On the Nature of Ultra-faint Dwarf Galaxy Candidates. I. DES1, Eridanus III, and Tucana V

Blair C. Conn1, Helmut Jerjen1,2, Dongwon Kim1, and Mischa Schirmer2

1 Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia; blair.conn@anu.edu.au
2 Gemini Observatory, Casilla 603, La Serena, Chile

Received 2017 September 12; revised 2017 November 29; accepted 2017 November 29; published 2018 January 8

Abstract

We use deep Gemini/GMOS-S g, r photometry to study the three ultra-faint dwarf galaxy candidates DES1, Eridanus III (Eri III), and Tucana V (Tuc V). Their total luminosities, \( M_V(DES1) = -1.42 \pm 0.50 \) and \( M_V(\text{Eri III}) = -2.07 \pm 0.50 \), and mean metallicities, [Fe/H] = -2.38±0.19 and [Fe/H] = -2.40±0.12, are consistent with them being ultra-faint dwarf galaxies, as they fall just outside the 1σ confidence band of the luminosity–metallicity relation for Milky Way satellite galaxies. However, their positions in the size–luminosity relation suggest that they are star clusters. Interestingly, DES1 and Eri III are at relatively large Galactocentric distances, with DES1 located at \( D_{\text{GC}} = 74 \pm 4 \) kpc and Eri III at \( D_{\text{GC}} = 91 \pm 4 \) kpc. In projection, both objects are in the tail of gaseous filaments trailing the Magellanic Clouds and have similar 3D separations from the Small Magellanic Cloud (SMC): \( \Delta D_{\text{SMC,DES1}} = 31.7 \) kpc and \( \Delta D_{\text{SMC,Eri III}} = 41.0 \) kpc, respectively. It is plausible that these stellar systems are metal-poor SMC satellites. Tuc V represents an interesting phenomenon in its own right. Our deep photometry at the nominal position of Tuc V reveals a low-level excess of stars at various locations across the GMOS field without a well-defined center. An SMC Northern Overdensity–like isochrone would be an adequate match to the Tuc V color–magnitude diagram, and the proximity to the SMC (12±1; \( \Delta D_{\text{SMC,Tuc V}} = 13 \) kpc) suggests that Tuc V is either a chance grouping of stars related to the SMC halo or a star cluster in an advanced stage of dissolution.

Key words: galaxies: dwarf – Galaxy: halo – globular clusters: general – Hertzsprung–Russell and C–M diagrams – Local Group

1. Introduction

In recent years, around 35 new Milky Way satellites (dwarf galaxies and star clusters) have been discovered (Balbinot et al. 2013; Belokurov et al. 2014; Laevens et al. 2014, 2015a, 2015b; Bechtol et al. 2015; Drlica-Wagner et al. 2015; Kim et al. 2015a, 2015b; Kim & Jerjen 2015a, 2015b; Koposov et al. 2015, 2016b; Luque et al. 2016; Torrealba et al. 2016a, 2016b; Koposov et al. 2017). This is a dramatic jump in number, and once their true nature has been established these objects will provide crucial empirical input for testing near-field cosmology predictions and verifying formation scenarios of the Milky Way. However, since the majority of the discoveries are based on shallow SDSS, Pan-STARRS1, or DES imaging surveys, most new objects are still poorly constrained in terms of their stellar population, structural parameters, distance, and luminosity. The only path forward to accurately determine these fundamental properties is to analyze deep photometric follow-up observations.

In this paper, we use deep Gemini Multi-object Spectrograph South (GMOS-S) g, r photometry to derive more accurate constraints on the three ultra-faint dwarf galaxy candidates DES1 (Luque et al. 2016), Eridanus III (Bechtol et al. 2015; Koposov et al. 2015a; DES J0222.7–5217), and Tucana V (Drlica-Wagner et al. 2015; DES J2337–6316). DES1 was detected in first-year DES data with a peak Poisson significance of 11.6 as a compact Milky Way companion at

\( \alpha(J2000) = 0^h33^m59^s7 \) and \( \delta(J2000) = -49^\circ 02' 20'' \) located at approximately 80 kpc.

Its total luminosity is estimated in the range \(-3.00 \leq M_V \leq -2.21 \). Eridanus III, at \( \alpha(J2000) = 0^h22^m45^s.5 \), \( \delta(J2000) = -52^\circ 17' 01'' \) and detected at a significance level of 10.1, resides at a heliocentric distance of ~87 kpc with a total luminosity of \( M_V = -2.0 \pm 0.3 \). Tucana V was discovered at \( \alpha(J2000) = 23^h37^m24^s.0 \), \( \delta(J2000) = -63^\circ 16' 12'' \) with a peak significance of 8.0 at an estimated distance of 55 ± 9 kpc and has a total luminosity of \( M_V = -1.60 \pm 0.49 \).

Interestingly, all three objects have half-light radii \( r_h(\text{DES1}) \sim 10 \), \( r_h(\text{Eri III}) = 14.0^{+1.2}_{-0.5} \), and \( r_h(\text{Tuc V}) = 17 \pm 6 \) pc that puts them in the transition zone between ultra-faint star clusters and dwarf galaxies. Figure 1 shows the location of these three stellar overdensities among others with respect to the Magellanic Clouds and the gaseous Magellanic Stream.

Each of these three objects resides at the very limit of the DES photometry (\( \lim_r \sim 23 \)) in which they were discovered. This introduced large uncertainties into all of their known properties, including the half-light radius, which can be used to discriminate between a baryon-dominated star cluster and dark matter–dominated dwarf galaxy. The data presented here will significantly improve our understanding of these faint stellar systems and allow us to refine their locations in the size–luminosity plane and in the luminosity–metallicity parameter space where there is a known relation between these parameters for dwarf galaxies (Kirby et al. 2013). Additionally, by probing several magnitudes below the main-sequence turnoff (MSTO), we can take advantage of the stellar mass differences of main-sequence (MS) stars to probe for any evidence of mass segregation as witnessed in the stellar cluster Kim 2 (Kim et al. 2015b). Evidence of mass segregation can confirm...
The neutral hydrogen gas of the Magellanic Stream. The HI column density \( \log(N_{\text{HI}}) \) in units of cm\(^{-2}\) is shown over six orders of magnitude, ranging from \( \log(N_{\text{HI}}) = 16 \) (black) to 22 (red). For more details, see Nidever et al. (2010). The three candidates discussed in this study are highlighted with cyan circles.

Table 1

| Field         | R.A. (deg, J2000) | Decl. (deg, J2000) | Position Angle (deg) | Filter | Observation Date | Airmass | Exposure (s) | Seeing (arcsec) |
|---------------|-------------------|--------------------|----------------------|--------|------------------|---------|--------------|----------------|
| DES1          | 8.4987            | -49.0389           | 180                  | g\_G0325 | 2016 Aug 30      | 1.058–1.056 | 600          | 0.55           |
|               |                   |                    | 180                  | r\_G0326 | 2016 Aug 30      | 1.058–1.067 | 600          | 0.52           |
| Eridanus III  | 35.6897           | -52.2837           | 180                  | g\_G0325 | 2016 Aug 30      | 1.081–1.094 | 600          | 0.60           |
| (DES J0222.7–5217) |            |                    | 180                  | r\_G0326 | 2016 Aug 30, 31  | 1.078–1.101 | 600          | 0.43           |
| Tucana V      | 354.3500          | -63.2700           | 160                  | g\_G0325 | 2016 Sep 27      | 1.259–1.297 | 520          | 0.51           |
| (DES J2337–6316) |             |                    | 160                  | r\_G0326 | 2016 Sep 27      | 1.316–1.356 | 520          | 0.51           |

2. Observations and Data Reduction

The imaging data were obtained with GMOS-S at the 8 m diameter Gemini South Telescope through Program ID GS-2016B-Q-7. The observing conditions, following the Gemini Observatory standards, were dark, clear skies (SB50/CC50) and seeing typically better than 0.6 (IQ20) on the nights of 2016 August 30 and 31 and September 27 (see Table 1). By taking advantage of the excellent seeing (0.4–0.6), we were able to utilize the 1 × 1 binning mode of GMOS-S and achieve a pixel scale of 0.08 pixel\(^{-1}\). The field of view was 5 × 5, and each object was observed in the \( g \) (g\_G0325) and \( r \) (r\_G0326) bands with a short 60 s exposure centered on the target followed by three dithered exposures of 600 s each. Figures 2–4 present the false-color images of the coadded frames for DES1, Eri III, and Tuc V, respectively.

The basic data reduction steps of generating master biases and twilight flats, bias subtraction and flat fielding, and astrometry and coaddition have been performed using the THELI pipeline (Schirmer 2013). Point-spread function (PSF) photometry has been undertaken on the coadded files using DOLPHOT (Dolphin 2000). The DOLPHOT parameters have been adjusted to minimize the residuals by adjusting the PSF solution. In particular, we have employed the sum of a Lorentzian and a circular Gaussian model PSF to achieve better residuals.

2.1. Photometric Calibration

The photometry generated by DOLPHOT was cross-matched with APASS\(^9\) (Henden et al. 2015) calibrated DECam photometry\(^10\), using the built-in routines of TOPCAT (Taylor 2005), and then quality cuts were applied to the matched stars. These cuts first removed objects with extremely large photometric errors, followed by cuts on the color error (\( \sigma_{c-r} < 0.3 \)), the range in color (0.0 < \( g - r \) < 1.5), object sharpness in both filters (sharpness\(^2 < 0.1 \)), object type (Objtype = 1), and photometry quality flag (class = 0). The resulting subset was fit with a linear function to determine the color term, zero-point offset, and atmospheric extinction correction for calibration. Since the color term is related to the physical differences

---

\(^6\) SB50—Sky brightness 50th percentile.
\(^7\) CC50—Cloud cover 50th percentile.
\(^8\) IQ20—Image quality 20th percentile.

\(^9\) AAVSO Photometric All-Sky Survey.

\(^10\) DECam photometry generated using the procedures outlined in Kim & Jerjen (2015b).
between the GMOS-S and APASS filter sets, all objects will therefore require the same color term in the calibration. A nominal instrumental zero point of 30.00 is chosen for all fields and filters, then a correction is applied that calibrates the data with APASS. This offset encapsulates both the true photometric zero point and the atmospheric extinction correction, since they cannot be separated in this data set. Due to the relatively small number of APASS stars available in each field to determine the photometric calibration of the data, we utilized the python package EMCEE (Foreman-Mackey et al. 2013) to perform a Markov chain Monte Carlo (MCMC) analysis of all of the calibration fits simultaneously. This leveraged all of the data to establish the best color term while allowing the remaining zero-point and atmospheric extinction correction to stay unique to each field. Table 2 lists the color terms and offsets, with their corresponding errors, used to calibrate the data.

Table 2

|                      | g Band       | r Band       |
|----------------------|--------------|--------------|
| Color term \((g - r)\) | +0.026\,\,0.045 | -0.059\,\,0.042 |
| DES1 offset          | -3.213\,\,0.051 | -2.979\,\,0.048 |
| Eridanus III offset  | -3.237\,\,0.034 | -2.696\,\,0.028 |
| Tucana V offset      | -3.162\,\,0.034 | -2.798\,\,0.030 |

Note. Color terms and magnitude offsets derived from comparison with APASS-calibrated DES photometry. All photometry assumed an instrumental zero point of 30.00 for both filters prior to the offsets being applied. The offset values listed are a combination of the true zero-point correction and the atmospheric extinction correction.

2.2. Catalog Generation

The raw instrumental magnitudes from DOLPHOT were corrected using the results from Section 2.1, creating a catalog of photometrically calibrated objects. These formed the basis for the analysis presented in this paper. The criteria for selecting stellar objects from this catalog were less stringent than those used in the calibration step and consisted of finding objects where...
1. in either filter, sharpness \( \leq 0.1 \),
2. in both filters, signal-to-noise ratio \( \geq 3.5 \),
3. and the object type corresponds to “good stars” (Objtype = 1).

Spurious or saturated objects were again identified and removed based on either their extremely large magnitude errors or zero magnitude error, respectively.

### 2.3. Artificial Star Experiments

To determine the completeness of our photometry, we have performed an artificial star experiment in each field using DOLPHOT’s built-in routine. The input catalog of artificial stars was generated by taking the cumulative histogram of the magnitudes from the data at approximately 0.3 mag intervals. A base level of around 70 stars per magnitude bin was added to ensure that the brighter magnitudes were sufficiently populated and the color of each star was randomly selected in the range \(-1.3 < (g - r) < +2.0\). This approach allows the artificial star distribution to mimic the actual stellar distribution in the data and forces each subsequent magnitude bin to have more artificial stars than the previous bin. Therefore, as the intrinsic photometric completeness of the data drops with fainter magnitudes, the number of artificial stars injected increases to compensate for the expected decrease in recovered stars. This helps ensure that at the faint end of the photometry we have confidence that the ratio of recovered stars to injected stars is robust. For DES1 and Eri III, a single star at the bright end of the photometry contributes about \( \pm 1.4\% \) to the resultant completeness, while at the faint end, a single star contributes only \( \pm 0.015\% \). A single star at the faint end of the Tuc V photometry contributes \( \pm 0.026\% \) due to the fewer number of artificial stars used when compared to the other two fields. This list is then supplied to DOLPHOT along with the pixel position of each artificial star, and these are added individually into the frame to avoid potential crowding issues. Then, DOLPHOT determines whether it can recover the star or not, and Figure 5 shows the number ratio of recovered stars to input stars. The artificial stars are subjected to the same selection criteria used when selecting real stars from the data, as outlined in Section 2.2. To calculate the 50% completeness level, the data in Figure 5 have been fit with a logistic function

\[
\text{Completeness} = \frac{1}{1 + e^{m - mc}/\lambda},
\]

\[
\text{Error} = \sqrt{NC(1 - C)/N},
\]

where \( m \) is the magnitude, \( mc \) is the 50% completeness value, and \( \lambda \) is roughly the width of the rollover. For the error, \( N \) is the number of artificial stars per bin and \( C \) is the completeness in that bin. Table 3 lists the 50% photometric completeness estimates for each field, number of artificial stars used in the experiment, and median solution from the MCMC fitting routine EMCEE (Foreman-Mackey et al. 2013).

We note that the recovery rate for each magnitude bin is derived from a large number of artificial stars distributed over the entire GMOS-S field. As such, the level of completeness reflects any variation of the recovery rate across the field. For instance, a bright foreground star will inhibit the recovery of

---

The logistic function was developed in 1838 by Pierre-François Verhulst of Ghent, Belgium; see Bacaër (2011) for a short history on the topic.
artificial stars in its vicinity. The error bars shown represent the statistical uncertainties in the recovery rate due to the chosen sample size in the artificial star experiment.

Given the known presence of a stellar overdensity in each field, we used the results of the artificial star test to generate a rough radial photometric completeness profile. Each field was sampled using four concentric annuli around an inner circle with a radius of 44″. Each annuli had the same area as the inner circle, and we found that there was no radial dependence in the photometric completeness of the data out to a radius of 98″.

The variation in the 50% completeness level between the annuli was of the order ~0.06 mag for DES1 and Eri III and ~0.2 mag for Tuc V in both filters. The errors on the fit typically doubled, although Tuc V, with fewer artificial stars, had a larger variation, as expected. These results confirmed that crowding is not an issue in any of these fields, and for this reason, the photometric completeness results quoted in Table 3 and used throughout this paper were derived from the entire field, as this ensured the smallest errors on the completeness estimates.

### 2.4. Color–Magnitude Diagrams

The panels in Figure 6 show the extinction-corrected \((g - r)\) versus \(g\) color–magnitude diagrams (CMDs) of the entire GMOS-S field using all objects classified as stars from our photometric analysis (see Section 2.2) that were found in the vicinity of each ultra-faint stellar system. The calibrated photometry was corrected for Galactic extinction based on the reddening map by Schlegel et al. (1998) and the correction coefficients from Schlafly & Finkbeiner (2011). The CMDs reveal stars ~4 mag fainter than the MSTO and down to the 50% completeness level \(g_{\text{lim}} \sim 26\). The rectangular boxes correspond approximately to the color–magnitude windows presented in the discovery papers for DES1 (Luque et al. 2016), Eri III (Koposov et al. 2015a; Bechtol et al. 2015), and Tuc V (Drlica-Wagner et al. 2015).

### 3. Parameter Analysis

For determining the fundamental properties of each ultra-faint stellar system—mean age, mean metallicity \([\text{Fe/H}]\), the \([\alpha/\text{Fe}]_{\text{ZAMS}}\) ratio, heliocentric distance \((D_\odot)\), central coordinates \((\alpha_0, \delta_0)\), position angle from north to east \((\theta)\), ellipticity \((e = 1 - b/a)\), and half-light radius \((r_h)\)—we employed an iterative process. The CMDs of the entire field for each object can be seen in Figure 6, with their on-sky distribution shown in Figure 7. First, we established the Dartmouth model isochrone (Dotter et al. 2008) that best fit the CMD of the entire GMOS-S field (Figure 6) using the maximum-likelihood (ML) method introduced in Frayn & Gilmore (2002). This method was used in our previous studies (Kim & Jerjen 2015a; Kim et al. 2015b, 2016b). We calculated the ML values \(L_i\) over a grid of Dartmouth isochrones as defined by Equations (1) and (2) in Fadely et al. (2011). The grid points in the multidimensional parameter space covered ages from 7.0 to 13.5 Gyr, a broad range of chemical composition \(-2.5 \text{dex} \leq [\text{Fe/H}] \leq -0.5 \text{dex}, -0.2 \text{dex} \leq [\alpha/\text{Fe}] \leq +0.6 \text{dex},\) and a distance interval \((m - M) \pm 0.5\), where \((m - M)\) is the initial guess for the distance modulus for the object from the discovery papers.

Grid steps were 0.5 Gyr, 0.1 dex, 0.2 dex, and 0.05 mag, respectively. For each object, we present the matrix of likelihood values after interpolation and smoothing over two grid points.

The best-fitting model isochrone was then used to identify stars that are sufficiently close to the stellar population of the object in color–magnitude space. These stars were defined to have a \(g\)-band magnitude in the interval \(19.5 < g < 27.0\) and a color \((g - r)\) that fulfills the requirement

\[
\frac{1}{\sqrt{2\pi \sigma_{\text{tot}}^2}} \exp\left(-\frac{(g - r - (g - r)_{\text{iso}})^2}{2\sigma_{\text{tot}}^2}\right) > 0.5, \tag{3}
\]

where \((g - r)_{\text{iso}}\) is the color of the model isochrone at \(g_{\text{iso}}\) and \(\sigma_{\text{tot}}^2 = \sigma_{\text{int}}^2 + \sigma_{g}^2 + \sigma_{r}^2\). The quantity \(\sigma_{\text{int}} = 0.1\) mag was chosen as the intrinsic color width of the isochrone mask, \(\sigma_{g}^2\), and \(\sigma_{r}^2\) are the photometric uncertainties of a star. Restricting the measurement of the parameters \((\alpha_0, \delta_0, \theta, \epsilon, r_h)\) on this subsample reduces the level of contamination in the R. A.–decl. distribution and thus significantly increases the number ratio between member stars of the stellar system and foreground.

To determine the center coordinates \((\alpha_0, \delta_0)\) and structural parameters of the stellar system, we employed the ML routine from Martin et al. (2008), which was previously used by us in Kim et al. (2016b) based on the likely member stars, i.e., stars that are within the isochrone mask. We used a two-dimensional elliptical exponential profile plus foreground,

\[
E(r, r_h, \Sigma_r, \Sigma_f) = \Sigma_r \exp(-1.68r/r_h) + \Sigma_f, \tag{4}
\]

to model the member star distribution on the sky, where

\[
r = \left\{\left[\frac{1}{1 - e} (x \cos \theta - y \sin \theta)\right]^2 + (x \sin \theta + y \cos \theta)^2\right\}^{1/2}
\]

is the elliptical (semimajor axis) radius, \((x,y)\) is the spatial position of a star, \(e\) is the ellipticity of the distribution, \(\theta\) is the positional angle of the major axis, \(r_h\) is the half-light radius, \(\Sigma_r\) is the central star density, and \(\Sigma_f\) is the foreground star density.

Based on the first estimates for these quantities, we constructed a new CMD from stars that are within an ellipse with a semimajor axis length \(a = 3.9r_h\), semiminor axis length \(b = a(1 - e)\), and position angle \(\theta\) of the nominal center of the stellar overdensity. Assuming an underlying exponential profile, this area contains 90% of the total number of member stars, and we refer to it as the 90% ellipse in the following sections. We then recalculated refined values for age, \([\text{Fe/H}]\), \([\alpha/\text{Fe}]\), and \(D_\odot\) and generated the associated isochrone mask to recalculate \(\alpha_0, \delta_0, \theta, \epsilon, r_h\). This process of measuring the two sets of parameters typically converged to the final values after two to three iterations. Given the relatively small number of bright stars in DES1 and Eri III around the MSTO, we investigated the effect that individual stars have on the age, \([\text{Fe/H}]\), \([\alpha/\text{Fe}]\), and distance by running a jackknife experiment: each star within 0.5 mag above and below the

| Object     | No. of Artificial Stars | \(m_{c,0}\) | \(m_{c,2}\) |
|------------|-------------------------|------------|------------|
| DES1       | 75,307                  | 26.092 ±0.015 | 25.569 ±0.017 |
| Eridanus III | 75,392                  | 26.156 ±0.018 | 25.839 ±0.020 |
| Tuc V      | 42,462                  | 25.923 ±0.023 | 25.595 ±0.026 |
MSTO was dropped once from the sample, and the ML analysis was repeated. The observed variations were well within the quoted uncertainties for each parameter, confirming the internal consistency of the results. We finally calculated the number of stars $N_p$ that belong to the overdensity with Equation (5) from Martin et al. (2008) and fitted a King profile (King 1966),

$$E(r, r_c, r_t, \Sigma_0) = \Sigma_0 \left( \frac{1}{\sqrt{1 + r^2/r_c^2}} - \frac{1}{\sqrt{1 + r_t^2/r_c^2}} \right)^2,$$

at the stellar distribution using the final values for the center coordinates, position angle, and ellipticity. The $r_t$ and $r_c$ parameters are the tidal and core radii. All parameters derived in this section are summarized in Tables 4 and 5. We will discuss the results for DES1 in Section 4 and Eri III in Section 5. The special case Tuc V is discussed in Section 6.

4. Properties of DES1

The analysis outlined in Section 3 is highly iterative and produces many intermediate results; here we present the outcomes of that process. The on-sky distribution of the DES1 stars is shown in Figure 8, and their corresponding radial profile is shown in Figure 9. The stellar population of those stars inside the 90% ellipse is given in Figure 10, and their most likely age and metallicity properties are given in Figure 11. Finally, we generate the luminosity function (LF) of the system in Figure 12 and estimate its absolute magnitude. The parameters for DES1 are listed in Table 4.

4.1. Structural Parameters

Figure 8 highlights the on-sky distribution of the DES1 ultra-faint dwarf galaxy candidate with stars selected based on their proximity to the best-fitting isochrone. The inner ellipse with a semimajor axis length of $3.9 r_h$ encompasses 90% of the DES1 stellar population, and the outer ellipse has a semimajor axis length of $5.5 r_h$. The size of the outer ellipse is chosen such that the area difference between the two ellipses is equivalent to the area of the inner ellipse. Stars located between the inner and outer ellipse are then used to populate the comparison field CMD. The values for the central coordinates ($\alpha_0$, $\delta_0$), position angle ($\theta$), and ellipticity ($\epsilon$) that best describe the stellar distribution of DES1 are listed in Table 4. DES1 is a rather elongated system with an apparent axis ratio of 0.59, which translates to an ellipticity of $\epsilon = 0.41^{+0.03}_{-0.06}$. The position angle is $\theta = 112^\circ \pm 3^\circ$.

Overplotted in Figure 8 are the positions of two putative horizontal-branch (HB) stars as cyan circles. Red open circles are objects from the ALLWISE survey (Wright et al. 2010). The ALLWISE objects are scaled in size to reflect their magnitude and highlight the position of the bright objects in the field. These include both bright foreground stars and bright background galaxies.

Figure 9 shows the star number density in elliptical annuli around DES1, where $r_e$ is the elliptical radius. Overplotted are the best-fitting exponential (black dotted line) and King (red dotted line) profiles using the modal values from the ML analysis. The error bars were derived from Poisson statistics. We measure a half-light radius of $r_h = 5.5^{+0.8}_{-0.7}$ pc, which is similar in size to, e.g., Muñoz 1 ($r_h = 7.1$ pc, $M_V = -0.4 \pm 0.9$; Muñoz

All Wide-field Infrared Survey Explorer mission, http://wise2.ipac.caltech.edu/docs/release/allwise/.

Figure 6. The $g_0$ vs. ($g - r$), CMDs of stars in the 5.5 x 5.5 GMOS-S field centered on the ultra-faint stellar systems DES1, Eri III, and Tuc V. The rectangular boxes correspond to the color–magnitude windows presented in the discovery papers (Drlica-Wagner et al. 2015; Koposov et al. 2015a; Luque et al. 2016). The error bars running vertically along the color ($g - r$) = −1 in 1 mag intervals represent the typical photometric uncertainties.

Figure 8 highlights the on-sky distribution of the DES1 ultra-faint dwarf galaxy candidate with stars selected based on their proximity to the best-fitting isochrone. The inner ellipse with a semimajor axis length of $3.9 r_h$ encompasses 90% of the DES1 stellar population, and the outer ellipse has a semimajor axis length of $5.5 r_h$. The size of the outer ellipse is chosen such that the area difference between the two ellipses is equivalent to the area of the inner ellipse. Stars located between the inner and outer ellipse are then used to populate the comparison field CMD. The values for the central coordinates ($\alpha_0$, $\delta_0$), position angle ($\theta$), and ellipticity ($\epsilon$) that best describe the stellar distribution of DES1 are listed in Table 4. DES1 is a rather elongated system with an apparent axis ratio of 0.59, which translates to an ellipticity of $\epsilon = 0.41^{+0.03}_{-0.06}$. The position angle is $\theta = 112^\circ \pm 3^\circ$.

Overplotted in Figure 8 are the positions of two putative horizontal-branch (HB) stars as cyan circles. Red open circles are objects from the ALLWISE survey (Wright et al. 2010). The ALLWISE objects are scaled in size to reflect their magnitude and highlight the position of the bright objects in the field. These include both bright foreground stars and bright background galaxies.

Figure 9 shows the star number density in elliptical annuli around DES1, where $r_e$ is the elliptical radius. Overplotted are the best-fitting exponential (black dotted line) and King (red dotted line) profiles using the modal values from the ML analysis. The error bars were derived from Poisson statistics. We measure a half-light radius of $r_h = 5.5^{+0.8}_{-0.7}$ pc, which is similar in size to, e.g., Muñoz 1 ($r_h = 7.1$ pc, $M_V = -0.4 \pm 0.9$; Muñoz
et al. 2012) and SMASH 1 ($r_h = 7.1\pm3.5$ pc, $M_V = -1.0 \pm 0.9$; Martin et al. 2016b). The latter object is considered to be a star cluster tidally disrupted by the Large Magellanic Cloud (LMC).

### 4.2. Stellar Population

The CMD of all stars within the 90% ellipse of DES1 is shown in the left panel of Figure 10. The red giant branch (RGB) and subgiant branch are completely absent. However, we notice two HB star candidates at $19.7 < g < 20.0$, $0.3 < (g - r) < +0.3$. The MS of DES1 is well defined down to $g \approx 26.0$ mag, below which star numbers are getting scarce. We note that our photometry is around 50% complete at this magnitude, and it is clearly beginning to influence our ability to identify probable DES1 members. The middle panel shows the comparison CMD of field stars distributed over an equal-sized area between the 90% ellipse and the concentric ellipse with the same ellipticity and position angle and a semimajor axis length of $5.50r_h$. The field CMD was then used to statistically decontaminate the DES1 CMD: for every field star, we removed the nearest DES1 star in color–magnitude space if it was within the error ellipse defined by the 1σ photometric uncertainties in $g$, and $(g - r)$. The right panel shows the foreground-subtracted Hess diagram with the best-fitting Dartmouth isochrone superimposed.

Figure 11 shows the smoothed ML density map of the age–metallicity space, and the location of the best fit is highlighted with a cross. The stars used to generate this map were selected from inside the 90% ellipse as seen in Figure 8. The isochrone that best represents the DES1 features has an age of 11.2 Gyr and a metallicity of $[\text{Fe/H}] = -2.17$ 05. The right panel shows the foreground-subtracted Hess diagram with the best-fitting Dartmouth isochrone superimposed.

### 4.3. LF and Total Luminosity

The total V-band luminosity of DES1 is estimated from all stars that are within the isochrone mask and 90% ellipse. For that purpose, the observed g-band LF is corrected for photometric incompleteness using the logistic function (Equation (1)) with the parameters determined in Section 2.2 for this system. We
then scaled the normalized theoretical LF associated with the best-fitting Dartmouth isochrone (11.2 Gyr, \([\text{Fe}/\text{H}] = -2.38, [\alpha/\text{Fe}] = +0.2\), shifted to a distance of 76 kpc) to the observed level in the magnitude interval, \(22.0 < g_o < 26.2\) (see Figure 12). The theoretical model LF is based on a power-law initial mass function with a Salpeter slope of \(-2.35\). The model LF closely follows the observed LF over the entire magnitude range. We calculate the integrated flux of DES1 to be \(-\pm M_{1.13}^{0.2} g\) mag. A comparison with the total flux of the corresponding Dartmouth LF in the \(V\) band yields a color of \(-g_V = 0.29\), which then converts the \(M_{\text{Mg}}\) luminosity into \(-M_{1.4}^{2} V\) mag. Since the method of fitting the LF relies on the overall shape of the DES1 LF instead of individual stellar flux, the result is statistically resistant to the inclusion of some Galactic foreground stars. However, the exclusion of bright member stars of the system can still carry uncertainties of up to \(\sim 25\% (\sim 0.5\text{ mag})\). Hence, a realistic estimate of the total luminosity of DES1 with error is \(-\pm M_{1.4}^{2.5} V\) mag. For example, adding the fluxes of the two HB candidates increases the total absolute \(V\) magnitude of DES1 to \(-M_{1.73}^{2.0} V\) mag. All derived parameters presented in this section are summarized in Table 4.

5. Properties of Eri III

The properties of Eri III have been determined using the same procedure as outlined in Section 3. The on-sky distribution of the Eri III stars is shown in Figure 13, and their corresponding radial profile is shown in Figure 14. The stellar population of those stars inside the 90% ellipse is given in Figure 15, and their most likely age and metallicity properties are given in Figure 16. Finally, we generate the LF of the system in Figure 17 and estimate its absolute magnitude. The parameters for Eri III are listed in Table 5.

5.1. Structural Parameters

Figure 13 highlights the on-sky distribution of the Eri III ultra-faint dwarf galaxy candidate with stars selected based on their proximity to the best-fitting isochrone. The inner ellipse with a semimajor axis length of \(3.9r_h\) encompasses 90% of the Eri III stellar population, and the outer ellipse has a semimajor axis length of \(5.5r_h\). The size of the outer ellipse is chosen such that the area difference between the two ellipses is equivalent to
the area of the inner ellipse. Stars located between the inner and outer ellipse are then used to populate the comparison field CMD. The two HB and nine RGB candidates are overplotted as cyan and red circles, respectively, while the four blue straggler (BS) candidates (g − r ∼ 0, 21.5 < g_0 < 23.5) are shown in green. The locations of bright objects in the field from the ALLWISE survey are shown as open red circles, the size of which reflects their magnitude. These objects include both bright foreground stars and bright background galaxies.

Figure 10. Left: CMD of all stars within the ellipse centered on the nominal celestial coordinates of DES1 shown in Figure 8. The major and minor axes are 0'84 and 0'49, respectively, with a position angle of 112°. Middle: comparison CMD of the stars between the inner and outer circles, showing the distribution of the foreground stars in color–magnitude space. Right: Hess diagram of the foreground-subtracted CMD superimposed with the best-fitting Dartmouth isochrones as dashed lines bracketing the 1σ confidence level of the metallicity estimate. Both isochrones are 11.2 Gyr, [α/Fe] = +0.2, and m − M = 19.40 mag, with the left isochrone having an [Fe/H] = −2.50, while the right has an [Fe/H] = −2.17. Note: [Fe/H] = −2.50 is the lowest metallicity available for the Dartmouth model isochrones.

Figure 11. Smoothed ML density map in age–metallicity space for all stars within the 90% ellipse around DES1. Contour lines show the 68%, 95%, and 99% confidence levels. The diagonal flow of the contour lines reflects the age–metallicity degeneracy inherent to such an isochrone-fitting procedure. The 1D marginalized parameters around the best fit (cross) with uncertainties are listed in Table 4.

Figure 12. Completeness-corrected DES1 luminosity function of all stars that are within the isochrone mask and the 90% ellipse. The best-fitting Dartmouth model luminosity function shifted by the distance modulus 19.40 mag and scaled to a total luminosity of M_g = −1.13 mag is overplotted.
and two HB, nine RGB, and four BS candidates are noticeable above the MSTO in the luminous system than DES1 with a clear hint of an RGB. Nine RGB star candidates are highlighted in Figure 13. Similar to DES1, there are two possible HB stars in Eri III (g_r \approx 20.1, (g - r)_0 \approx -0.22), as well as four BSs. The sky positions of the RGB, HB, and BS stars are highlighted in Figure 13.

5.2. Stellar Population

Figure 15 (left panel) shows the CMD of all stars within 3.9r_h of the center of Eri III. The middle panel, as in Figure 10, shows the CMD of field stars outside the 90% ellipse, covering the same area. The right panel shows the Hess diagram for the foreground-corrected Eri III CMD with the best-fitting Dartmouth isochrone superimposed. We note that the statistical decontamination was performed the same way as for DES1.

Figure 16 shows the smoothed ML density map of the age-metallicity space, and the location of the best fit is highlighted with a cross. The stars used to generate this map were selected from inside the 90% ellipse as seen in Figure 13. Similar to DES1, Eri III consists of an old (12.5 Gyr), metal-poor ([Fe/H] = −2.40) stellar population with [α/Fe]_avg = 0.2. Eri III is 20% further away at a heliocentric distance of 91 kpc (m − M = 19.80 mag).

Based on its CMD, Eri III appears to be a slightly more luminous system than DES1 with a clear hint of an RGB. Nine RGB star candidates are noticeable above the MSTO in the range 21.2 < g_r < 23.0. Similar to DES1, there are two possible HB stars in Eri III (g_r \approx 20.1, (g - r)_0 \approx -0.22), as well as four BSs. The sky positions of the RGB, HB, and BS stars are highlighted in Figure 13.

5.3. LF and Total Luminosity

The total luminosity of Eri III has been derived in the same manner as that for DES1 (Section 4.3) and is presented in Figure 17. We calculated the integrated light by comparing the completeness-corrected observed LF with the Dartmouth model LF that corresponds to the best-fitting isochrone of 12.5 Gyr, [Fe/H] = −2.40, and [α/Fe] = +0.2. We measured a total g-band luminosity of M_g = −1.75 ± 0.2. The integrated Dartmouth model LFs in g and V have a color of g − V = 0.32, which converts the M_g magnitude into M_V = −2.07.

For the same reasons as outlined in Section 4, a more realistic estimate for the uncertainty of the total luminosity of Eri III is \sigma_{M_V} = 0.50. We also note that adding the fluxes of the HB and BS candidates would increase the total absolute magnitude to M_V = −2.33 mag, well within the quoted uncertainty. All derived parameters presented in this section are summarized in Table 5.
6. Properties of Tuc V

Tuc V, also known as DES J2337–6316, was reported as discovered in the second year of optical imaging data from the DES (Drlica-Wagner et al. 2015). Interestingly, it is not only the closest object known to the SMC in projection (see Figure 1), but its heliocentric distance of $55 \pm 9$ kpc is also comparable. The best-fit half-light radius, as Drlica-Wagner et al. (2015) derived from an iterative MCMC analysis, was found to be $r_h = 1.0^{+0.3}_{-0.03}$ arcmin and well matched by the $5'5 \times 5'5$ GMOS-S field of view. However, looking at the false-color image in Figure 4, there is no obvious stellar overdensity visible, as opposed to both DES1 (Figure 2) and Eri III (Figure 3).

6.1. Stellar Population

Despite the false-color image not revealing a clear overdensity in the field, the CMD of the full GMOS-S field (right panel of Figure 6) nonetheless shows RGB and MS-like features. Given the absence of a well-defined overdensity and thus a center (see Figure 7) in the base catalog, we determine...
the age and metallicity of that population by fitting the entire field. Figure 18 shows the ML density map with the location of the best-fit model isochrone with an age of 11.8 Gyr, \([\text{Fe/H}] = -2.09\) dex, and \([\alpha/\text{Fe}] = +0.4\) dex. In this field, we use \(E(B - V)_{\text{SFR11}} = 0.0190\), \(A_g = 0.072\), and \(A_r = 0.050\) to extinction-correct the data. This isochrone is a good match with the observed features in the CMD, as can be seen in Figure 19.

The associated distance of the Tuc V population is measured at 59.5 kpc, confirming the agreement with the SMC distance.

The on-sky stellar distribution of Tuc V stars that are close to the best-fit isochrone can be seen in the top panel of Figure 20; the bottom panel shows the distribution of nonstellar objects in the same region of the CMD. In both panels, the bright ALLWISE objects are shown to highlight the location of the bright foreground stars and background galaxies, with larger circles representing brighter magnitudes. As with DES1 and Eri III, the bright objects in the Tuc V field generally do not correspond to any apparent low-density regions in the stellar distribution. As seen in Figure 7, there is no concentrated overdensity in this field, even after selecting likely Tuc V stars. The slight excesses visible by eye are not sufficiently concentrated to be considered the core of an object.

The initial discovery of Tuc V was made with the Dark Energy Camera (DECam). In Figure 21, we show the locations of all stars that lie in the Tuc V isochrone mask selected over the entire DECam field (3 deg\(^2\)). They are overplotted on the 2D star density histogram, with our GMOS-S field shown as a box outline at 354.35°, -63.27°. The figure confirms that there is indeed a significant stellar overdensity as reported by Drlica-Wagner et al. (2015) and that our GMOS-S field is in the correct location. In Figure 22, after selecting only stars located close to the Tuc V isochrone and plotting their on-sky distribution, we can see how going from the shallow DES data \((g_{\text{lim}} \approx 23.0\), top panel\) to the much deeper GMOS-S data \((g_{\text{lim}} \approx 26.0\), bottom panel\) breaks up the peak of the Tuc V structure into several hot spots with similarly high star densities. The improved number statistics from the deeper photometry reveal that there is no single overdensity in this field consistent with a cluster-like or dwarf galaxy–like morphology. Additionally, the locations of the bright objects in the field do not correspond to the low-density regions between the peaks of the Tuc V stellar distribution and therefore are not influencing our ability to accurately map this object. Returning to the wider DECam field (Figure 21), there is also no evidence of a more diffuse stellar cluster or stream that would possibly make the GMOS-S field too small for such an object. Given the lack of a center in the Tuc V stellar distribution, it is not possible to conduct a structural analysis for Tuc V. Nevertheless, we will discuss its potential nature in Section 7.4.

7. Discussion

The fundamental properties of the stellar populations of DES1 and Eri III are remarkably similar. They have the same metallicity \([\text{Fe/H}] = -2.38^{+0.20}_{-0.19}\) versus \([\text{Fe/H}] = -2.40^{+0.12}_{-0.13}\) and mean \(\alpha\) abundance \(((\alpha/\text{Fe})_{\text{avg}} = +0.2^{+0.1}_{-0.0}\) for both), and they have comparable ages (11.2\(^{+1.0}_{-0.9}\) versus 12.5\(^{+0.5}_{-0.7}\) Gyr). Structurally, they also share similar properties: ellipticity (0.41\(^{+0.03}_{-0.06}\) versus 0.44\(^{+0.02}_{-0.03}\)) and position angle (112° \(\pm\) 3° versus 109° \(\pm\) 5°). Eri III \((r_h = 8.6^{+0.9}_{-0.8}\) pc) is about 1.5 times larger than DES1 \((r_h = 5.5^{+0.5}_{-0.7}\) pc\) and, consequently, slightly more luminous \((M_V = -2.07 \pm 0.50\) versus \(M_V = -1.42 \pm 0.50\)). When it comes to their location in the Milky Way halo, they are projected onto the trailing filaments of neutral hydrogen gas from the Magellanic Stream (see Figure 1). However, both systems are more distant than the Magellanic Clouds. DES1 \((D_{\text{GC}} = 74 \pm 4\) kpc\) is 37% and Eri III \((D_{\text{GC}} = 91 \pm 4\) kpc\) is 69% further away. They have similar angular separations (23°\(^2\) versus 22°\(^2\)) and 3D distances (31.7 versus 41.0 kpc) to the SMC.

DES1 is the less massive of the two and has demonstrably fewer stars than Eri III, as is noticeable in the CMDs (Figures 10 and 15) and quantified by the parameter \(N_9\) in Tables 4 and 5. DES1 lacks an obvious RGB, and the MS is less populated when compared to Eri III. Despite these
differences, both objects have observed LFs that are well matched with a Salpeter IMF and power-law slope of $a = -2.35$. This suggests that they have always been small stellar systems and have not lost significant amounts of mass.

DES1 and Eri III are shown as red diamonds in the size–luminosity diagram (Figure 23) in a region dominated by ultra-faint star clusters. DES1’s half-light radius and stellar content put it close to the recently discovered objects Balbinot I (Balbinot et al. 2013) and SMASH 1 (Martin et al. 2016b), while Eri III is the most luminous among objects with half-light radii less than 10 pc. They are all significantly fainter than the bulk of the Milky Way globular clusters, plotted as open circles. The closest star clusters to DES1 are AM4 (Carraro 2009) and Koposov 1 and 2 (Koposov et al. 2007), in order of decreasing luminosity. Interestingly, Paust et al. (2014) determined that Koposov 1 and 2 are intermediate-age, open star clusters possibly related to the Sagittarius dwarf galaxy, and Carraro (2009) speculated that AM4 might be associated with Sagittarius too. Since the bulk of objects in this part of the size–luminosity diagram around DES1 and Eri III are known to be star clusters, and they appear distinct from the Milky Way population, the conclusion that Koposov 1 and 2 and perhaps AM4 are related to the Sagittarius dwarf raises the possibility that all of them are star clusters of non-Galactic origin.

7.1. Metallicity \([\text{Fe/H}]\) and \(\alpha\) Abundance \([\alpha/\text{Fe}]\)

Milky Way satellite galaxies are known to follow a well-defined relationship between their total luminosity $M_V$ and average metallicity $\langle [\text{Fe/H}] \rangle$, e.g., Kirby et al. (2013). Given the small intrinsic scatter, the relation can be used together with or as an alternative to the size–luminosity relation as a diagnostic tool to discriminate between a dwarf galaxy and star cluster. Figure 24 shows this luminosity–metallicity (LZ) parameter space. The solid and dotted lines are the least-squares fit with the $1\sigma$ confidence band about the relation based on 13 galaxies taken from Kirby et al. (2013). It corresponds to the fit of the data for the chemically best-studied dwarf galaxies. We complemented that plot with data for new stellar systems: Hya II (Martin et al. 2015), Kim 1 (Kim & Jerjen 2015a), Kim 2 (Kim et al. 2015b), Kim 3 (Kim et al. 2016b), Laevens 1 (Laevens et al. 2014; Belokurov et al. 2014), Pisces II (Kirby et al. 2015), Ret II
Walker et al. 2015; Koposov et al. 2015b, Hor I (Koposov et al. 2015b), Tri II (Laevens et al. 2015a; Martin et al. 2016a), Balbinot I (Balbinot et al. 2013), Boötes II (Koch & Rich 2014), Muñoz I (Muñoz et al. 2012), and Peg III (Kim et al. 2015a, 2016a). DES1 and Eri III are just outside of the 1σ confidence band. They are close to Segue 1 (Belokurov et al. 2007) and Segue 2 (Belokurov et al. 2009). The error bar for ([Fe/H]) also brings DES1 close to SMASH 1. Segue 1, DES1, and Eri III share a similar total luminosity and mean stellar metallicity, as well as the same ellipticity ($-0.48^{+0.10}_{-0.06}$ versus $-0.44^{+0.06}_{-0.05}$; Geha et al. 2009). The two fundamental differences are the half-light radius ($29^{+8}_{-3}$ versus $5.5^{+0.8}_{-0.7}$ versus $8.6^{+0.9}_{-0.8}$ pc) and the distance from the Milky Way. Segue 1 is at a Galactocentric distance of 28 kpc, while DES1 is 2.6 times and Eri III is 3.2 times further away.

Segue 1 and 2 are both classified as ultra-faint dwarf galaxies based on the high mass-to-light ($M/L$) ratio estimates and a large intrinsic metallicity spread of more than 2 dex (Segue 1: Geha et al. 2009; Frebel et al. 2014; Segue 2: Kirby et al. 2013). The metallicity spread is a signature observed in ultra-faint dwarf galaxies, while star clusters do not show that characteristic. DES1 and Eri III have $\alpha$/Fe$_{avg}$ ~ 0.2 dex, consistent with the mean value observed for ultra-faint dwarf galaxies (Figure 6 of Vargas et al. 2013).

There are two pieces of evidence that suggest that DES1 and Eri III have a non-Galactic origin. First, they are at large...
Figure 24. Luminosity–stellar metallicity relation for classical Milky Way satellite galaxies (black dots) complemented with data from the literature for Hyades; Kim 1, 2, and 3; Lalande 1; Pisces II; Ret II; Hor I; Peg II; SMASH 1; Tuc II; and Boötes II (blue dots). The solid and dotted lines represent the least-squares fit and 1σ rms from Kirby et al. (2013), based on spectroscopically studied stars in 13 galaxies (Segue 2 was excluded). DES1 and Eri III (red diamonds) fall just outside of the 1σ confidence band. DES1 is next to Segue 1, whereas the higher luminosity of Eri III moves this system closer to the LZ relation. The open circles are the data from the Milky Way globular clusters (Harris 1996; 2010 version).

Galactocentric distances, which is unusual for star clusters, Galactic or non-Galactic. Only eight known clusters have $D_{\text{GC}} > 70$ kpc (Kim et al. 2015b). Second, they are close to the two dwarf galaxies Segue 1 and 2 in LZ space and only $\approx 0.2$–0.3 dex more metal-rich than the LZ relation predicts for systems of their luminosities. Belokurov et al. (2009) and Kirby et al. (2013) speculated that Segue 1 and 2 may be the remnants of tidally stripped dwarf galaxies. DES1 and Eri III could be other examples of Milky Way satellite galaxies that came to be ultra-faint through tidal stripping, but their small size implies that either they were intrinsically smaller to begin with or they underwent significantly more tidal stripping than Segue 1 and 2. Keep in mind that the LF of these systems, as discussed in the previous section, implies that they have not undergone much disruption during their lifetime. In which case, these would be the smallest known galaxies to fit this scenario.

A key piece of evidence for this hypothesis would be a metallicity spread in the stellar population, which can be tested with spectroscopic follow-up.

Figure 25. Cumulative distribution functions for DES1 (top) and Eri III (bottom) MS stars out to $2r_h$ from the nominal center. The $\approx 3$ mag from the MSTO down to the 50% completeness limit were subdivided into two magnitude intervals that correspond to two stellar mass bins of equal size: $0.61 < M/M_\odot < 0.71$ and $0.71 < M/M_\odot < 0.81$ for DES1 and $0.63 < M/M_\odot < 0.71$ and $0.71 < M/M_\odot < 0.79$ for Eri III. No evidence of mass segregation is found in the two stellar systems as concluded from the large $p$ values of a two-sided KS test: $p = 0.18$ and 0.92, respectively.

7.2. Mass Segregation

Similar to the analysis conducted for Kim2 (Kim et al. 2015b), we performed a two-sample Kolmogorov–Smirnov (KS) test (Massey 1951) to investigate whether MS stars with different masses in DES1 or Eri III follow the same spatial distribution. Figure 25 shows the cumulative distribution functions for DES1 (top) and Eri III (bottom) MS stars out to $2r_h$ from the nominal cluster center. The $\approx 3$ mag from the MSTO down to the 50% completeness limit were subdivided into two magnitude intervals that correspond to two equal-size mass bins: $\Delta M/M_\odot = 0.1$ for DES1 and $\Delta M/M_\odot = 0.08$ for Eri III. For comparison, the confirmation of mass segregation in Kim 2 utilized three mass bins of $\Delta M/M_\odot = 0.1$. The KS test yields relative large $p$ values of $p = 0.18$ and 0.92, respectively, implying no evidence of mass segregation in the MS population of the two stellar systems.

These results suggest that neither DES1 nor Eri III has experienced substantial mass loss from two-body relaxation and tidal stripping. This picture is also consistent with our finding that the observed LFs of DES1 and Eri III are well described with a model LF using a Salpeter IMF.

We note that the stellar mass covered by MS stars in old ($\sim 10$–12 Gyr), metal-poor ($-2.5 < [\text{Fe/H}] < -1.5$) stellar populations is inherently small. Accessing a mass range of the order of $M/M_\odot = 0.3$ would require photometry 4–5 mag below the MSTO.
7.3. DES1 and Eri III: Star Cluster or Dwarf Galaxy?

Using the derived properties of DES1 and Eri III, we attempt to determine what is the most likely nature of these objects. One of the main challenges in interpreting these data is that, given the location of these objects in multidimensional parameter space, we can expect the following possible explanations for their origins: Milky Way globular cluster, Milky Way dwarf galaxy, LMC/SMC star cluster, or LMC/SMC dwarf galaxy.

Size ($r_h$). Both DES1 and Eri III are small stellar systems with half-light radii less than 10 pc and, as such, are consistent with star clusters. In comparison to the few known globular clusters at comparable Galactocentric distances (Eridanus, AM1, Pal 4, Pal 3, NGC 2419, and Pal 14, in increasing size order), these clusters are 2.2–4.9 times larger than DES1 and 1.4–3.2 times larger than Eri III; see Harris (1996).

Galactocentric distance. There are only a few known Milky Way globular clusters at the distances of DES1 and Eri III ($D_{GC} = 74$ and 91 kpc), so it appears unlikely that they are Milky Way star clusters. Their distances are more compatible with Milky Way dwarf galaxies; however, their proximity to the Magellanic Cloud system and their location in the trailing component of the Magellanic Stream provides two alternative views. They might be star clusters or dwarf galaxies that are infalling with the LMC and SMC galaxies.

Ellipticity ($\epsilon$). Milky Way globular clusters are spherical systems with a mean ellipticity of ($\epsilon$) = 0.08 and a standard deviation of $\sigma_\epsilon = 0.06$. The maximum ellipticities were measured for the clusters NGC 6144 ($\epsilon = 0.25$) and M19 ($\epsilon = 0.27$) from (Harris 1996; 2010 version). Hence, DES1 and Eri III are significantly more elliptical than all of the known Milky Way globular clusters. Their compact size effectively rules them out as ultra-faint dwarf galaxies and suggests that they are probably unusual star clusters, most likely dark matter free star clusters in the process of dissolution. Their elongated stellar distributions could be due to the tidal fields of the LMC/SMC or Milky Way. In this context, the elongated star cluster SMASH 1 close to the LMC comes to mind.

$LF$ and mass segregation. The completeness-corrected $LF$s for DES1 and Eri III are consistent with a Salpeter IMF. There is no evidence for a flatter $LF$ through the lack of low-mass stars. This suggests that DES1 and Eri III have always been small clusters and have not lost significant amounts of mass at the current stage. This picture is also consistent with the absence of mass segregation in the MS populations covering the approximate mass range $0.60 < M/M_\odot < 0.80$.

Size–luminosity relation. DES1 and Eri III are located in the ultra-faint regime of the size–luminosity relation as exhibited by the Milky Way satellite galaxies. However, that part of the parameter space ($M_V > -2$, $r_h \lesssim 10$ pc) is now populated by a number of ultra-faint star clusters. In terms of size, DES1 shares properties with other confirmed star clusters, like AM4 and Balbinot 1, but DES1 has twice the Galactocentric distance of those two. Eri III, despite its brighter luminosity ($M_V = -2.07$), is closer in properties to star clusters than to dwarf galaxies. It is about five times smaller than the dwarf galaxy candidate Tri II, which has a similar luminosity, and Eri III is fainter and roughly half the size of the ultra-faint dwarf galaxy candidate Draco II. Eri III is probably a star cluster too.

Luminosity–metallicity relation. DES1 has almost identical properties to the dwarf galaxy Segue 1, despite being approximately six times smaller. Although the error in [Fe/H] allows for the possibility that DES1 is a dwarf galaxy, its luminosity suggests that it is more likely to be a star cluster. Eri III is also found close to the 1σ confidence line of the dwarf galaxy LZ relation (Kirby et al. 2013) and has properties intermediate to Tuc III and DES1, although it is about five times smaller than Tuc III. With regard to the outer halo globular cluster population, only NGC 2419 ($D_\odot = 82.6$ kpc) has a similarly low metallicity ([Fe/H] = −2.19; Harris 1996; 2010 version), but this object is much more luminous ($M_V = -9.42$) and, as such, is considerably different.

DES1 and Eri III have equivalent luminosities to ultra-faint dwarf galaxies more than five times larger, and this suggests that they reside in a gravitational potential that is, locally, more concentrated than those objects of similar luminosities (e.g., Segue 1, Segue 2, and Tri II). Their metallicities, however, are considerably lower than those of the Milky Way globular clusters, so we propose that DES1 and Eri III are most likely dissolving star clusters associated with the Magellanic Clouds. They are simply too distant and different to be considered part of the Milky Way globular cluster system and both lie in close proximity to the Magellanic Clouds.

7.4. Tuc V: A False-positive Ultra-faint Candidate?

As demonstrated in Section 6, our deep photometry of Tuc V did not reveal a stellar overdensity within the GMOS-S field and, in particular, none that could correspond with the expected properties of Tuc V as outlined in Drlica-Wagner et al. (2015; see Figure 7, right panel). Determining the best-fit stellar population to all of the stars in the field and selecting only stars belonging to that isochrone also failed to recover any stellar overdensity that resembles a star cluster or dwarf galaxy radial profile (Figure 22, bottom panel). This rules out a bound star cluster or dwarf galaxy as the explanation for the Tuc V phenomenon. However, Tuc V is not a false positive. These stars clearly belong to a coherent stellar population, and the next obvious origin for this stellar excess is the Milky Way stellar halo, the SMC stellar halo, or a disrupted star cluster.

To test the possibility that the Tuc V stars are related to the Milky Way halo, we employed the GALAXIA code (Sharma et al. 2011) to generate the expected stellar populations in the direction of Tuc V out to 100 kpc. In Figure 26, the histogram of $(g - r)$ colors between the $g$-band magnitudes of 20 and 24 mag are plotted for both our data (gray) and the Galaxia model (blue). To scale the two data sets, we use the observed number of red stars around $(g - r) = +1.5$ in the data as a calibration reference for the model. Aside from the small color differences between the samples, it is clear that our Tuc V CMD contains significantly more stars in the color range $0.1 < g - r < 0.4$ mag and that the MS in the Tuc V data cannot be attributed to Galactic halo stars.

Another possible origin for the Tuc V stars is an extended structure related to the SMC. If we take the center of the SMC from de Grijs & Bono (2015) as $(\alpha, \delta) = (15^h12^m, -72^\circ72^\prime)$ at a distance of $D_\odot = 61.94$ kpc and the Tuc V field position as $(l, b) = (316^\circ31^\prime, -51^\circ89^\prime)$ at a distance of $D_\odot = 59.7$ kpc, we can compute the three-dimensional distance using the Astropy

---

13 Tuc V best-fit isochrone: $m - M = 18.8$, $D_\odot = 59.7$ kpc, age $\sim 11.8$ Gyr, [Fe/H] = −2.09 dex, [$\alpha$/Fe] = +0.4 dex.
The counts have been scaled such that the expected number of stars from the GMOS-S data presented in gray and the GALAXIA galactic model data for the Tuc V field (Sharma et al. 2011) presented in blue. The counts have been scaled such that the expected number of stars from GALAXIA approximately matches the data in the region around $(g-r) \sim +1.5$. There is a clear excess of blue stars in the region of the Tuc V MS as compared to the model.

The closest known SMC halo substructure is the SMC Northern Overdensity (SMCNOD) from Pieres et al. (2017), which is 8° or 8 kpc from the SMC. If we overlay the SMCNOD isochrone with a distance of $\sim 59.7$ kpc on our Tuc V CMD (Figure 19, blue line), we find that it is roughly consistent with the photometry. This isochrone requires the MSTO to be around $g \sim 22$ mag, but given the small size of the GMOS-S field, it is possible that the turnoff from the best-fit isochrone is being biased by the small grouping of stars around $g \sim 22.5$. Those MSTO stars are spread across the entire field, with only about half of them in locations that could be considered inside Tuc V. From Figure 18, it is clear that a 6 Gyr, [Fe/H] = −1.3 dex SMCNOD isochrone is broadly consistent with the age–metallicity degeneracy of this stellar population. At this distance, although it is outside the nominal 7°:5 break radius seen in the SMC halo density profile (Figure 4 from Pieres et al. 2017), could these Tuc V stars be part of the SMC halo? The SMC halo does show an increasing excess in star counts along some position angles (e.g., P.A. $\sim 200^\circ$; Figure 4 of Pieres et al. 2017), and it seems that even the typical SMC halo density profile has not yet reached the background at the angular distance of Tuc V. Taking all these factors into account, it appears that Tuc V either could be a chance grouping of SMC halo stars or represents an SMC halo substructure like the SMCNOD. It is not an ultra-faint stellar system as originally thought.

Finally, Tuc V could be a tidally disrupted star cluster in its final stages of dissolution. It is uncertain how the final stage of a disrupting star cluster would appear on the sky, and, unfortunately, such analysis is beyond the scope of this paper. Spectroscopic analysis of the Tuc V stars would be desirable to confirm that the subgroups seen in Figure 22 are chemically similar and likely to have a common origin.

Tuc V is not an ultra-faint dwarf galaxy candidate in the classical sense, leaving us to speculate about other systems reported in the literature that have strong similarities to Tuc V. In particular, the CMD of the Draco II dwarf galaxy candidate (Laevens et al. 2015a, middle panel of their Figure 1) has the same truncated MS as Tuc V, and the isochrone fit struggles to fit this feature because it is constrained by the apparent RGB. If we consider the field and object CMDs above the MSTO ($i_{P1,0} < 20$ mag), we see that they are almost identical, and the on-sky distribution is small, sparse ($r_h = 27^{+1.0}_{-0.8}$), and not centrally concentrated. As with Tuc V, there is obviously a coherent stellar population within the field, as seen by the manifest MS in the CMD, but it lacks a conspicuous progenitor. Draco II is somewhat isolated on the sky from other large dwarf galaxies, but even though it is relatively high above the Galactic plane at $(l, b) = (98^\circ.3, 42^\circ.9)$, it is well within the Milky Way stellar halo ($D_{GC} = 22 \pm 3$ kpc). As such, it may represent an equivalent chance overdensity of Milky Way halo stars in much the same manner that Tuc V may be a chance overdensity of SMC halo stars. Similarly, Cetus II (Drlica-Wagner et al. 2015), $(l, b) = (156^\circ.48, -78^\circ.53)$ at $D_{GC} \sim 32$ kpc with a half-light radius of only $r_h \sim 1.9$, is another interesting case. As candidate systems become fainter and less populated, deep follow-up photometry of all the ultra-faint dwarf galaxy candidates is crucial to better understand the nature of these systems and use their properties to refine and improve the current search algorithms.

7.5. The Trough of Uncertainty

In the previous section, we identify the Tuc V stellar excess as a likely chance overdensity in the SMC halo or a dissolving star cluster, and after examining the CMDs of other ultra-faint dwarf galaxy candidates, we concluded that Draco II and Cetus II may also represent systems of that nature. Serendipitously, all of these objects appear in the same part of the size–luminosity diagram. In Figure 23, we highlight the region (gray box) encompassed by these objects, showing that on either side of the region there is an apparent clear distinction between those objects tentatively identified as star clusters (to the left) and dwarf galaxies (to the right). To honor Tuc V as the potential prototype false-positive identification, we label this region the Trough of Uncertainty (TUC). The TUC illuminates the region of the size–luminosity plane where potential false-positive identifications might be occurring and might also serve to divide the size–luminosity plane between star clusters and dwarf galaxies.

If we compare objects on either side of the TUC in the luminosity–metallcity relation (Figure 24), we find that those to the left of the TUC (plotted as diamonds) do not fall on the LZ relation, while those to the right of the TUC (plotted as circles) are consistent with the relation. It is important to note that many of the objects below $M_h = -4$ only have preliminary metallicity estimates at this stage, and so the true scatter of the relation at these metallicities is uncertain. While we have raised possible issues with Draco II and Cetus II, it is obvious from Figure 23 that by simply removing Tuc V, a clear gap has opened between the star clusters and dwarf galaxies in this relation. Deep photometry of the objects in the TUC is crucial to resolving their status, and it seems that the TUC is delimiting the border between star clusters and dwarf galaxies.

Inside the TUC, the objects are either of the specific dimension where dissolving star clusters are still coherent.
enough to be mistaken for dwarf galaxies or at the point at which random fluctuations within the predominantly smooth stellar halos can be detected. While Tuc V is a cautionary tale of interpreting data dominated by small-number statistics, it has highlighted the fascinating intersection in the size–luminosity plane where star clusters meet dwarf galaxies.

8. Conclusion

This deep photometry of DES1 and Eri III has revealed them to be old, small, and highly elliptical stellar populations with very low metallicity at the outer reaches of the Milky Way. Our analysis has shown that their observed LFs and lack of any apparent mass segregation both point to systems that have undergone very little tidal stripping. Coupling these results together, we conclude that they are most likely star clusters infalling with the Magellanic Clouds. In this regard, they join SMASH 1 and Tuc III as probable MC star clusters.

Tuc V represents a different challenge. There is an excess of stars in this field compatible with a single stellar population; however, this overdensity does not have a well-defined center and does not follow a radial density profile consistent with any other ultra-faint system. Ever since Klypin et al. (1999) highlighted the “missing satellites” problem, the race has been on to scrutinize the low-mass end of the Milky Way’s galaxy LF. The expectation has been that there should be hundreds of smaller satellites of the Milky Way if the hierarchical formation scenario of a ΛCDM universe was to be validated. While the latest all-sky surveys have delivered a few dozen more candidates, as these systems become smaller and fainter, it becomes even more important to confirm their status as dwarf galaxies. With so few known systems in the ultra-faint regime, any incorrectly classified objects could skew the distribution away from the true solution. In this paper, we have shown that Tuc V is almost certainly one of these false-positive candidates, and we propose that it is either a disrupted SMC star cluster or an anomaly in the SMC stellar halo.

We speculate that Draco II and Cetus II may be other false-positive detections and, along with Tuc V, occupy a region of the size–luminosity plane (TUC) that may be peculiar to this sort of object. Our results demonstrate that the shallow discovery data are potentially insufficient in unambiguously identifying objects like Tuc V and that deeper follow-up observations are crucial to avoid further false positives from entering the sample of Milky Way satellites.

The authors would like the thank the anonymous referee for work in improving this manuscript.

BCC and HJ acknowledge the support of the Australian Research Council through Discovery project DP150100862.

BCC would like to thank Andrew Dolphin for his assistance with DOLPHOT for the photometry.

This paper is based on observations obtained at the Gemini Observatory (GS-2016B-Q-7), which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina), and Ministério da Ciência, Tecnologia e Inovação (Brazil).

This research has made use of the Aladin sky atlas developed at CDS, Strasbourg Observatory, France (Bonnarel et al. 2000; Boch & Fernique 2014); the AAVSO Photometric All-sky Survey (APASS), funded by the Robert Martin Ayers Sciences Fund; TOPCAT in exploring and understanding this data set (Taylor 2005); Astropy, a community-developed core Python package for astronomy (Astropy Collaboration et al. 2013); and the SIMBAD database, operated at CDS, Strasbourg, France.

This project used public archival data from the Dark Energy Survey (DES). Funding for the DES projects has been provided by the U.S. Department of Energy, the U.S. National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, the Center for Cosmology and Astro-Particle Physics at the Ohio State University, the Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico and the Ministério da Ciência, Tecnologia e Inovação, the Deutsche Forschungsgemeinschaft, and the Collaborating Institutions in the Dark Energy Survey. The Collaborating Institutions are Argonne National Laboratory, the University of California at Santa Cruz, the University of Cambridge, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Madrid, the University of Chicago, University College London, the DES-Brazil Consortium, the University of Edinburgh, the Eidgenössische Technische Hochschule (ETH) Zürich, Fermi National Accelerator Laboratory, the University of Illinois at Urbana-Champaign, the Institut de Ciències de l’Espai (IEEC/CSIC), the Institut de Física d’Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig-Maximilians Universität München and the associated Excellence Cluster Universe, the University of Michigan, the National Optical Astronomy Observatory, the University of Nottingham, the Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Accelerator Laboratory, Stanford University, the University of Sussex, and Texas A&M University.

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/Columbia Institute of Technology, funded by the National Aeronautics and Space Administration.

ORCID iDs
Blair C. Conn @ https://orcid.org/0000-0001-6959-4546
Helmut Jerjen @ https://orcid.org/0000-0003-4624-9592
Dongwon Kim @ https://orcid.org/0000-0002-6658-5908
Mischa Schirmer @ https://orcid.org/0000-0003-2568-9994

References
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bacaër, N. 2011, in A Short History of Mathematical Population Dynamics (London: Springer), 35
Balbinot, E., Santiago, B. X., da Costa, L., et al. 2013, ApJ, 767, 101
Bechtol, K., Drlica-Wagner, A., Balbinot, E., et al. 2015, ApJ, 807, 50
Belokurov, V., Irwin, M. J., Koposov, S. E., et al. 2014, MNRAS, 441, 2124
Belokurov, V., Walker, M. G., Evans, N. W., et al. 2009, MNRAS, 397, 1748
Belokurov, V., Zucker, D. B., Evans, N. W., et al. 2007, ApJ, 654, 897
