at the first faint satellite.
Figure 3. Surface brightness profiles in the r band for the two dwarfs as a function of elliptical (circular) radius for CenA-MM-Dw1 (CenA-MM-Dw2). First, the number density profiles for RGB stars have been corrected for incompleteness, and the field level has been subtracted from the profiles. Subsequently, these have been converted into surface brightness by tagging them onto the integrated photometry within the innermost \(\sim 0.2/0.1\) arcmin for CenA-MM-Dw1 and CenA-MM-Dw2, respectively. Error bars are Poissonian. CenA-MM-Dw2 can be recognized in CenA-MM-Dw1’s profile as an overdensity at \(\sim 4.0\) arcmin, while CenA-MM-Dw1 starts to dominate CenA-MM-Dw2’s profile beyond \(\sim 0.75\) arcmin. Filled symbols indicate the data points included in the Sersic fit. The overplotted best-fitting Sersic profiles are consistent with exponential profiles (see Table 1). The upper x-axes report galactocentric distances in physical units.

Figure 4. Left panel: absolute V-band magnitude as a function of half-light radius for MW/M31 dwarf galaxies (black points/triangles from McConnachie 2012 or Sand et al. 2012), CenA-MM-Dw1 and CenA-MM-Dw2 (blue stars), and Scl-MM-Dw1 (red inverted triangle, Sand et al. 2014). Right panel: central V-band surface brightness as a function of absolute magnitude. CenA-MM-Dw1’s properties place it among M31 companions with the lowest central surface brightnesses and largest half-light radii.

of a satellite in an external group of galaxies. According to simulations, groups of dwarfs infalling into the potential well of a giant host are common (D’Onghia & Lake 2008), although the predicted pairs of satellites (with comparable luminosities) are fewer than those observed in the LG (e.g., Fattahi et al. 2013).

Examples of dwarf associations are present within the LG: the Magellanic Clouds, NGC 147/NGC 185 (Fattahi et al. 2013; Crnojević et al. 2014; but see also Watkins et al. 2013), Leo IV/Leo V/Carina (Belokurov et al. 2008; de Jong et al. 2010; Belokurov et al. 2014; but see Sand et al. 2010, 2012; Jin et al. 2012), and for all these pairs a common infall to the LG has been suggested (Evslin 2014). Note that all the galaxies within these pairs display similar luminosities, while CenA-MM-Dw1 is \(\sim 2.5\) mag brighter than CenA-MM-Dw2. In some cases, stellar streams/overdensities with small angular separation are interpreted as dynamically associated structures, or even remnants of infalling groups onto the MW’s halo, where the most massive of the dwarfs has already been disrupted (Belokurov et al. 2009; Deason et al. 2014, and references therein). Deason et al. (2014) suggest that 30% of faint dwarfs are likely to have fallen onto the MW as satellites of more massive dwarfs.

For some of the cited pairs, tidal perturbances/streams have been observed, even though their origin is still under discussion. Intriguingly, CenA-MM-Dw2 lies only \(\sim 3\) arcmin in projection away from its more massive companion and does not display clear signs of distortion, however, the upper limit for its ellipticity (\(\epsilon = 0.67\)) is high, and possible substructures may be hiding at fainter magnitudes. We compute CenA-MM-Dw1’s tidal radius from a King profile, obtaining 6.3 \(\pm 0.9\) kpc, while its Jacobi radius is 2.2 \(\pm 0.3/4.7 \pm 0.5\) kpc (assuming \((M/L)_V = 10–100\), a projected radius from CenA of
92 kpc, and a CenA mass of $0.5 \times 10^{12} M_\odot$; Karachentsev et al. 2007), thus CenA-MM-Dw2 may be within its gravitational influence. The CMDs derived from deeper HST imaging will allow for an improved rejection of background galaxies, and thus a more accurate investigation of CenA-MM-Dw2’s structural parameters and possible tidal distortions. If this speculation is confirmed, we might be looking at the last moments of CenA-MM-Dw2 before it is accreted by its more massive companion CenA-MM-Dw1.

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