Pegasus V - a newly discovered ultra-faint dwarf galaxy on the outskirts of Andromeda

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ABSTRACT

We report the discovery of an ultra-faint dwarf in the constellation of Pegasus. Pegasus V (Peg V) was initially identified in the public imaging data release of the DESI Legacy Imaging Surveys and confirmed with deep imaging from Gemini/GMOS-N. The colour-magnitude diagram shows a sparse red giant branch (RGB) population and a strong over-density of blue horizontal branch stars. We measure a distance to Peg V of \( D = 692^{+33}_{-29} \) kpc, making it a distant satellite of Andromeda with \( M_V = -6.3 \pm 0.2 \) and a half-light radius of \( r_{\text{half}} = 89 \pm 41 \) pc. It is located \( \sim 260 \) kpc from Andromeda in the outskirts of its halo. The RGB is well-fit by a metal-poor isochrone with [Fe/H] \( \approx -3.2 \), suggesting it is very metal poor. This, combined with its blue horizontal branch could imply that it is a reionisation fossil. This is the first detection of an ultra-faint dwarf outside the deep Pan-Andromeda Archaeological Survey area, and points to a rich, faint satellite population in the outskirts of our nearest neighbour.

Key words: galaxies: individual – galaxies: dwarf

1 INTRODUCTION

The last two decades have seen an explosion in the detection of faint dwarf galaxies in the Local Group (e.g. Willman et al. 2005a,b; Belokurov et al. 2006, 2007, 2008; McConnachie et al. 2008; Martin et al. 2009; Bechtol et al. 2015; Koposov et al. 2015; Torrealba et al. 2016, 2018, 2019; Mao et al. 2020; Cerny et al. 2021a,b). Wide-field imaging surveys such as the Sloan Digital Sky Survey (Abazajian et al. 2009), Pan-STARRS (Chambers et al. 2016), the Pan-Andromeda Archaeological Survey (PAndAS, McConnachie et al. 2009), the Dark Energy Survey (DES, Abbott et al. 2018) and the DECam Local Volume Exploration Survey (DELVE, Drlica-Wagner et al. 2021) have uncovered a wealth of substructures orbiting the Milky Way (MW) and Andromeda (M31) galaxies. Despite the discovery of dozens of new dwarf satellites, it is complex to reconcile the numbers of satellites with theoretical predictions (e.g. Tollerud et al. 2008; Koposov et al. 2009; Walsh et al. 2009; Bovill & Ricotti 2011b; Bullock & Boylan-Kolchin 2017; Kim et al. 2018).

At the brighter end (\( L \gtrsim 10^5 L_\odot \)), studies find that predictions and observations are in good agreement (e.g. Sawala et al. 2016; Read & Erkal 2019; Kim et al. 2018; Engler et al. 2021). As such, it is likely that the remaining gap will be resolved as we push to ever-lower luminosities with new surveys, such as the Vera C. Rubin Legacy Survey of Space and Time (Tollerud et al. 2008; Bovill & Ricotti 2011a). The faintest galaxies detected thus far – the ultra-faint dwarfs (UFDs) with \( M_V > -7.7 \) (Bullock & Boylan-Kolchin 2017) – have only been detected nearby or in deep, focused surveys (e.g. Belokurov et al. 2007; Geha et al. 2009; Richardson et al. 2011). However, based on a cold dark matter (LCDM) cosmology, they are expected to populate the full halos of the MW and M31, and the wider field (e.g. Bovill & Ricotti 2011a; Fattahi et al. 2020). In M31, detection of the faintest galaxies has been limited to the central 150 kpc probed by PAndAS, which has discovered dwarf galaxies down to luminosities of \( L \sim 2 \times 10^4 L_\odot \) (\( M_V \sim -6 \), e.g. McConnachie et al. 2009; Richardson et al. 2011; Martin et al. 2013b). Work by Martin et al. (2016) demonstrated that there are likely many more faint dwarfs within this region, lurking just below the detection limit of the survey, and discoveries of brighter dwarfs at much greater distances (\( \gtrsim 200 \) kpc) in shallower surveys (Martin et al. 2013a,c) suggest that there is a wealth of galaxies to be found out to the virial radius of the system.

These faintest dwarfs provide tight constraints on reionisation and stellar feedback physics as their gas reservoirs can more easily escape their low mass potentials. Deep imaging studies with the Hubble Space Telescope have shown that UFDs tend to have their star formation quenched early (e.g. Brown et al. 2014; Sacchi et al. 2021), representing the relics of the very first galaxies (Bovill & Ricotti 2009). They are also extremely dark matter dominated (e.g. Simon & Geha 2007; Martin et al. 2007; Geha et al. 2009; Simon 2019)

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and so their detection and further study may allow us insight into the nature of the dark matter particle.

With the value of finding new dwarfs to address these problems in mind, we have been conducting a visual inspection of imaging data from the DESI Legacy Imaging Survey (Dey et al. 2019) in the vicinity of M31 and Triangulum (M33) to search for ultra-faint companions to both systems. We have already identified a potential UFD satellite of M33 – Pisces VII/Triangulum III (Martínez-Delgado et al. 2022). In this paper, we report on a newly discovered UFD satellite of M31 in the constellation of Pegasus – Pegasus (Peg) V. In § 2 we discuss the DESI Legacy Survey imaging, plus our deep follow-up observations with Gemini/GMOS-N, then in § 3 we present the properties of, and distance to, Peg V. Finally we discuss the significance of our findings in § 4.

2 IDENTIFICATION AND GEMINI OBSERVATIONS

Peg V was identified as a partially resolved over-density in the DESI Legacy Imaging Survey (see left panel of Fig. 1) by amateur astronomer Giuseppe Donatiello. Given its position on-sky, it was a good candidate for an ultra-faint M31 or M33 satellite (projected distance of ~ 240 kpc and 400 kpc from each respectively). We were awarded directors discretionary time (proposal ID GN-2021B-DD-106) to perform deep imaging with Gemini/GMOS-N with the aim of resolving its stellar populations down to its horizontal branch (HB). These observations were carried out on the nights of 2021-11-01 and 2021-11-25 and employed the $g$– and r–band filters. The total imaging time was 2250 s in $g$–band (split into 5 × 450 s exposures) and 1500 s in r–band (split into 5 × 300 s exposures). The images were pre-processed using the Gemini DRAGONS pipeline which performs standard bias, flat field and cosmic ray corrections to the images before producing a final stacked image (which can be seen in the right hand panel of Fig. 1). The stacked images were then reduced using DAOPHOT/ALLFRAME (Stetson 1987, 1994) in largely the same manner as Monelli et al. (2010) and Martínez-Delgado et al. (2022). Briefly, we search for stellar sources on each stacked image and then perform aperture photometry, PSF derivation and PSF photometry with ALLSTAR. The resulting list of stars is then passed to ALLFRAME to construct individual catalogues with better determined position and instrumental magnitude of the input sources and provides the final photometry. We perform the photometric calibration using local standard stars from the Pan-STARRS1 3σ survey (Chambers et al. 2016). The mean magnitudes were calibrated with a linear relation for the $g$–band, and a zero point for the r–band. We extinction correct the data using the reddening maps from Schlegel et al. (1998), re-calibrated by Schlafly & Finkbeiner (2011).

Star-galaxy separation was performed using the sharpness parameter. In the left panel of Fig. 2 we show the distribution of stars across the GMOS field of view, with the right panel showing the galaxy distribution. A clear over-density can be seen in the centre of the stellar map. In in the left panel of Fig. 3 we show a colour-magnitude diagram (CMD) for all stars within 0.8 arcmin of this over-density compared to an equal area annulus beyond 1.6 arcmin in the centre panel. An old (12.5 Gyr), metal-poor ([Fe/H] = −3.2) BaSTI isochrone (Hidalgo et al. 2018)1 is overlaid, shifted to a distance of ~ 700 kpc to highlight what we assume is a red-giant branch (RGB) and horizontal branch (HB) feature.

3 PROPERTIES OF PEGASUS V

We determine the structural parameters for Peg V using the same Markov-Chain Monte Carlo (MCMC) inference technique as presented in Martínez-Delgado et al. (2022). We defer to that work for a detailed discussion, and briefly outline this process below. The method is based on that of Martin et al. (2016) and uses EMCEE (Foreman-Mackey et al. 2013) to sample the posterior. We include all stars which fall within a broad colour-magnitude cut of $r_0 < 25.5$ and $0.5 < (g − r)_0 < 0.9$, giving 79 stars total. We then assume these stars comprise both members of the dwarf galaxy, and a foreground/background population. We assume the radial density profile, $\rho_{\text{dwarf}}$, of the dwarf can be modelled as an exponential profile, with

\begin{align}
\rho_{\text{dwarf}}(r) &= \rho_0 \exp \left( -\frac{r}{\rho_{\text{scale}}(r)} \right) \\
\rho_{\text{scale}}(r) &= \rho_{\text{scale0}} + \rho_{\text{scale1}} r
\end{align}

where $\rho_{\text{scale0}}$ and $\rho_{\text{scale1}}$ are the scale lengths at large and small radii respectively. The scale length is determined as the half-light radius (HLR), which is the point at which the light intensity is half of the central value. We then perform a Bayesian analysis to infer the parameters of the model. The results are shown in Table 1. We find that Peg V is consistent with being a satellite of M31, with a distance to the dwarf of $\rho_{\text{dwarf}}(r) = 25.4 \pm 0.4$ kpc. This is within the projected distance of M31 to Peg V of $\rho_{\text{dwarf}}(r) = 26.8 \pm 0.8$ kpc. We also find that the mass-to-light ratio of Peg V is $M/L_g = 15.3 \pm 0.3$ solar masses, which is consistent with other known satellites of M31.
an ellipticity of $\epsilon = 1 - (b/a)$ and $r_{\text{half}}$ is the half-light radius. $N^*$ is the number of likely member stars inside the CMD selection box associated to the dwarf.

We assume the fore/background contamination, $\Sigma_b$, is constant across the field and determine this by subtracting the dwarf galaxy stars (which we calculate by integrating the radial density profile) from the total number of potential members identified, $n$.

We combine these assumptions into a likelihood function which is then used in the MCMC analysis:

$$p_\text{model}(r) = p_\text{dwarf}(r) + \Sigma_b.$$  \hspace{1cm} (1)

We use broad, flat uniform priors for all parameters. The emcee routine used 100 walkers, over a total of 10,000 iterations with a burn in of 9,250. These numbers were determined based on a visual inspection of the traces. We show the final corner plot in Fig. 4 and summarise the resulting structural parameters and their 68% confidence intervals in Table 1. We find a position for Peg V of $\alpha = 23:18:27.8 \pm 0.1$, $\delta = 33:21:32 \pm 3$, a half-light radius of $r_{\text{half}} = 0.44 \pm 0.1$ arcmin, and do not resolve an ellipticity.

A visual inspection of the CMD for Peg V presents us with a sparse RGB and a well-populated HB feature. Given its projected distance from Andromeda of $D_{\text{proj}} \sim 245$ kpc, the most likely scenario is that Peg V is an M31 satellite. To determine its distance, we use two techniques that focus on the RGB and HB populations. For the RGB, we employ the same Bayesian tip of the red giant branch (TRGB) approach as in Tollerud et al. (2016) and Martínez-Delgado et al. (2022), which we briefly summarise below. We model the RGB and background population simultaneously as a broken power law with slopes of $\alpha$ and $\beta$ in luminosity respectively. We assume a fraction $f$ of stars in the background population (such that the fraction on the RGB is $1 - f$) with the break located at the TRGB, $m_{\text{TRGB}}$.

We use Bayesian inference to determine posterior probabilities for $m_{\text{TRGB}}$, using uniform priors for all parameters, with $U(0, 1)$ for $f$ and $U(0, 2)$ for $\alpha$ and $\beta$. For $m_{\text{TRGB}}$ we use a broad prior of $U(17, 22.5)$. We use the same colour selection as for the structural parameters of $(-0.5 < g - r < 0.9)$, but only include stars with $r_0 < 24$ to isolate the RGB. We use only stars within $2r_{\text{half}}$, as if we include stars beyond this, the model has trouble distinguishing between background and dwarf (given the sparsity of RGB stars). We numerically integrate this luminosity function over a grid of $m$ using the trapezoid rule for each set of parameters, and take the total likelihood as the sum of the logarithm of this over all stars.

We use emcee to sample the posterior distribution for the model parameters and find a solution of $m_{\text{TRGB}} = 21.2^{+1.0}_{-1.2}$, corresponding to a distance of $D = 682^{+391}_{-355}$ kpc. This fit is poorly constrained owing to the small number of sources on the RGB.

A more precise distance can be determined by assuming the stars at $g_0 \sim 24.5$ constitute the HB. In the right-hand panels of Fig. 3 we show the luminosity function in the $g$-band for Peg V. There is a pronounced bump at $g_0 \sim 24.8 \pm 0.1$ which we assume is the HB. With $M_{g,\text{HB}} = 0.6$ (Irwin et al. 2007), we measure a distance of $D = 692^{+331}_{-313}$ kpc, entirely consistent with the RGB approach but with far smaller uncertainties.

In panel 1 of Fig. 3 we show our isochrones shifted to this distance. We see that the HB and RGB features for the 12.5 Gyr isochrone perfectly overlap with the stellar populations of Peg V, suggesting that our candidate is an extremely metal poor M31 satellite.

Armed with a distance, we follow the approach of Martin et al. (2016) and Martínez-Delgado et al. (2022) to measure the luminosity of Peg V. Using theoretical luminosity functions generated the PARSEC stellar models (Marigo et al. 2008; Girardi et al. 2010), we define a probability distribution function (PDF) which describes the expected number of RGB stars per magnitude bin. To generate the PDF, we use an old (12 Gyr), metal-poor ([Fe/H] = $-2.5$), $\alpha$ enhanced ([α/Fe] = +0.4) isochrone and a Kroupa IMF. We then randomly sample from this luminosity function to reproduce our observed dwarf which is simplified as having $N_s$ stars (where $N_s$ is taken from our MCMC analysis for the structural properties) above our magni-
This would place it close to the virial radius of M31 (estimated to be between ~250 – 300 kpc, e.g. Patel et al. 2018; Kafle et al. 2018; Blaña Díaz et al. 2018). It would also be the faintest M31 satellite detected outside of the area covered by the deep PanAS Survey.

The strong blue HB of Peg V makes it somewhat unique when compared with the known satellite population of Andromeda. M31 dwarf satellites typically possess redder HBs (e.g. Da Costa et al. 1996, 2000, 2002) with only a handful showing a significant blue component. Martin et al. (2017) present homogeneous single orbit HST observations for 20 M31 satellite galaxies which well-resolve their HBs. They assess the colour of their HB features by computing the ratio, η, of the number of blue HB stars (n_BHB) to the total number of HB stars (n_BHB + n_RHB). They find only two examples of dwarfs with relatively high fractions of blue HB stars, giving η ~ 0.4 (Andromeda XI and XVII). If we repeat their analysis for Peg V, we find η = 0.5 ± 0.1, setting it apart from the rest of the system. As blue HB stars are typically considered to trace ancient stellar populations, this could imply Peg V was quenched very early compared to the other M31 dwarfs, making it a good candidate for a reionisation fossil (Bovill & Ricotti 2009). It is also more similar to the UFDs of the MW, all of which appear to have been quenched ≥10 Gyr ago (Brown et al. 2014; Weisz et al. 2014; Sacchi et al. 2021) and possess blue HB features.

The RGB stars of Peg V are also extremely blue, and are well described by the most metal-poor BaSTI isochrone (see Fig. 3), suggesting it is a very metal-poor dwarf galaxy. Combined with its blue HB, this may imply it underwent very little chemical enrichment before having its star formation rapidly quenched by reionisation. If true, further study of its chemical properties may allow us to place constraints on the earliest epochs of star formation.

With deep space-based imaging we could further probe the star formation history of Peg V, and learn if it is a candidate for a fossil formation history.

Table 1. The final structural and photometric properties for Peg V.

| Property       | Value                      |
|----------------|----------------------------|
| RA             | 23h 18m 27.8 ± 0.1°       |
| Dec            | 33°21’ 32” ± 3”           |
| r_half (arcmin)| 0.4±0.2                   |
| D (kpc)        | 692±33                    |
| D_M31 (kpc)    | 24±12                     |
| n_half (pc)    | 87±54                     |
| M_V            | -6.3 ± 0.2                |
| m_H0 (mag arcsec^-2) | 26.3 ± 0.3  |
| L (L☉)         | 2.5±0.6 × 10^4           |
| ε              | 0.01 ±0.01                |
| θ (°)          | 96±8                      |
| N^*            | 41±11                     |

4 DISCUSSION & CONCLUSIONS

We have discovered a new Local Group ultra-faint dwarf in the constellation of Pegasus and characterised it using deep Gemini/GMOS-N imaging. Peg V is a far-flung M31 satellite with a strong blue HB, $M_V = -6.3 ± 0.2$, located 242 kpc from the centre of the system.

Figure 3. In the first two panels, we show the CMD for all stars within 2$r_{half}$ of Peg V (left) compared to the stellar populations in an equal area annulus beyond the dwarf to demonstrate the field contamination (right). We overlay a metal poor ([Fe/H] = -3.2) isochrone with age 12.5 Gyr shifted to 692 kpc (centre), representing the distance measured from the HB. Finally, we show the luminosity function in the right most panels. The top shows all stars within 2$r_{half}$ (cyan) and the field population (grey), and the lower panel shows the background corrected case. The dashed grey line shows the position of the blue HB feature.
Figure 4. A corner plot showing the 2D and marginalised posteriors for the structural parameters of Peg V. We show the central coordinates, $x_0$ and $y_0$, the half-light radius, $r_{\text{half}}$, ellipticity, $\epsilon$, position angle, $\theta$ and the number of stars belonging to Peg V, $N_*$. The dashed lines represent the median value and $1\sigma$ uncertainties.

galaxy quenched by reionisation. It also has a few bright RGB stars which can be targeted with 8-10m telescopes to measure their velocities and chemistry. Given its remote position in the halo, kinematics may also allow constraints of its orbit around M31 and the likelihood of previous interactions with its host that may also have quenched its star formation.

The discovery of Peg V in the DESI Legacy Imaging Survey bodes well for future discoveries of ultra-faint dwarfs in M31 and the wider Local Group with current and future surveys. It paints a rosy picture for simultaneously solving both the missing satellite and field galaxy problems in our cosmic backyard. Our systematic visual inspection of the DESI images successfully detects partially resolved ultra-faint dwarf satellites in the M31/M33 system, which might be overlooked in the automatic detection of over-densities in stellar density maps (e.g. DELVE). Thus, both approaches are extremely complementary.

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DATA AVAILABILITY

The DESI Legacy Imaging data are all publicly available at www.legacysurvey.org. The Gemini/GMOS-N images are hosted at archive.gemini.edu/searchform. They are associated with program ID: GN-2021B-DD-106 and made publicly available 6 months after acquisition. Reduced photometry can be obtained from the lead author upon reasonable request.

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