Search for Ultra-faint Milky Way Satellites

by

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To my mother in heaven, Young-Hee Lee...
Disclaimer

I hereby declare that the work in this thesis is that of the candidate alone, except where indicated below or in the text of the thesis. The work was undertaken between March 2014 and April 2017 at the Australian National University (ANU), Canberra. It has not been submitted in whole or in part for any other degree at this or any other university.

This thesis has been submitted as a Thesis by Compilation in accordance with the relevant ANU policies. Each of the six main chapters is therefore a completely self-contained article, which has been published in a peer-reviewed journal. The candidate has written each paper incorporating suggestions and feedback from the co-authors and the referee. I hereby acknowledge the more significant contributions made by some co-authors and others.

Chapter 3: H. Jerjen estimated the mean metallicity, age, and distance modulus of Kim 1 using a maximum likelihood algorithm (Section 3.4.2). H. Baumgardt provided N-body simulations to estimate the initial mass of Kim 1 (Figure 3.7).

Chapter 4: D. Mackey produced the size-luminosity plane diagram (Figure 4.4).

Chapter 5: The Magellan/IMACS images of Pegasus III were taken by A. Chiti during his observing run at LCO. M. Geha obtained the Keck/DEIMOS spectra of stars in Pegasus III, determined their kinematic membership, and measured radial velocities (Section 5.5). G. Da Costa estimated the metallicities of the kinematic member stars using the DEIMOS data (Section 5.6).

Chapter 7: The Gemini/GMOS data were taken in queue mode by Gemini scientific staffs. A. P. Milone performed ePSF photometry over the Gemini/GMOS (Figure 7.2). H. Jerjen estimated the mean metallicity, age, and distance modulus of Kim 2 using a maximum likelihood algorithm (Section 7.4.2).

Chapter 8: H. Jerjen produced the Hammer-Aitoff projection map describing Stromlo Milky Way Satellite Survey footprint (Figure 8.1). H. Jerjen estimated the mean metallicity, age, and distance modulus of Kim 3 using a maximum likelihood algorithm (Section 8.3.2).

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This thesis also made use of Astropy, a community-developed core Python package for Astronomy, and Matplotlib library.
Abstract

The current standard cosmological model is a remarkable achievement in providing an excellent description of the formation of largest-scale structures in the observable universe. However, there have been persistent tensions between observations and the theoretical model on galactic and sub-galactic scales. One of the most pressing issues was the “plane of satellite” problem: the distribution of observed Milky Way satellite galaxies appears to form a thin polar plane, which is largely inconsistent with the prediction of the standard cosmological model, i.e. an isotropic distribution of dark matter sub-halos. This problem was often seen as a consequence of observational biases because many of previously known satellite galaxies were discovered by the Sloan Digital Sky Survey whose survey footprint mainly focused on the northern Galactic pole region. Subsequent surveys to map the southern sky were thus required for an unbiased observational assessment of the standard cosmological model.

This thesis presents the discovery of five new low-luminosity Milky Way companions i.e. dwarf spheroidal galaxies and star clusters from the Sloan Digital Sky Survey, Dark Energy Survey, and the Stromlo Milky Way Satellite survey project: Pegasus III, Horologium II, and Kim 1–3. Pegasus III is an ultra-faint outer halo dwarf satellite in the constellation of Pegasus. The large mass-to-light ratio inferred from photometric and spectroscopic analysis indicates a substantial amount of dark matter component in Pegasus III. Horologium II is one of the ultra-faint dwarf satellites in the vicinity of the Magellanic Clouds discovered in the Dark Energy Survey Year 1 data. Its proximity to a satellite dwarf Horologium I implies their possible companionship. Kim 1 is an extremely low-mass star cluster in the constellation of Pegasus with an unusually high ellipticity and low central surface brightness, which implies that it is being tidally disrupted. Kim 2 is a low-mass outer halo star cluster in the constellation of Indus. Although this stellar system falls in between the realms of star clusters and dwarf galaxies on the size-luminosity plane, evidence of pronounced mass segregation in the object argues in favour of star cluster-like nature. Kim 3 is another extremely low-luminosity star cluster in the constellation of Centaurus. With the lack of well-defined centre and evidence of mass segregation, Kim 3 is also classified as a star cluster in the final stage of tidal disruption.

Both Pegasus III and Horologium II, as well as the majority of new dwarf satellites discovered by other recent studies, turn out tightly aligned with the original plane of satellites defined by previously known objects. This result confirms the presence of the plane of
satellites throughout the whole sky, formerly speculated based on the distribution of classical satellite galaxies decades ago. These findings largely conflict with the prediction of the current standard cosmological model and thus request its reexamination or an alternative model to account for the observation. The discovery of Kim 1–3 implies the possible existence of a large population of such extremely low-mass star clusters. These objects are possibly stripped down versions of formerly more massive star clusters or born extremely low-mass clusters that have survived to the present time. Dedicated observational and theoretical follow-up studies are required to determine their origin, which will shed light on the formation and evolution history of star clusters in general.
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CHAPTER 1

Introduction

The hardest thing of all is to find a black cat in a dark room, especially if there is no cat. — Confucius

How did structure form in the universe? Why is the universe expanding? Over the last few decades, the Λ Cold Dark Matter (CDM) cosmological model has been largely successful in answering these questions, by simulating the formation of large structure and matching observational data, and established as a standard model of cosmology (e.g., Springel et al., 2006). According to the ΛCDM model, small dark matter halos hierarchically merged to form larger structures and grew as protogalaxies. These large dark matter halos were populated by leftover building blocks that had escaped the hierarchical merging process. The host dark matter halos turned into large and bright galaxies like the Milky Way (MW) and Andromeda (M31), containing a huge number of stars made up of shining baryonic matters, while the sub-halos became optically elusive “satellite” dwarf galaxies dominated by dark matter components.

Until a few decades ago, the population of MW satellite galaxies were at eleven including the Small and Large Magellanic Clouds and nine luminous dwarf spheroidal (dSph) galaxies: Ursa Minor, Draco, Leo I & II, Sextans, Carina, Fornax, Sculptor, and Sagittarius. With the advent of wide-field CCD cameras, systematic astronomical surveys like the Sloan Digital Sky Survey (SDSS; York et al., 2000) have revolutionised our view to the Milky Way revealing large numbers of previously unseen low-luminosity stellar systems including satellite dwarf galaxies (e.g. Willman et al., 2005; Zucker et al., 2006; Belokurov et al., 2006; Irwin et al., 2007; Walsh et al., 2007; Kim et al., 2015) and star clusters (Koposov et al., 2007; Belokurov et al., 2010; Balbinot et al., 2013; Kim & Jerjen, 2015a) as well as extended substructures (e.g., Odenkirchen et al., 2003; Grillmair, 2009). The most remarkable objects of these are so-called ‘ultra-faint dwarf (UFD) galaxies’. UFDs share extremely low stellar contents and densities. The most extreme UFDs such as Segue
Figure 1.1 The absolute magnitude vs. half-light radius for Local Group galaxies and the Galactic globular clusters. The filled markers represent objects compiled in Harris (1996, and 2010 edition) and McConnachie (2012). The open markers represent more recently discovered objects discussed in Bechtol et al. (2015), Drlica-Wagner et al. (2015), Laevens et al. (2014, 2015a,b), Martin et al. (2013, 2015), Kim & Jerjen (2015a,b); Kim et al. (2016), and Torrealba et al. (2016).

Belokurov et al., 2007) and Bootes II (Walsh et al., 2008) share comparable luminosities to the faintest globular clusters known but have 10–100 times larger characteristic radii than that of a typical globular cluster (Figure 1.1), which make them nearly transparent over the night sky. Colour-magnitude diagrams indicate that the UFDs are generally dominated by an old ($\gtrsim 12$ Gyr) stellar population (Brown et al., 2014), while radial velocities indicate a substantial dark matter component with inferred mass-to-light ratios up to $\sim 3000 M_\odot/L_\odot$ (Simon & Geha, 2007; Simon et al., 2011). UFDs are comprised of metal-poor stellar populations ([Fe/H] $\lesssim -2.0$ dex) that exhibit large internal dispersions in [Fe/H] of up to 0.7 dex (Kirby et al., 2008), which suggests that their gravitational well is deep enough to retain supernova ejecta to form multiple generation of stars. In this regard, UFDs are the best tracers of early dark matter sub-halos (Willman & Strader, 2012).
The SDSS was instrumental in the systematic search for ultra-faint MW satellite galaxies in the modern era. Although the sky coverage of the survey was limited to only $\sim 30\%$ of the entire sky, the SDSS has revealed 16 new MW satellite dwarf galaxies, the number of which is greater than that of the previously known objects. More recent surveys including the Pan-STARRS 3$\pi$ survey (Chambers et al., 2016) and Dark Energy Survey (DES; The Dark Energy Survey Collaboration, 2005) have upheld the success of their predecessor revealing nearly 20 new MW satellite candidates distributed over the rest of the sky (e.g., Bechtol et al., 2015; Drlica-Wagner et al., 2015; Laevens et al., 2015a; Martin et al., 2015; Kim & Jerjen, 2015b; Torrealba et al., 2016). Subsequent discoveries of such extreme galaxies now question the lower mass limit of galaxy formation.

1.1 Internal Dynamics of Ultra-faint Dwarf Galaxies

Large dynamical mass-to-light ratios ($M/L_V \gtrsim 10^{1-3}[M/L_V]_\odot$) were first observed in classical dSphs including Draco (Aaronson, 1983) and Sculptor (Armandroff & Da Costa, 1986). Assuming an isotropic dispersion of radial velocities and dynamical equilibrium, their large velocity dispersions imply mass-to-light ratio significantly greater than expected from baryonic components (stellar evolution) alone and thus the presence of a substantial amount of non-baryonic dark matter (Figure 1.2). Until the SDSS discovered a number of UFDs, all Local Group dSphs with luminosity of $M_V \lesssim -8$ appeared to have a constant dark matter halo mass of $\sim 3 \times 10^7 M_\odot$ within their optical radii, independent of luminosity (Mateo et al., 1993; Gilmore et al., 2007). Subsequent discoveries of UFDs with luminosity of $M_V \gtrsim -8$, however, suggest that the total halo mass declines down to $\sim 10^6 M_\odot$ as total luminosity decreases (Simon & Geha, 2007; Simon et al., 2011; Kirby et al., 2013a). The hypothesis of a common halo mass scale was raised again by Strigari et al. (2008), arguing that all MW satellite galaxies have $\sim 10^7 M_\odot$ within the central 300 pc, an average radius for all MW satellites known at the time (Figure 1.3). However, this argument requires observational evidence that the dark matter halos of the smallest galaxies ($r_h \sim 30$ pc) do significantly extend beyond their optical radii to $\sim 300$ pc (Walker et al., 2009). In contrast to the observed common mass scale, high-resolution $\Lambda$CDM simulations predict a weak trend of increasing halo mass within 300 pc with luminosity (Font et al., 2011), which is not obvious in the data of Strigari et al. (2008). Possible reasons for this disagreement are small observational sample size, large uncertainties in kinematic measurements, and/or influence of baryon physics. The existence of a minimum halo mass required for galaxy formation thus remains uncertain.

The interpretation of the large velocity dispersions measured in some extreme UFDs has been controversial until recently. For instance, Segue 1 has been claimed to be a disrupted
Figure 1.2 Left panel: dynamical mass estimates within the half-light radius as a function of absolute magnitude of Local Group galaxies. Right panel: the same as the left panel but for dynamical mass-to-light ratio. Figures taken from McConnachie (2012).

Figure 1.3 Dynamical mass within 300 pc as a function of stellar luminosity for Local Group galaxies. Red open circles represent UFDs discovered in SDSS. Blue open squares represent classical dSphs. Figure from Strigari et al. (2008).
star cluster of which the kinematic measurements have been polluted by unresolved binaries or the Sagittarius stream (Niederste-Ostholt et al., 2009). Simon et al. (2011) argue, however, that the velocity dispersion corrected for the influence of binaries in their 71 spectroscopic member sample is still as high as \(3.7^{+1.4}_{-1.1}\) km s\(^{-1}\), implying a mass-to-light ratio of \(M/L \approx 3400\ M_{\odot}/L_{\odot}\). Their analysis also suggests that the fraction of contaminants from the Sagittarius stream in their sample is unlikely to be more than a few percent, which is not enough to explain the large velocity dispersion. The possibility of a population of low luminosity star clusters mimicking UFDs has also arisen. Contenta et al. (2017) argue that if star clusters formed in low-density environments like luminous dSphs and retained stellar mass black holes, their physical size could expand up to \(\sim 20\) pc and exhibit velocity dispersion as large as observed from Segue 1. This argument, however, assumes that the clusters could retain 100 per cent of stellar mass black holes initially (i.e. no black hole natal kick). Further discoveries of gravitational waves would provide more constraints on the black hole natal kick and enable more realistic simulations to test this idea (Abbott et al., 2016).

1.2 Chemical Properties of Ultra-faint Dwarf Galaxies

The chemical abundances of stars in satellite galaxies also provide a window on galaxy formation and evolution. Early spectroscopic studies of classical dSphs pointed out that metal-poor stars often found in the MW halo were rarely observed in the bright satellite systems, challenging the hierarchical formation scenarios for Milky Way in the ΛCDM paradigm: the MW halo was made of the destruction of a number of dwarf satellite galaxies (Helmi et al., 2006). Newly discovered UFDs have been filling the gap between chemical abundances of stars in the most luminous satellite galaxies and the MW halo. Kirby et al. (2008) first discovered stars with [Fe/H] < −3.0 outside the MW halo in UFDs discovered with SDSS. Norris et al. (2008) and Frebel et al. (2010) also reported the discoveries of stars with such extremely low metallicity in Bootes I, Ursa-Major II, and Coma Berenices. UFDs are now considered as excellent candidate sites to look for evidence of rare ‘rapid neutron capture process (r-process)’ enrichment in low-metallicity stars (Ji et al., 2016).

The metallicity measurements of stars in UFDs extend the luminosity-metallicity and luminosity-metallicity spread relations earlier established by more luminous Local Group dwarf galaxies: more massive systems exhibit higher mean metallicities and smaller dispersions (Figure 1.4 and 1.5). The consistency between classical dSphs and UFDs in those relations supports the idea that UFDs are indeed dSphs with extreme properties rather than simply extended versions of globular clusters. These phenomena can be explained by the retention of metals and gas in the gravitational wells of the satellite systems (e.g.,
Figure 1.4 Mean stellar metallicity based on Keck/DEIMOS measurements as a function of stellar luminosity of Local Group galaxies. Black diamonds, blue triangles, and red squares represent the measurements of MW dSphs, M31 dSphs, and other Local Group dwarf irregular galaxies, respectively. The dashed line and the dotted lines indicate the least-squares fit and the rms determine by the data points, excluding M31 satellites andSegue 2. Figure taken from Kirby et al. (2013b).

Dekel & Silk, 1986). A stellar system with a deeper gravitational potential well could have better resisted the expulsion of metals and gas by supernovae or stellar winds and maintained star formation over multiple generations. An increase in metallicity spread at low luminosity would reflect inhomogeneous stochastic enrichment in low mass and low metallicity environment (Norris et al., 2010). In this context, however, understanding the observed relations between luminosity and metallicity would be less intuitive if dSphs do share a common halo mass scale.

1.3 Tensions between $\Lambda$CDM Simulations and Observations

Despite the numerous discoveries of new MW satellite galaxies, there have been persistent tensions between the $\Lambda$CDM model and observations on galactic and sub-galactic scales over the past few decades as follows: (i) the “missing satellites” problem: significantly smaller number of MW satellite dwarf galaxies have been observed than predicted by dark-matter-only cosmological simulations (Klypin et al., 1999; Moore et al., 1999; Diemand et al., 2007; Springel et al., 2008), (ii) the “too big to fail” problem: the simulations predict too many massive dense sub-halos compared to the most luminous MW satellites (Boylan-Kolchin et al., 2011), and (iii) the “core-cusp” problem: the inner DM density profiles of
the satellite dwarf galaxies have favoured a constant density core over a cuspy profile as the \( \Lambda \)CDM model predicts (Navarro et al., 1996).

As a way of alleviating the missing satellite problem, theories have adopted an idea that reionization could have resulted in the suppression of star formation in the smallest sub-halos (e.g., Bullock et al., 2000). If only massive sub-halos form stars and turn into galaxies, this can decrease the predicted number of satellites significantly, from thousands to tens, but even then the other two problems (ii) and (iii) still remain unsolved. Instead, recent theoretical studies have suggested that baryonic physics (i.e., stellar feedback and tidal shocking/stripping from the stellar disk of the host galaxy) can drive strong gas inflows/outflows and reduce the dark matter mass in the central regions of dwarf galaxies. Simulations including both dark matter and baryons have made notable progress in reconciling the problems (i) - (ii) (e.g., Wetzel et al., 2016) and (iii) (e.g., Chan et al., 2015)
with observed satellite galaxies more luminous than $M_V \approx -8$ and yet do not provide a robust prediction on the population of fainter satellite galaxies.

There is another critical issue largely independent of baryon physics, namely the “plane of satellites” problem: the majority of satellite dwarf galaxies around the Milky Way (Lynden-Bell, 1976; Kroupa et al., 2005; Pawlowski et al., 2015a) and Andromeda (Ibata et al., 2013; Conn et al., 2013) are distributed in a vast thin plane structure (Figure 1.6 and 1.7), whereas ΛCDM cosmological simulations predict sub-halos to be isotropically distributed.

In addition, the proper motion measurements of classical MW satellites and the radial velocity measurements of M31 satellites suggest that the majority of satellites within each plane share coherent rotational motions (Pawlowski & Kroupa, 2013; Ibata et al., 2013). Such highly flattened, co-orbiting planes of sub-halos are extremely rare in ΛCDM simulations (e.g., Ibata et al., 2014; Pawlowski et al., 2014). The distribution of satellites reflects the infall pattern of primordial sub-halos, which mainly depends on the large-scale mass.
distribution of their host galaxy, rather than baryons (Pawlowski et al., 2015b). As such, accounting for baryonic physics alone is not able to reconcile the discrepancy.

The origin of the planar distribution has been a matter of debate since Kroupa et al. (2005) first argued that the alignment of 11 classical MW dSphs is in conflict with the predicted distribution on the ΛCDM framework. This plane structure has become one of the most critical issues in ΛCDM model as the majority of newly discovered MW UFDs have also turned out consistent with the trace of the previously known planar structure. One of possible scenarios is that the satellite dwarf galaxies on the planes are tidal dwarf galaxies that formed from the tidal debris of a formerly much larger progenitor object at high redshift (e.g., Pawlowski et al., 2012; Zhao et al., 2013; Yang et al., 2014). It remains to be tested if model tidal dwarf galaxies could reproduce the observed properties of MW and M31 satellite galaxies including stellar proper motion, luminosity-metallicity, and luminosity-metallicity dispersion relations.

Yet, there is no unifying solution that addresses the missing satellite problem, the too big to fail problem, the core-cusp problem, and the plane of satellites problem simultaneously.

### 1.4 Photometric Surveys for Milky Way Satellites

From the observational perspective, the efforts towards solving the small scale problems in ΛCDM paradigm have been realised as large-scale systematic photometric surveys.
Finding ultra-faint MW satellites in such large data sets requires a sophisticated search algorithm because they are so faint and resolved into individual stars that often a whole stellar system is completely buried in foreground MW halo stars and impossible to identify by eye. Currently used algorithms are designed to detect overdensities of stars with the signature of an underlying old (> 10 Gyr) and metal-poor stellar population ([Fe/H] > −2.0 dex), which reflects the typical properties of ultra-faint dwarf satellites, over a range of heliocentric distances within the virial radius of Milky Way (e.g., Walsh et al., 2009). Deep imaging and/or spectroscopic follow-up observations are often crucial to confirm the true identity and nature of the detected overdensities unless their statistical significance is sufficiently large in the shallow survey data.

Even the recent surveys such as the SDSS have reached only a small fraction of the volume of the MW halo due to their limited photometric depth and the incompleteness of the search algorithms (Figure 1.8). The next generation survey such as the Large Synoptic Survey Telescope (LSST) survey will cover the entire southern sky and significantly improve the detection limit at the virial radius of the Milky Way down to $M_V \sim -1$ with deeper photometric depth thanks to the large collecting area of the telescope. The LSST survey is, however, expected to begin in 2022 and take around 10 years to complete. Before then, the search for MW satellites must be continued using currently available observational resources and a wide range of different detection algorithms, in order to verify forthcoming high-resolution cosmological simulations.

1.5 Aim of This Study

Until 2015, the majority of ultra-faint Milky Way satellites were discovered in the SDSS footprint that initially focused on a region close to the north Galactic north pole. It was thus reasonable to argue that the uneven sky coverage possibly biased the satellites to delineate such a planar distribution (although see Pawlowski, 2016). In addition, most of the southern Galactic sky remained unexplored in terms of searching for ultra-faint MW satellites.

This PhD thesis study aims to develop a highly sensitive, sophisticated detection algorithm and search for UFDs overlooked in previous surveys and new objects in recent surveys covering formerly unexplored regions. This research is part of a long-term endeavour to investigate if the predictions of the standard cosmological model are consistent with observations. To determine whether the new stellar systems are indeed dwarf galaxies or simply extended star clusters, deep imaging and spectroscopic follow-up studies are essential.
Figure 1.8 Maximum radius ($R_{\text{comp}}$) in kpc for detection of satellite galaxies as a function of absolute magnitude for SDSS, SkyMapper, DES, single exposures of LSST, and co-added full LSST lifetime exposures. The red filled circles represent UFDs discovered in SDSS and Local Group galaxies discovered pre-SDSS. Figure taken from Tollerud et al. (2008).

If this study reveal a large number of new satellite galaxies outside the plane of satellites, it may imply a big step forward in alleviating one of the small scale problems in cosmology and add more strength to the current ΛCDM paradigm. On the other hand, if the new satellite galaxies discovered in the extended surveys also turn out consistent with the plane of satellites, this study may contribute to the confirmation of the plane of satellite and call for revisiting the standard cosmological model.

Apart from the plane of satellites problem, new MW satellite galaxies provide laboratories for testing the different relationships that were originally defined by the classical dSphs. New objects will also allow us to better understand the differences between DM dominated UFDs and pure baryonic stellar systems.

1.6 Outline of the Papers to be Presented

This thesis consists of a series of six papers already published in peer-review journals that describe the discovery and analysis of new ultra-faint Milky Way companions in the SDSS,
Chapter 1 Introduction

DES and the Stromlo Milky Way Satellite (SMS) survey (PI: Helmut Jerjen). Each paper is presented as a chapter of this thesis.

Chapter 2 describes the new detection algorithm developed for this thesis in detail. Chapter 3 presents the first result of the re-analysis of the SDSS photometric catalogue, the discovery of the dissolving star cluster Kim 1. The SDSS footprint covers $\sim 14,000$ deg$^2$ of sky around the northern Galactic pole. This object remained undetected for seven years, since the SDSS star catalog covering this region of sky was publicly released in 2008. Chapters 4 and 5 present the discovery of another MW companion in the SDSS, an ultra-faint dwarf galaxy Pegasus III, and its photometric/spectroscopic properties. This object is one of the most distant MW satellite galaxies discovered in the SDSS footprint. Both objects appear extremely faint and highly elliptical, which implies that the new algorithm provides extra sensitivity for such objects.

Chapter 6 presents Horologium II, a new dwarf satellite in the constellation of Horologium discovered in the DES Year 1 data. The DES Year 1 footprint covers $\sim 2000$ deg$^2$ in the vicinity of the Magellanic Clouds. This object has been overlooked by previous searches using the same data set (Koposov et al., 2015; Bechtol et al., 2015). Horologium II is found only $\sim 7$ degrees away on the sky from an earlier discovered UFD Horologium I. The fact that Horologium II also appears highly elliptical again confirms the sensitivity of the new algorithm for such objects.

Chapters 7 and 8 present Kim 2 and Kim 3, two faint star clusters discovered as part of the SMS survey using the Dark Energy Camera at the CTIO 4-m Blanco telescope. The SMS survey is a imaging survey project that aims to search UFDs in the southern sky, complementing the coverage of other southern sky surveys like DES. The SMS survey footprint as of 2016 covers $\sim 1000$ deg$^2$ around the Small Magellanic Cloud and the constellation of Centaurus. Both Kim 2 and Kim 3 exhibit evidence of pronounced mass segregation, which indicates that they are star clusters as mass segregation is not expected in collisionless stellar systems like dwarf galaxies.

Chapter 9 briefly summarises the main conclusions of this PhD research and suggests future work on the satellites of the Milky Way and other MW-like galaxies in the Local Volume.

1.7 Presentation and Style

Chapters 3 to 8 of this thesis have been published in the American “Astrophysical Journal”. Hence, American spelling has been used to match the requirements of the Astrophysical
Journal. In accordance with the format of the journal, each chapter contains an Abstract, Introduction, Conclusion and Bibliography. For this reason, some duplication of introductory material is unavoidable.
Frebel, A., Kirby, E. N., & Simon, J. D. 2010, Nature, 464, 72
McConnachie, A. W. 2012, AJ, 144, 4
CHAPTER 2

SEARCH ALGORITHM

This chapter is dedicated to explain how our search algorithm identifies stellar overdensities in survey data. We note that this algorithm was built upon the method of Walsh et al. (2009) and also introduced in Kim (2013).

2.1 Principles of the Search Algorithm

The very first step of the algorithm is photometric filtering process in colour-magnitude space using an isochrone mask consistent with old and metal poor stellar populations (see the upper panels of Figure 2.1). This process effectively reduces field contamination and enhances contrast between the residual field stars and the clustering of satellite member stars in RA-Dec space (Walsh et al., 2009). The width of an isochrone mask reflects the ranges of metallicity and age observed from previously known satellites (e.g., Simon & Geha, 2007; Brown et al., 2014) as well as the photometric uncertainties of given survey data. Shifting an isochrone mask over a range of distance moduli, one can sample stars that possibly include satellite member stars at specific heliocentric distances.

Once the positions of selected stars from the filtering process are restored in RA-Dec space, the algorithm characterises candidate satellites as follows. First, a two-dimensional (2D) spatial density map is constructed with a pixel scale $k$ determined by:

$$k = \frac{1}{4\sqrt{\rho}} \tag{2.1}$$

where $\rho$ is the local spatial density of a selected sky area within a $1^\circ \times 1^\circ$ window, i.e. the number of stars per square degree. Assuming that the stars are in random distribution, this scale length corresponds to the half of the inradius of a square area each star occupies on
Chapter 2 SEARCH ALGORITHM

Figure 2.1 Detection of the Bootes II dwarf satellite in the SDSS star catalog with our search algorithm. Upper left panel: colour-magnitude diagram showing all stars in the vicinity of Bootes II. Upper right panel: the same as the top left panel but only for stars selected by an isochrone mask consistent with old (13.5 Gyr) and metal-poor ([Fe/H] = −2.3) stellar populations at the distance modulus of \((m - M) = 18.1\). Lower left panel: the 2D density map of the selected stars smoothed by a Gaussian kernel with FWHM of 2.634 times a pixel scale. The colour of pixels represents the levels of smoothed spatial densities \((s)\). Lower right panel: the positions of the selected stars and pixels 2.5\(\sigma_s\) above the background level \(\bar{s}\), highlighted in yellow. Images taken from Kim (2013).

average. This adaptive pixel scale allows us to characterise in a consistent manner stellar overdensities over different levels of spatial densities. The density map is then smoothed by a Gaussian kernel with full width at half maximum (FWHM) of 2.355 times a pixel scale (i.e. \(\sigma\) for the Gaussian = 1 pixel), or greater for identifying largely extended satellites, at a given spatial density. Background level is determined as the mean of kernel-smoothed spatial densities after 3-sigma clipping with 5 iterations. A stellar overdensity is defined on the density map as a group of adjacent pixels 2.5 times the standard deviation of the smoothed spatial densities above the background level. The signal-to-noise ratio (SNR) of the overdensity is then calculated as follows:
Figure 2.2 The mean (filled circles) and 3-sigma range (error bars) of SNRs of Poisson noise-generated artificial stellar overdensities as a function of spatial densities. Each spatial density map was binned with a pixel scale determined by Equation 2.1 and smoothed by a Gaussian kernel with $\sigma = 1$ pixel, i.e., FWHM of 2.355 times a pixel scale. Image taken from Kim (2013).

\[
\text{SNR} = \frac{\sum_{i=1}^{n} (s_i - \bar{s})}{\sqrt{\sum_{i=1}^{n} (s_i - \bar{s})^2 + n \cdot \sigma_s}}
\]  

(2.2)

where $s_i$ is kernel-smoothed spatial density at the $i^{\text{th}}$ pixel of the overdensity that consists of $n$ pixels, $\bar{s}$ and $\sigma_s$ are the mean and standard deviation of the signals, respectively.

Finally, statistical significance is determined by how unlikely an observed overdensity is to be generated by Poisson noise. This can be measured by means of either randomly distributed artificial stars in the same spatial density or real stars in a control field sufficiently away from the satellite candidate of interest. Figure 2.2 illustrates the mean and 3-sigma range of SNRs of artificial stellar overdensities that Poisson noise can generate as a function of the number of stars per area. As the ranges of the SNRs of Poisson noise-generated overdensities are constrained by local spatial density, one can compare the SNRs of observed overdensities to the ranges of those of Poisson noise-generated overdensities at the same background spatial density level and identify significant satellite candidates.

Figure 2.1 visually summaries the identification process of our algorithm with Bootes
II dwarf satellite in the Sloan Digital Sky Survey (SDSS)\textsuperscript{1} data as an example. We adopt this “model-independent” search algorithm in order to look for even satellites that exhibit extremely irregular or extended morphologies, which are not fully characterised by current dwarf galaxy models with survey data alone, due to tidal disruption of satellites or the incompleteness of the observational data. As demonstrated in Figure 2.1, our algorithm clearly identifies Bootes II, one of statistically least significant objects in previous searches (e.g., Koposov et al., 2008; Walsh et al., 2009), despite its extremely irregular appearance.

### 2.2 Testing with the Sloan Digital Sky Survey

We ran our search algorithm over the SDSS star catalog to test its performance. In this testing, we recovered all the previously known Milky Way satellites and found a few additional satellite candidates: two at 7 sigma level, one at 6 sigma level, and one at 5 sigma level. Although our algorithm misidentified some artifacts as stellar overdensities such as diffraction patterns around bright sources or extended background galaxies, they were easily noticed and excluded by visual inspection. We note that such misidentifications are not attributed to the algorithm itself but to the difficulty of the SDSS photometry in the classification of point sources.

In our follow-up observations, the two candidates at 7 sigma level turned out to be real stellar systems, namely Kim 1 and Pegasus III, while the one at 6 sigma level turned out to be a false positive. We note that we could not follow up the last candidate at 5 sigma level within the time frame of this PhD research. Given that the candidate at 6 $\sigma$ turned out not a real object, however, the expectation for the last candidate is low. The main reason for the detection of such false positives is that our algorithm assumes locally pure Poisson distribution of foreground stars in both colour-magnitude and RA-Dec spaces. However, this assumption is not always the case, especially in the vicinity of the Galactic plane or large substructures such as the Sagittarius stream or Magellanic Clouds. Instrumental/observational defects also cause an unnatural nonuniform distribution of stars. In such cases, comparing the SNRs of observed overdensities to those of Poisson noise-generated ones would result in the overestimation of their statistical significance. For the this reason, we do not address overdensities at low significance level ($< 6\sigma$) for detailed analysis in this work.

\textsuperscript{1}http://www.sdss3.org/


CHAPTER 3

DISCOVERY OF A DISSOLVING STAR CLUSTER IN PEGASUS


Abstract

We report the discovery of an ultra-faint stellar system in the constellation of Pegasus. This concentration of stars was detected by applying our overdensity detection algorithm to the SDSS-DR10 and confirmed with deeper photometry from the Dark Energy Camera at the 4-m Blanco telescope. The best-fitting model isochrone indicates that this stellar system, Kim 1, features an old (12 Gyr) and metal-poor ([Fe/H] ~ −1.7) stellar population at a heliocentric distance of 19.8 ± 0.9 kpc. We measure a half-light radius of 6.9 ± 0.6 pc using a Plummer profile. The small physical size and the extremely low luminosity are comparable to the faintest known star clusters Segue 3, Koposov 1 & 2, and Muñoz 1. However, Kim 1 exhibits a lower star concentration and is lacking a well defined center. It also has an unusually high ellipticity and irregular outer isophotes, which suggests that we are seeing an intermediate mass star cluster being stripped by the Galactic tidal field. An extended search for evidence of an associated stellar stream within the 3 sqr deg DECam field remains inconclusive. The finding of Kim 1 is consistent with current overdensity detection limits and supports the hypothesis that there are still a substantial number of extreme low luminosity star clusters undetected in the wider Milky Way halo.
3.1 Introduction

Modern imaging surveys like the Sloan Digital Sky Survey (York et al., 2000; Ahn et al., 2014) have significantly contributed to the discoveries of new stellar objects in the Milky Way halo including satellite galaxies (e.g. Willman et al., 2005; Belokurov et al., 2006; Irwin et al., 2007; Walsh et al., 2007) and star clusters (Koposov et al., 2007; Belokurov et al., 2010; Muñoz et al., 2012; Balbinot et al., 2013; Belokurov et al., 2014; Laevens et al., 2014). The new satellite galaxies are characterised by low luminosities ($-8 \lesssim M_V \lesssim -1.5$) (Martin et al., 2008) and low metallicities down to $[\text{Fe/H}] < -3$ (Kirby et al., 2008; Norris et al., 2010; Simon et al., 2011; Koch & Rich, 2014). The emergence of this new class of dwarf galaxies now questions previous ideas about the low mass limit of galaxy formation. The other new MW halo objects are star clusters with extremely low luminosities ($-2.5 \lesssim M_V \lesssim 0$) and small half-light radii ($< 10$ pc). Globular clusters of such extreme nature are thought to be suffering stellar mass loss via dynamical processes such as tidal disruption or evaporation (Gnedin & Ostriker, 1997; Rosenberg et al., 1998; Koposov et al., 2007), and there is growing evidence based on observations to support this hypothesis (Carraro et al., 2007; Carraro, 2009; Niederste-Ostholt et al., 2010; Fadely et al., 2011). The discoveries of new ultra-faint star clusters in the Galactic halo will provide valuable resources for studies of their evolutionary phases as well as the formation history of the Galactic halo.

In this chapter we present the discovery of a new ultra-faint stellar system named Kim 1, in the constellation of Pegasus found in SDSS Data Release 10 and confirmed with deep DECam imaging (Sections 2 & 3). Its total luminosity is measured to be $\sim 0.3$ magnitudes fainter than that of Segue 3 ($M_V = 0.0 \pm 0.8$) known to be probably the faintest star cluster to date (Fadely et al., 2011). Kim 1 lies at a heliocentric distance of approximately 20 kpc, is highly elongated ($\epsilon = 0.42$) and has a half-light radius of $\sim 7$ pc (Section 4). In Section 5 we discuss the possible origin of the stellar overdensity and draw our conclusions.

3.2 Discovery

The SDSS imaging data are produced in the $ugriz$ photometric bands to a depth of $r \sim 22.5$ magnitudes (York et al., 2000). Data Release 10 (DR10) includes all the previous data releases, covering 14,555 deg$^2$ around the north Galactic pole (Ahn et al., 2014), and is publicly available on the SDSS-III Web site$^1$.

$^1$http://www.sdss3.org/dr10/
Chapter 3 DISCOVERY OF A DISSOLVING STAR CLUSTER IN PEGASUS

We use an overdensity detection algorithm built upon the method of Walsh et al. (2009) to analyse the SDSS-DR10 point source catalogue. The algorithm has been designed to detect stars consistent with an old and metal-poor population, which reflects the typical characteristics of Milky Way satellite galaxies (see e.g. Kirby et al., 2013). At given heliocentric distance intervals we apply a photometric filter in color-magnitude space employing isochrone masks based on the Dartmouth models (Dotter et al., 2008) and the SDSS photometric uncertainties. We then bin the RA, Dec positions of the selected stars into a 1.0° × 1.0° array with a pixel size between 18 − 25 arcsec. This array is then convolved with a Gaussian kernel with a FWHM between 42 − 59 arcsec. We empirically measure the statistical significance of potential overdensities by comparing their signal-to-noise ratios (SNRs) on the array to those of random clustering in the residual Galactic foreground. This process is repeated by shifting the isochrone masks over a range of distance moduli \((m - M)\) from 16 to 22 magnitudes, corresponding to the heliocentric distance interval \(16 < D < 250\) kpc, where the upper limit is the virial radius of the Milky Way.

The detection algorithm successfully recovered all of the recently reported MW galaxy companions in the SDSS footprint as well as other resolved stellar overdensities such as Balbinot 1 (Balbinot et al., 2013). Our measured statistical clustering significances of the MW satellites, including Leo V and Bootes II that were reported as marginal detections by Walsh et al. (2009) and Koposov et al. (2008), were all at least 6.0σ above the Poisson noise of Galactic stars while the significance of a newly found stellar overdensity reached \(\sim 6.8\sigma\) at its maximum. This object that we chose to call Kim 1 was found at the location \(22^h11^m41.28^s, +07^d01^m31.8^s\) (J2000). It is also worth to mention that we detected a few more stellar concentrations over the entire SDSS-DR10 footprint with comparable significance but at larger distance moduli \((m - M) > 20\). They will require deeper follow-up imaging observations to reach the main sequence turn-off in the color-magnitude diagram to confirm their identities.

3.3 Follow-up Observations and Data Reduction

To investigate the nature of Kim 1, we conducted deep follow-up observations using the Dark Energy Camera (DECam) at the 4-m Blanco Telescope at Cerro Tololo Inter-American Observatory (CTIO) on 17th July 2014. DECam has an array of sixty-two 2k × 4k CCD detectors with a 2.2 degrees field of view and a pixel scale of 0.′27 (unbinned). We obtained a series of 8×210s dithered exposures in \(g\) and 5×210s in \(r\) band under photometric conditions. The mean seeing was 1′0 in both filters. The fully reduced and stacked images were produced by the DECam community pipeline (Valdes et al., 2014). We used WeightWatcher (Marmo & Bertin, 2008) for weight-map combination and SExtractor (Bertin & Arnouts, 1996) for source detection and photometry. Sources
Figure 3.1 Artificial star tests: detection completeness as function of magnitude in the $g$-band (upper panel) and $r$-band (lower panel). Overplotted are the best-fitting analytic interpolation functions. The 90% completeness levels (dashed line) correspond to $g = 23.15$ and $r = 22.80$ respectively.

were morphologically classified as stellar or non-stellar objects. We cross-matched the extracted point sources with SDSS stars in our field-of-view using the STILTS software (Taylor, 2005) with a 1′′ positional tolerance. The photometric calibration was restricted to stars in the magnitude range $19.25 < r_0 < 21.25$ mag to stay below the saturation limit of our DECam images and above the $5\sigma$ limit of the SDSS photometry. Finally, all magnitudes of the calibrated sources were extinction-corrected with the Schlegel et al. (1998) extinction maps.

We performed artificial star tests to determine the photometric completeness as a function of magnitude. We use the `starmist` function in the IRAF package `artdata` to generate 1000 randomly distributed artificial stars for each $g$ and $r$ band in the range of $19 < g, r < 24,$
and then employ the `mkobjects` function to inject them into the DECam images. We then extract the stars from the images using the same pipeline as we used on the original science images, and cross-match all the point sources with the list of input artificial stars using STILTS to measure the recovery rate as a function of magnitude. Figure 3.1 shows the completeness levels for both photometric bands. The error bars for each bin are derived from the binomial distribution as in Bolte (1989). Overplotted are the best-fitting interpolation functions described in Fleming et al. (1995). We determine the 90% completeness levels of our photometry at $g = 23.15$ and $r = 22.80$, respectively.

Figure 3.2 shows the stellar overdensity in the running window after applying the photometric filter with a Dartmouth isochrone of 12 Gyr and $[\text{Fe/H}] = -1.7$ (Dotter et al., 2008). The top left panel shows the sky positions of DECam stars fainter than the saturation limit ($r_0 \approx 19$ mag) and brighter than the 90% completeness level ($r_0 = 22.80$), passing the isochrone filtering process at the distance modulus $(m - M) = 16.5$ magnitudes. The top right panel shows the spatial density plot with a pixel size $23\text{.}\text{4}$ and convolved with a Gaussian kernel with a FWHM of $55\text{.}\text{1}$, where the colours of the pixels represent the output signals ($s$) of the convolution. The pixels above the foreground density with values $\tilde{s} + 2.5\sigma_s \approx 0.3$ are marked in yellow in the bottom left panel. These contiguous pixels are concentrated on the central region and there is no other comparable overdensity, in terms of both integrated signal and area, in the vicinity of Kim 1 at the same distance. The bottom right panel shows the corresponding contour plot, where the contours represent the different levels of normalised star density in units of standard deviation of the output signals above the Galactic foreground.

### 3.4 Candidate Properties

#### 3.4.1 Color-Magnitude Diagram

The upper left panel of Figure 3.3 shows the distribution of all objects classified as stars by the SDSS pipeline in the vicinity of Kim 1. For comparison we show the SDSS data for Segue 3 (Belokurov et al., 2010; Fadely et al., 2011) in the second row. Kim 1 has a lower star density and appears less prominent, until the photometric cut has been applied. The panels in the middle column of Figure 3.3 show the extinction-corrected CMDs of the two overdensities, and the panels in the right column that of the foreground stars around them. The CMDs of the foreground stars have been established following the same procedure as in Belokurov et al. (2006, 2007) from the area between two concentric rings covering the same area as Kim 1 and Segue 3 respectively. Kim 1 has an equally well defined main sequence (MS) as Segue 3 down to $r_0 = 22$ mag. There are also five stars
Chapter 3 DISCOVERY OF A DISSOLVING STAR CLUSTER IN PEGASUS

Figure 3.2 Upper left panel: Spatial positions of DECam stars, in the magnitude range from the saturation level to the 90% completeness level for each $g$ and $r$ band, passing the photometric selection criteria. Upper right panel: Binned spatial density with a pixel size of 23.4 and convolved with a Gaussian kernel with FWHM of 55.1. The color of the pixels represent the output signals ($s$) of the convolution. Lower left panel: Selected bins of which the output signals are above the foreground density $\tilde{s} + 2.5\sigma_s \approx 0.3$. Lower right panel: Contour plot of the convolved density map. The contours show the levels of the output signals in units of $\sigma_s$ above the Galactic foreground.
Chapter 3 DISCOVERY OF A DISSOLVING STAR CLUSTER IN PEGASUS

Figure 3.3 SDSS view of Kim 1 (top) and Segue 3 (middle), and DECam view of Kim 1 (bottom). Left panels: Distribution of all objects classified as stars in a $9'\times9'$ field centred on the star cluster. The circles mark a radius of 2', 5' and 5' for Kim 1, and 0', 2' and 2' for Segue 3. Middle panels: CMD of all stars within the inner-most circle marked on the left panel, dominated by the members of the star cluster. Right panels: Comparison CMD of all stars between the middle and the outer circles, showing the foreground stars. The dotted lines in the bottom row mark the 90% completeness level of our photometry. The Dartmouth (solid) and PARSEC (dashed) isochrones of age 12 Gyr and $[\text{Fe/H}]=-1.7$ are overplotted at a distance of 19.8 kpc for Kim 1, and the same isochrones at 17 kpc for Segue 3 (Fadely et al., 2011).
Figure 3.4 Smoothed maximum likelihood density map in age-metallicity space for all stars within a radius of 2′0 around Kim 1, combined with SDSS \((r < 19)\) and DECam \((r > 19)\) coverage. Contour lines show the 68%, 95%, and 99% confidence levels. The diagonal flow of the contour lines reflect the age-metallicity degeneracy inherent to such an isochrone fitting procedure. The 1D marginalized parameters around the best fit are:

\[
\text{age} = 12.0^{+1.5}_{-3.0} \text{Gyr}, \ [\text{Fe/H}] = -1.7^{+0.8}_{-0.2} \text{dex}, \ m - M = 16.48 \pm 0.10.
\]

with \(r_0\) magnitudes brighter than 18 mag and colours consistent with RGB and red clump stars. Finally, the panels in the bottom row of Figure 3.3 show the results for Kim 1 based on our DECam photometry reaching \(\sim 2\) mag fainter than SDSS with S/N values for point sources of 35 and 20, in \(g\) and \(r\) respectively, at \(23^{rd}\) AB mag. The DECam data reveals a tight main sequence between \(19.5 < r_0 < 24.0\) mag.

### 3.4.2 Age and Metallicity

We estimate the age, [Fe/H], and distance of Kim 1 using the maximum likelihood method described in Frayn & Gilmore (2002) and Fadely et al. (2011). We use all stars within a radius of 2′0 around Kim 1, combining SDSS \((r < 19)\) and DECam \((r > 19)\) photometry. We calculate the maximum likelihood values \(L\) over a grid of Dartmouth model isochrones (Dotter et al., 2008) covering an age range from 7.0–13.5 Gyr, a metallicity range \(-2.5 \leq [\text{Fe/H}] \leq -0.5\) dex, and a distance range \(16 < (m - M) < 17\). Grid steps are 0.5 Gyr, 0.1 dex, and 0.05 mag. In Figure 3.4, we present the matrix of likelihood values for the sample described above after interpolation and smoothing over 2 grid points. We find the Dartmouth isochrone with the highest probability has an age of 12.0 Gyr and \([\text{Fe/H}] = -1.7\) dex. The 68%, 95%, and 99% confidence contours are also overplotted in the figure. The marginalized uncertainties about this most probable location correspond to
Figure 3.5 6 × 6 arcmin$^2$ DECam cutout g-band image of Kim 1. North is up, east is to the left. Circled are all stars within 2$r_h$ from Kim 1 that are consistent in color-magnitude space with the best-fitting isochrone (12 Gyr, [Fe/H]=−1.7) at a distance of 19.8 kpc. The main-sequence stars are fainter than $r_0 ≈ 19.5$ and have colours within $0.1 < (g−r)_0 < 0.6$.

an age of $12.0^{+1.5}_{−3.0}$ Gyr, a metallicity of [Fe/H]=−1.7$^{+0.5}_{−0.2}$ dex, and a distance modulus of $(m − M)_0 = 16.48 ± 0.10$ ($d_⊙ = 19.8 ± 0.9$ kpc). We adopt a heliocentric distance of 19.8 kpc in the calculation of physical size and absolute magnitude in Section 4.2.

The best-fitting Dartmouth and PARSEC (Bressan et al., 2012) isochrones of age 12 Gyr and [Fe/H]=−1.7 that match the location of the RGB, red clump and MS of Kim1 are overplotted at a distance of 19.8 kpc to illustrate the consistency with an old metal-poor stellar population independently of the theoretical model. Segue 3 happens to have the same age and metallicity (Fadely et al., 2011). We adopted a distance of 17 kpc for the isochrone shown in the CMD of Segue 3.
3.4.3 Size, Ellipticity, and Luminosity

Figure 3.5 shows the $6 \times 6 \text{arcmin}^2$ DECam cutout $g$ band image of Kim 1. The circles indicate the locations of all stars within $2r_h$ from Kim 1 in Figure 3.3 that passed our photometric cut based on the isochrone-fit in color-magnitude space.

The left panel of Figure 3.6 shows the sky distribution of all DECam stars, in the magnitude range from the saturation level to the 90% completeness level for each $g$ and $r$ band, passing the photometric cut based on the best-fitting model isochrone, in a $0.3^\circ \times 0.3^\circ$ window centred on Kim 1. The right panel shows the associated radial profile of the stellar number density, i.e. star counts in elliptical annuli around Kim 1, where $r$ is the elliptical radius. For the center of the overdensity we adopted the centre of mass calculated in terms of the normalised signals on the array into which the stars were binned and smoothed as described in Section 2. We derive an ellipticity $\epsilon = 0.42 \pm 0.10$ and a position angle $\theta = -59 \pm 6$ deg by using the fit_bivariate_normal function of the astroML package (VanderPlas et al., 2012). The error bars in the right panel of Figure 3.6 were derived from Poisson statistics, i.e. $\sqrt{N}/\text{arcmin}^2$. Overplotted is the best-fit Plummer profile (Plummer, 1911) to parametrise the underlying stellar distribution. We obtain a half-light radius of $1.2 \pm 0.1 \text{arcmin}$ or $r_h = 6.9 \pm 0.6 \text{pc}$, adopting the distance modulus of 16.48 mag.

In analogy to Walsh et al. (2008) we estimate the total luminosity of Kim 1 by integrating the radial number density profile shown in Figure 3.6 to calculate the total number of Kim 1
Table 3.1. Properties of Kim 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{J2000}$</td>
<td>22:11:41.3</td>
<td>h:m:s</td>
</tr>
<tr>
<td>$\delta_{J2000}$</td>
<td>+07:01:31.8</td>
<td>°:′:″</td>
</tr>
<tr>
<td>$l$</td>
<td>68.5148</td>
<td>deg</td>
</tr>
<tr>
<td>$b$</td>
<td>-38.4256</td>
<td>deg</td>
</tr>
<tr>
<td>$(m - M)$</td>
<td>16.48 ± 0.10</td>
<td>mag</td>
</tr>
<tr>
<td>$d_\odot$</td>
<td>19.8 ± 0.9</td>
<td>kpc</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>$-1.7^{+0.5}_{-0.2}$</td>
<td>dex</td>
</tr>
<tr>
<td>Age</td>
<td>$12^{+1.5}_{-3.0}$</td>
<td>Gyr</td>
</tr>
<tr>
<td>$r_h$ (Plummer)</td>
<td>6.9 ± 0.6$^a$</td>
<td>pc</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.42 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>−59 ± 6</td>
<td>deg</td>
</tr>
<tr>
<td>$M_{tot,V}$</td>
<td>0.3 ± 0.5</td>
<td>mag</td>
</tr>
</tbody>
</table>

$^a$ Adopting a distance of 19.8 kpc

stars $N_*$ within the photometric limits. Using the ratio of this number $N_*$ to the probability density of a normalised theoretical luminosity function (LF) in the same magnitude range as for the radial profile, we scale the theoretical LF to the number densities of stars as a function of $r$ magnitude. Integrating the scaled LF inclusive of the missing flux from stars brighter than the saturation limit and fainter than the 90% completeness limit, gives a total luminosity $M_{r,Kim1} = 0.04$ based on the PARSEC isochrone and $M_{r,Kim1} = -0.07$ based on the Dartmouth isochrone, both for a 12 Gyr old stellar population with [Fe/H] = −1.7. Due to the intrinsic faintness of the stellar overdensity and the low number of stars, the estimates of the total luminosity has a large uncertainty. From the $V - r$ colours (0.32 mag and 0.22 mag) of the two best-fitting model isochrones we derive the corresponding $V$-band luminosities $M_{V,Kim1} = 0.36$ mag and $M_{V,Kim1} = 0.15$, respectively. We note that both model isochrones give consistent results. Since this method relies on the number of stars in such an ultra-faint stellar system instead of their individual flux, the inclusion or exclusion of a single RGB or red clump star in the system can change its total luminosity still by $\sim 0.5$ mag. Hence, a realistic estimate of the total luminosity of Kim 1 is $M_V = 0.3 ± 0.5$. All derived parameters are summarised in Table 3.1.
3.5 Discussion and Conclusion

We report the new ultra-faint stellar overdensity, Kim 1, in the constellation of Pegasus. The best-fitting theoretical isochrone reveals a single 12 Gyr old, metal-poor ([Fe/H]=-1.7) stellar population at a well-defined heliocentric distance of 19.8 ± 0.9 kpc. Its total luminosity of $M_V = 0.3 ± 0.5$ shows that Kim 1 is among the faintest stellar systems discovered in the Milky Way halo to date. Other MW star clusters known to have comparable luminosities are Segue 3 ($M_V = 0.0 ± 0.8$; Fadely et al., 2011), Muñoz 1 ($M_V = -0.4 ± 0.9$; Muñoz et al., 2012), Balbinot 1 ($M_V = -1.21 ± 0.66$; Balbinot et al., 2013), and Koposov 1 & 2 ($M_V = -2, M_V = -1$; Koposov et al., 2007). Its physical size ($r_h = 6.9 ± 0.6$ pc) and low luminosity place Kim 1 close to these MW star clusters in the size-luminosity diagram (Fadely et al., 2011).

3.5.1 Kim 1, a dissolving star cluster?

Despite the fact that the stellar population of Kim 1 appears sufficiently old to be dynamically relaxed for the given physical size and the number of constituent stars, the overdensity has an unusually high ellipticity of 0.42 and a poorly defined central concentration. No other low luminous MW star cluster, with the exception of Koposov 1 (Koposov et al., 2007, see their Figure 2a) has comparable structural properties, which suggest that we are seeing a tidally disrupted star cluster or a remnant thereof. We note that the small size of Kim 1 and the absence of a large spread in [Fe/H] make it unlikely that Kim 1 is a ultra-faint satellite galaxy of the Milky Way (Willman & Strader, 2012).

Although a detailed simulation of Kim 1’s dynamical history is beyond the scope of this study due to the lack of kinematical data and orbital parameters, Baumgardt (private communication) kindly ran N-body simulations using NBODY6 (Aarseth, 1999) to estimate the initial mass of the progenitor star cluster, using a set-up similar to Baumgardt & Makino (2003). For that purpose a model star cluster with a Kroupa (2001) initial mass function was placed on circular or eccentric orbits in a spherical Milky Way potential with a constant rotation velocity of $V_G = 220 \text{ km s}^{-1}$. The integration of the orbits was halted after 12 Gyr, the age of Kim 1. Matching the bound mass of the remnant model star cluster with the current mass of Kim 1 (approximately 100 $M_\odot$) confines its initial stellar mass to the range $3500M_\odot < M_{\text{init}} < 5500M_\odot$, where the two limits correspond to a highly eccentric orbit with a perigalactic and apogalactic distance of 20 kpc and 100 kpc respectively, and a circular orbit at the distance of 25 kpc. In Figure 3.7 we show the line-of-sight stellar distribution of the model star cluster in the circular orbit after 12 Gyr for the DECam field-of-view (left) as well as the inner region (right). There are only a small number of extra tidal stars distributed over an area corresponding to the DECam field,
Figure 3.7 Result of N-body simulation assuming a spherical Milky Way potential with a constant rotation velocity of $V_G = 220 \text{ km s}^{-1}$ and a model star cluster with $M_{\text{ini}} = 5500 M_\odot$ in a circular orbit at the distance of 25 kpc. **Left panel:** Line-of-sight stellar distribution of the model star cluster after 12 Gyr for the DECam field-of-view. **Right panel:** The same as the left panel but for the inner region. Star counts and stellar distribution closely resemble Kim 1. and the remnant star cluster is highly asymmetric and elongated in the inner 30 pc×30 pc without a well-defined center. From these simulations we can conclude that the observational properties of Kim 1 are consistent with a dissolving star cluster that initially had a few thousand solar masses. No prominent stellar stream is expected to be associated to such a low mass star cluster. The few cluster stars found beyond the tidal radius would be completely hidden in the screen of stars from the Milky Way.

### 3.5.2 Is Kim 1 associated to a Stream?

The constellation of Pegasus, in which Kim 1, Segue 3 and Balbinot 1 are found, lies close to the Hercules-Aquila Cloud discovered in SDSS-DR5 (Belokurov et al., 2007). This Galactic halo substructure is centred at $l \sim 40^\circ$, and extends down to $b \sim -40^\circ$ at $l \sim 50^\circ$. In fact, de Jong et al. (2010) used main-sequence stars in SDSS-DR7 SEGUE data to identify a number of new halo overdensities that might be related to the cloud. As Segue 3 coincides spatially with one of the reported overdensities, there has been speculations about the possible association of Segue 3 with the Hercules-Aquila Cloud. A spectroscopic analysis (Fadely et al., 2011), however, found a kinematic offset that suggests Segue 3 is unlikely associated with that overdensity. For Balbinot 1 and Kim 1 located at $(l, b) = (75.1735^\circ, -32.6432^\circ)$ and $(l, b) = (68.5148^\circ, -34.4256^\circ)$ respectively, there is no corresponding overdensity out of all the detections listed in Table 4 of de Jong et
Figure 3.8 The same as the lower right panel of Figure 3.2 but for all stars in the field of view of DECam.

al. (2010). In addition, there is an argument that the true heliocentric distance of the Hercules-Aquila Cloud ranges only between 1 and 6 kpc (Larsen et al., 2011). Simion et al. (2014) conclude in their recent study using RR Lyrae stars in the Catalina Sky Survey data that the extension of the Hercules-Aquila Cloud is bound within $30^\circ < l < 55^\circ$ and $-45^\circ < b < -25^\circ$, and that there is no significant excess of stars in the region of sky at $55^\circ < l < 85^\circ$ and $-45^\circ < b < -25^\circ$. Since Kim 1, Segue 3, and Balbinot 1 are all located at $l > 68^\circ$, these star clusters are unlikely associated with the Hercules-Aquila Cloud.

Recent searches of SDSS DR8 and DR10 for extended stellar overdensities in the Galactic halo have discovered new stellar streams in a range of heliocentric distances from 15 to 35 kpc (Bonaca et al., 2012; Martin et al., 2013; Grillmair, 2014). These stellar streams are identified on extended stellar density maps by taking photometric cuts with weighted isochrone masks over a range of distance moduli. Due to the sparse and extended nature of the streams, their stellar populations are barely discerned from the Milky Way foreground in color-magnitude space unless a field-subtracted Hess diagram is constructed out of a sufficiently large sky area. None of those searches, however, have found any stellar stream that overlaps with the location of Kim 1 (e.g. Figure 2 in Bonaca et al., 2012), and the stellar population of Kim 1 is clearly distinguished from the foreground in the CMD of a localised region. In addition, unlike tidal debris detected around Pal 5 (Odenkirchen et al.,
2001), our DECam star distribution does not feature any extra significant clumps around Kim 1 out to 400 pc radius. There is also a hypothesis that ultra-faint dwarf galaxies are instead cusp caustics of cold stellar debris that formed during the disruption of low-mass satellites (Zolotov et al., 2011). A cusp caustic in projection appears as a highly elongated center of stars, along with a two-fold of tails as an indication. Although Kim 1 indeed appears highly elongated compared to other known ultra-faint star clusters, such small scale tails and their fold are not detected in our DECam data (see Figure 3.8).

It is worth noticing that Segue 3 (\(d_\odot = 17 \text{ kpc}, 12 \text{ Gyr}, [\text{Fe/H}]=-1.7\)), Kim 1 (\(d_\odot = 19.8 \text{ kpc}, 12 \text{ Gyr}, [\text{Fe/H}]=-1.7\)), and Balbinot 1 (\(d_\odot = 31.9 \text{ kpc}, 11.7 \text{ Gyr}, [\text{Fe/H}]=-1.58\)), are neighbours in projection and even lie within a considerably narrow range of heliocentric distances from 17 to 32 kpc. They are also spatially close to the globular cluster M2 (\(d_\odot=11.5 \text{ kpc};\) Harris, 1996), one of the most unusual globular clusters in the Milky Way halo with a number of distinct stellar subpopulations (Milone et al. 2014, submitted), and their locations coincide with the vast polar structure (VPOS), a thin (20 kpc) plane perpendicular to the MW disk defined by the 11 brightest Milky Way satellite galaxies (Kroupa et al., 2005; Metz et al., 2007, 2009; Kroupa et al., 2010; Pawlowski et al., 2012). Globular clusters and stellar and gaseous streams appear to preferentially aligned with the VPOS too (Forbes et al., 2009; Pawlowski et al., 2012). It might be a coincidence that all four stellar systems mentioned above are spatially close together and that their locations agree with the VPOS, but this finding naturally raises the question about these star clusters’ possible link to the Milky Way satellite galaxies. While more information is required to address Kim 1’s origin, the finding of such a small, extreme low luminosity stellar concentration in the inner halo is definitely consistent with current detection limits (Walsh et al. 2009, see Fig. 15) and points to a much larger parent population of star clusters that are still undetected in the Milky Way halo or must have been already destroyed by the Galactic tidal field.
Carraro, G. 2009, AJ, 137, 3809
Forbes, D. A., Kroupa, P., Metz, M., & Spitler, L. 2009, Mercury, 38, 24


CHAPTER 4

DISCOVERY OF AN ULTRA-FAINT MILKY WAY SATELLITE IN PEGASUS

This chapter has been previously published as “A hero’s dark horse: discovery of an ultra-faint Milky Way satellite in Pegasus”, Kim, D., Jerjen, H., Mackey, D., Da Costa, G. S., & Milone, A. P., 2015, 804, L44.

Abstract

We report the discovery of an ultra-faint Milky Way satellite galaxy in the constellation of Pegasus. The concentration of stars was detected by applying our overdensity detection algorithm to the SDSS-DR 10 and confirmed with deeper photometry from the Dark Energy Camera at the 4-m Blanco telescope. Fitting model isochrones indicates that this object, Pegasus III, features an old and metal-poor stellar population ([Fe/H]∼−2.1) at a heliocentric distance of 205±20 kpc. The new stellar system has an estimated half-light radius of \( r_h = 78^{+30}_{-24} \) pc and a total luminosity of \( M_V \sim −4.1 \pm 0.5 \) that places it into the domain of dwarf galaxies on the size–luminosity plane. Pegasus III is spatially close to the MW satellite Pisces II. It is possible that the two might be physically associated, similar to the Leo IV and Leo V pair. Pegasus III is also well aligned with the Vast Polar Structure, which suggests a possible physical association.

4.1 Introduction

Following the Sloan Digital Sky Survey (York et al., 2000), more recent wide-field imaging surveys such as the Stromlo Milky Way Satellite survey (Jerjen, 2010), the Dark Energy Survey (The Dark Energy Survey Collaboration, 2005), the Pan-STARRS 3\( \pi \) Survey
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(K. Chambers et al., in preparation), and the Survey of the Magellanic Stellar History (SMASH; PI D. Nidever) have been revealing new Milky Way companions including satellite galaxies (Koposov et al., 2015; Bechtol et al., 2015; Laeves et al., 2015; Martin et al., 2015) and star clusters (Belokurov et al., 2014; Laeves et al., 2014; Kim & Jerjen, 2015; Kim et al., 2015). The new Milky Way companions, many of which are in the southern sky, share the properties of previously discovered ultra-faint stellar systems, such as low luminosities ($-8 \lesssim M_V \lesssim -1.5$) (Martin et al., 2008) and low metallicities [Fe/H] $<-2$ (Kirby et al., 2008; Norris et al., 2010; Simon et al., 2011; Koch & Rich, 2014).

In this chapter we report the detection of the new ultra-faint Milky Way satellite Pegasus III (Peg III) found in SDSS Data Release 10 and confirmed with deep DECam imaging (Sections 2 & 3). Peg III appears to be located at a heliocentric distance of $\sim 205$ kpc and have a half-light radius of $\sim 78$ pc (Section 4). In the last section we discuss the possible origin of the new satellite galaxy and conclude with our results.

4.2 Discovery

The SDSS is a photometric and spectroscopic survey in the $ugriz$ photometric bands to a depth of $r \sim 22.5$ magnitudes (York et al., 2000). Data Release 10 (DR10), publicly available on the SDSS-III Web site\(^1\), covers 14,555 deg\(^2\) mostly around the north Galactic pole (Ahn et al., 2014).

The new object was first flagged by our detection algorithm in the search for stellar overdensities over the existing SDSS catalog as described in Walsh et al. (2009) and Kim & Jerjen (2015). Briefly, we used isochrone masks based on the PARSEC stellar evolution models (Bressan et al., 2012) as a photometric filter to enhance the presence of old and metal-poor stellar populations relative to the Milky Way foreground stars. We then binned the RA-Dec positions of the filtered stars and convolved the density-map with a Gaussian kernel. Based on the density-map, we calculate the signal to noise ratios (S/Ns) of potential overdensities and measure their significance by comparing their S/Ns to those of random clusters in the residual background. Moving the isochrone masks over a range of distance moduli ($m - M$) between 16 and 22 magnitudes, this process is repeated with different scales of bins and Gaussian kernels.

With this algorithm, we recovered all of the previously known MW companions in the SDSS coverage and found a few more promising candidates, one of which was reported in Kim & Jerjen (2015). The new object was detected with a significance of $\sim 7\sigma$ in the constellation of Pegasus.

\(^1\)http://www.sdss3.org/dr10/
4.3 Follow-up Observations and Data Reduction

Deeper follow-up observations of the Peg III field were conducted on during the night of 17th July 2014 using the Dark Energy Camera (DECam) at the 4-m Blanco Telescope located at Cerro Tololo Inter-American Observatory (CTIO) in Chile. DECam imager is equipped with a focal plane array containing sixty-two 2k × 4k CCD detectors with a wide field of view (3.0 square degrees) and a pixel scale of 0′′.27 (unbinned). Under photometric conditions, we obtained 840 s exposures in g and 1050 s in r band, divided over dithered single exposures of 210 s. The average seeing during the observing was 1′′.3 in the g and 1′′.1 in the r band. The single exposure images were fully reduced and stacked through the DECam community pipeline (Valdes et al., 2014). We carried out weight-map combination, source extraction and PSF photometry with the use of WeightWatcher (Marmo & Bertin, 2008) and SExtractor/PSFEx (Bertin & Arnouts, 1996; Bertin, 2011). For star/galaxy separation, we applied the threshold $|\text{SPREAD}\_\text{MODEL}| < 0.003 + \text{SPREADERR}\_\text{MODEL}$ as described in Koposov et al. (2015). We then positionally matched the star-like objects with SDSS stars with a maximum radius of 1′′.0 using the STILTS software (Taylor, 2005). We used this catalog for the photometric calibration in the magnitude range $17.0 < r_0 < 21.0$ mag, between the saturation limit of the DECam and the 5σ limit of the SDSS. Finally, the magnitudes of the calibrated point sources were dereddened by means of the Schlegel et al. (1998) extinction maps and the extinction correction coefficients of Schlafly & Finkbeiner (2011).

The upper panel of Figure 4.1 shows the contour map of star density centred on Peg III in the field of view of DECam after the photometric filtering process using a PARSEC isochrone of 13.5 Gyr and $[\text{Fe/H}] = -2.1$ (Bressan et al., 2012) at the distance modulus $(m - M) = 21.56$ magnitudes. High level density contours ($> 4\sigma$) clearly define Peg III in the central region of the image and no other comparable overdensity in terms of S/N. Our algorithm recovers the overdensity with a significance of $\sim 10\sigma$ in the DECam data. The irregular shapes of the outer isophotes are likely due to the fact that we sample only the brightest red-giant branch (RGB) and horizontal branch (HB) stars in the system or that we see the signature of tidal disturbance. In the lower panel we present the same kind of contour map as shown in the upper panel but for all galaxy-like objects classified by the threshold $\text{SPREAD}\_\text{MODEL} > 0.003$. There is no overdensity coincident with Peg III, ruling out the possibility of a background galaxy cluster.
Figure 4.1 Upper panel: Density contours of candidate stars in the field of view of DECam that pass the photometric filter with a PARSEC isochrone of 13.5 Gyr and \([\text{Fe/H}]=-2.1\) (Bressan et al., 2012) at the distance modulus \((m-M)=21.56\) magnitudes. The contours show the levels of star density in units of the standard deviation above the background. The dashed circle marks a radius of 2\('\)5 (see Section 4 for details).

Lower panel: Same as the upper panel but for all objects classified as galaxies. At the central region, there is no obvious overdensity coincident with that in the upper panel.
Figure 4.2 DECam view of Peg III. Upper left panel: Distribution of all objects classified as stars in a $20' \times 20'$ field that shares the central coordinates with Figure 4.1. The circles mark a radius of $2.5'$ (equal to the dashed circle in Figure 4.1), $8'0$ and $8'3$ respectively. The blue dots mark the seven BHB stars that fall into the color-magnitude range $-0.20 < (g-r)_{0} < 0.05$ and $21.80 < r_{0} < 22.30$, illustrated as a blue box in the upper right panel. Upper right panel: CMD of stars lying within the inner circle, dominated by the candidate stars of the dwarf galaxy. Lower left panel: Comparison CMD of stars lying in the annulus defined by the two outer circles, dominated by foreground stars. Lower right panel: Field-subtracted Hess diagram, the inner CMD minus the comparison CMD, showing an excess of stars at the locations of the BHB and RGB of Peg III. The best-fitting PARSEC (red) isochrone of age 13.5 Gyr and [Fe/H]=−2.1 and Dartmouth (Dotter et al., 2008) (blue) isochrone of age 14.2 Gyr and [Fe/H]= −2.3 are overplotted at a distance of 205 kpc.
4.4 Candidate Properties

The upper left panel of Figure 4.2 shows the RA-Dec distribution of all stellar objects identified by SourceExtractor in the vicinity of Peg III. The upper right panel of Figure 4.2 shows the extinction-corrected CMD of stars within 2.5′ (equal to the dashed circle in Figure 4.1) of the nominal centre of Peg III, and the lower left panel that of the foreground stars in the same manner as in Belokurov et al. (2010) from annulus defined by the outer radii of 8′.0 and 8′.3 covering the same area as the inner circle around Peg III. Finally, the lower right panel shows a field-subtracted Hess diagram, built on the CMDs in the middle. We note that Peg III shares a well defined RGB and blue-HB (BHB) with other distant MW satellite galaxies, namely, Leo V and Pisces II (Belokurov et al., 2008, 2010). The five BHB candidate stars clustering at \( r_0 \sim 22 \) mag and \( (g-r)_0 \sim -0.1 \) mag are highlighted as blue dots in the inner circle in the upper left panel of Figure 4.2. Fitting the horizontal branch of the PARSEC isochrone model yields an average heliocentric distance of \( \sim 205 \) kpc.

To derive the central position \( \alpha \) and \( \delta \), ellipticity \( \epsilon \), position angle \( \theta \) and half-light radius \( r_h \), we employed a maximum-likelihood algorithm similar to the procedure described in Martin et al. (2008) with the stars that passed the photometric filter. We obtained a half-light radius of \( 1.3^{+0.5}_{-0.4} \) arcmin, or \( 78^{+30}_{-24} \) pc adopting a heliocentric distance of 205 kpc. The radial density profile with the best-fitting exponential model is presented in Figure 4.3.
We estimate the total luminosity of Peg III in analogy to Walsh et al. (2008) as follows. First, we calculate the total number of Peg III stars $N_*$ within the photometric limit by integrating the best-fitting exponential profile shown in Figure 4.3. We use the ratio of the total number of stars $N_*$ to the probability density of a normalised theoretical luminosity function (LF) in the same magnitude range. Using this ratio, we scale the theoretical LF to the star number density as a function of $r$ magnitude. We then integrate the scaled LF taking into account the missing flux beyond the lower limit of our photometry and obtain a total luminosity $M_r = -4.23$ based on the initial mass function by Kroupa (2001) and PARSEC isochrone for a 13.5 Gyr old stellar population with $[\text{Fe/H}]=-2.1$. From the $V - r = 0.17$ mag luminosity weighted mean color for the model isochrone we derive the corresponding $V$-band luminosity $M_V = -4.1$. Since this method relies on total star counts instead of individual flux, the inclusion or exclusion of a single RGB in the system carries large uncertainties up to $\sim 0.5$ mag. Hence, a realistic estimate of the total luminosity of Peg III is $M_V = -4.1 \pm 0.5$. All derived parameters are summarised in Table 4.1.

### 4.5 Discussion and Conclusion

We report the discovery of a new ultra-faint Milky Way satellite, Peg III. The satellite hosts a typical old, metal-poor stellar population as it is observed in many other Milky Way satellite galaxies. Its large half-light radius ($\sim 78 \text{ pc}$) and luminosity ($-4.1 \pm 0.5$) puts Peg III among other systems classified as ultra-faint dwarf galaxies in the size-luminosity parameter space as shown in Figure 4.4. In particular, these physical properties of Peg III
Figure 4.4 The position of Peg III on the size-luminosity plane, marked with a star outlined in black. Also shown are all Milky Way globular clusters (filled circles), and the presently-known dwarf spheroidal satellites of the Milky Way (filled squares) and M31 (open squares). All points are colour-coded by ellipticity; those globular clusters lacking an ellipticity measurement are marked in black. Peg III clearly occupies the region inhabited by ultra-faint dwarf satellites of the Milky Way, and it has a comparable ellipticity to many of these objects. We note that Peg III directly falls on top of Coma Berenices, which is therefore invisible on this plot. Measurements for the globular clusters were taken from Harris (1996, and 2010 edition); those for the Milky Way dwarfs from McConnachie (2012), Belokurov et al. (2014), Lae vens et al. (2014, 2015), Kim et al. (2015), Koposov et al. (2015), Bechtol et al. (2015), and Martin et al. (2015); and those for the M31 dwarfs from McConnachie (2012), and Martin et al. (2013a,b) In the case where more than one independent set of luminosity and/or structural measurements exists for an object, we adopt their weighted mean.

are very similar to those of previously known remote MW satellites such as Leo IV ($d_\odot = 154\pm5\text{kpc}, r_h = 206^{+36}_{-31}\text{pc};$ Moretti et al., 2009), Leo V ($d_\odot = 196\pm15\text{kpc}, r_h = 65\pm30\text{pc};$ Sand et al., 2012) and Pisces II ($d_\odot = 183\pm15\text{kpc}, r_h = 58\pm10\text{pc};$ Sand et al., 2012). We note that we could have overestimated the half-light radius of Peg III due to the sampling of stars limited to RGB/HB and field-contamination. Deeper photometry down to the main-sequence stars tends to give smaller half-light radii as shown in previous studies (e.g. Leo V in de Jong et al., 2010; Sand et al., 2012). However, even if the true size is only half of the current estimate, Peg III would be still found in the region where ultra-faint dwarf galaxies populate in the size-luminosity parameter space.
It is interesting to note that Peg III and Pisces II are separated only by 8.5 deg on the sky and have fairly similar distances (205 ± 20 kpc and 183 ± 15 kpc). The spatial separation of the two satellite galaxies is ~30 kpc. A similar situation has already been encountered with the Leo IV and Leo V pair (de Jong et al., 2010). This suggests that Peg III and Pisces II could be associated with each other, although a velocity measurement will be required to confirm or reject this idea. As for the Leo IV–Leo V pair they might be related to a single disrupting or disrupted progenitor. It might be a pure coincidence but the Peg III–Pisces II and Leo IV–Leo V pairs are almost diametrically opposite (in fact 162 deg) in the sky, and have almost the same angular separation of ~90 deg from the barycenter of the Magellanic Clouds, i.e. 88 deg and 103 deg, respectively.

With an angular distance of ~13 deg, Peg III lies also close the vast polar structure (VPOS), a planar arrangement defined by the 27 previously known Milky Way satellite galaxies, including the Magellanic Clouds, perpendicular to the MW disk (Kroupa et al., 2005; Metz et al., 2007, 2009; Kroupa et al., 2010; Pawlowski et al., 2012). The majority of recently discovered Milky Way satellite candidates in the southern hemisphere (Koposov et al., 2015; Bechtol et al., 2015) are also well aligned with the VPOS (Pawlowski et al. 2015, in preparation). The origin of that plane is still a matter of debate. It could be the result of a major galaxy collision that left debris in form of tidal dwarfs and star clusters along the orbit (Pawlowski & Kroupa, 2013). Peg III might be part of that debris.
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McConnachie, A. W. 2012, AJ, 144, 4
CHAPTER 5

A PHOTOMETRIC AND SPECTROSCOPIC STUDY OF THE ULTRA-FAINT MILKY WAY SATELLITE PEGASUS III


Abstract

Pegasus III (Peg III) is one of the few known ultra-faint stellar systems in the outer halo of the Milky Way. We present the results from a follow-up campaign with Magellan/IMACS and Keck/DEIMOS. Deep stellar photometry down to $r_0 \approx 25$ mag at $50\%$ completeness level has allowed accurate measurements of its photometric and structural properties. The color-magnitude diagram of Peg III confirms that the stellar system is well described by an old ($\gtrsim 12$ Gyr) and metal-poor ([Fe/H]$\lesssim -2.0$ dex) stellar population at a heliocentric distance of $215 \pm 12$ kpc. The revised half-light radius $r_h = 53 \pm 14$ pc, ellipticity $\epsilon = 0.38^{+0.22}_{-0.38}$, and total luminosity $M_V = -3.4 \pm 0.4$ are in good agreement with the values quoted in our previous paper. We further report on the spectroscopic identification of seven, possibly eight member stars of Peg III. The Ca II triplet lines of the brightest member stars indicate that Peg III contains stars with metallicity as low as [Fe/H]$= -2.55 \pm 0.15$ dex. Peg III has a systemic velocity of $-222.9 \pm 2.6$ km s$^{-1}$ and a velocity dispersion of $5.4^{+3.0}_{-2.5}$ km s$^{-1}$. The inferred dynamical mass within the half-light radius is $1.4^{+3.0}_{-1.1} \times 10^6 M_\odot$ and the mass-to-light ratio $M/L_V = 1470^{+5660}_{-1240} M_\odot/L_\odot$, providing further evidence that Peg III is a dwarf galaxy satellite. We find that Peg III and another distant dwarf satellite Pisces II lie relatively close to each other ($\Delta d_{\text{spatial}} = 43 \pm 19$ kpc) and share similar radial
velocities in the Galactic standard-of-rest frame \( (\Delta v_{GSR} = 12.3 \pm 3.7 \text{ km s}^{-1}) \). This suggests that they may share a common origin.

5.1 Introduction

The census of satellite galaxies and star clusters associated with the Milky Way (MW) has been continuously updated for the last decade. Following the success of the Sloan Digital Sky Survey (SDSS; York et al., 2000), which revealed the presence of “ultra-faint” \((M_V > -5)\) MW satellites (e.g. Willman et al., 2005; Zucker et al., 2006; Belokurov et al., 2006; Irwin et al., 2007; Walsh et al., 2007; Koposov et al., 2007; Balbinot et al., 2013; Kim & Jerjen, 2015a), recent wide-field photometric surveys have been instrumental in finding many more such systems in the MW halo, and probing to increasingly faint levels (e.g. Bechtol et al., 2015; Drlica-Wagner et al., 2015; Kim et al., 2015a; Kim & Jerjen, 2015b; Kim et al., 2016; Koposov et al., 2015a; Laevens et al., 2015a,b; Luque et al., 2016; Martin et al., 2015; Torrealba et al., 2016a,b). A growing number of the newly discovered MW satellites are filling the gap between the classical dwarf galaxies and globular clusters in the size-luminosity plane, meaning that it is increasingly difficult to classify these systems using only these two parameters (Willman & Strader, 2012). Instead, the approach of determining their kinematics or chemistry still remains valid as a main diagnostic for distinguishing the two types of stellar systems (e.g. see discussions in Laevens et al., 2014; Belokurov et al., 2014; Kirby et al., 2015a; Weisz et al., 2016; Voggel et al., 2016). Spectroscopic follow-ups for the kinematic and chemical properties are rapidly catching up with the discoveries of the new satellites, but it is a technical challenge to study more than a handful of member stars in these systems due to their intrinsic low total luminosities and therefore lack of bright red giant branch stars (Simon et al., 2015; Walker et al., 2015, 2016; Koposov et al., 2015b; Kirby et al., 2015b; Martin et al., 2015, 2016a,b; Ji et al., 2016; Roederer et al., 2016).

Pegasus III (Peg III hereafter) is a MW satellite galaxy originally found in the SDSS Data Release 10 photometry (Ahn et al., 2014) by Kim et al. (2015b), who also provided detection confirmation at the \( \sim 10\sigma \) level based on DECam photometry. The follow-up imaging with DECam further revealed the presence of six blue-horizontal-branch (BHB) candidate stars. Their apparent magnitudes implied that Peg III is located at a heliocentric distance of \( 205 \pm 20 \text{kpc} \) in the outer region of the MW halo. From the relatively shallow DECam photometry, Peg III appeared to be elongated with a rather irregular stellar distribution possibly indicative of tidal disturbance. Deeper imaging was thus required to confirm its true nature.
Peg III is a member of the small population of presently known MW satellites in the distance range 130 kpc < \( d_{GC} < 250 \) kpc. It is also located close to another distant satellite, Pisces II (Psc II hereafter, \( d_{⊙} \approx 180 \) kpc; Belokurov et al., 2010). These two satellites seem to form a physical pair with an angular separation of 8.5° on the sky and a relatively small difference in line-of-sight distance of \( \approx 30 \) kpc. Other close pairs of MW satellites have been reported before – for example, Boötes I (Belokurov et al., 2006) and Boötes II (Walsh et al., 2007), Leo IV (Belokurov et al., 2007) and Leo V (Belokurov et al., 2008), or Horologium I (Koposov et al., 2015a; Bechtol et al., 2015) and Horologium II (Kim & Jerjen, 2015b), leading to speculations about their companionship or common origin. The most notable pair is Leo IV - V, another pair of distant satellites (\( d_{⊙} > 150 \) kpc), for which the systemic line-of-sight velocities differ only by \( \approx 40 \) km s\(^{-1}\) (Simon & Geha, 2007; Belokurov et al., 2008), supporting the scenario that the pair might be gravitationally bound as a “tumbling pair” (de Jong et al., 2010). In this context, the discovery of another close pair of distant MW satellites naturally raises the question as to whether their systemic velocities are also similar to each other. To find an answer requires spectroscopic follow-up to obtain their kinematic information.

We observed Peg III with Magellan/IMACS for deep photometry and Keck/DEIMOS for spectroscopy in order to firmly establish its luminosity and structural parameters, estimate its dynamic mass-to-light ratio and investigate its possible association with Psc II.

We observed Peg III on 2015 July 22nd with the f/4 mode of the Inamori-Magellan Areal Camera & Spectrograph (IMACS) at the Magellan/Baade Telescope in the \( g \) and \( r \) bands. Magellan/IMACS has eight 2k×4k CCDs with a total field of view of 15′4 × 15′4 and a pixel scale of 0′′2 pixel\(^{-1}\) (2 × 2 binning).

We obtained a series of 17 × 600s dithered exposures in \( g \) and 15 × 600s in \( r \) together with 20 bias frames, 10 dome flats in each filter taken before the science exposures, and 7 sky flats for each filter taken at the end of our observing night. During the observing run, the weather was clear and seeing ranged from 0′′8 to 1′′2. We produced the master bias and master flats using the zerocombine and flatcombine tasks in IRAF, and then carried out bias subtraction and flat fielding using the imarith task.

To find the astrometric solutions for the reduced science images, we used SCAMP (Bertin, 2006) and the SDSS DR 10 photometry catalog \(^1\). We then combined the reduced images into our final image stacks using SWARP (Bertin et al., 2002).

We performed point-spread function (PSF) photometry on the final image stacks using SExtractor/PSFex (Bertin & Arnouts, 1996; Bertin, 2011). These software programs provide the \texttt{SPREAD\_MODEL} parameter that allows morphological star/galaxy separation, for

\(^1\)http://www.sdss3.org/dr10/
which we set a threshold $|\text{SPREAD}_\text{MODEL}| < 0.003 + \text{SPREADERR}_\text{MODEL}$ (see e.g. Desai et al., 2012; Koposov et al., 2015a). This selection process was applied to the $g$ band image stack, which has a longer total integration time than the $r$ band image stack. After crossmatching the $g$ and $r$ catalogs using STILTS (Taylor, 2005) with a 1$''$0 tolerance, we converted the instrumental magnitudes of the matched catalog into the SDSS photometric system using unsaturated stars in common with our DECam photometry catalog for Peg III presented in Kim et al. (2015b), via bootstrap sampling with 500 iterations and 3-sigma clipping. Finally, we corrected the calibrated magnitudes for Galactic extinction based on the reddening map by Schlegel et al. (1998) and the correction coefficients from Schlafly & Finkbeiner (2011). In the studied field of view, the typical value of E(B-V) is $\sim 0.124$.

We note that the magnitudes of seven objects in the star catalog were replaced by average measurements from two best-seeing individual exposures as they fell onto the edges or corners of CCD chips in some individual exposures and suffered the extra-widening of the PSF relative to the typical full width half maximum (FWHM) in the process of image stacking. Such stacking-induced degrading of the PSF at CCD chip boundaries becomes more obvious when the individual exposures have a seeing difference as large as the pixel scale. We searched in our sample for stars brighter than $r_0 = 23$ mag that have been affected by the phenomenon, and found seven objects including the stars #1 and #8 in our spectroscopy sample (see Table 5.2). This effectively accounts to $\sim 2\%$ of all objects in that magnitude range\(^2\). The number of such objects in the fainter magnitude range of $r_0 > 23$ mag where a typical FWHM is not well defined are not precisely determined. This phenomenon is, however, unlikely to significantly affect the rest of our analysis as the portion of the affected stars is small, the resulting magnitude difference smaller than 0.1 mag, and the width of the photometric filtering mask used in Section 4 sufficiently wide to take the effect into account.

We also measured the completeness levels of our photometry as a function of color and magnitudes using artificial stars as described in Kim et al. (2016). At the color $(g - r)_0 = 0.40$, the 90% and 50% completeness levels correspond to $r_0 = 22.65$ and $r_0 = 24.92$, respectively.

\(^2\) We found the stars affected by the degrading of PSF in $g$ or $r$ band by crossmatching catalogs from the stacked image and best-seeing individual frames, and filtering the matched catalog with the following criteria:

- $\text{fwhm}_{\text{indi}} < \text{fwhm}_{\text{indi}} + 3\sigma_{\text{fwhm}_{\text{indi}}}$
- $\text{fwhm}_{\text{stack}} > \text{fwhm}_{\text{stack}} + 3\sigma_{\text{fwhm}_{\text{stack}}}$
- $|\text{SPREAD}_\text{MODEL}_{\text{indi}}| < 0.003 + \text{SPREADERR}_\text{MODEL}_{\text{indi}}$
Figure 5.1 Upper panel: distribution of all objects classified as stars in a 10'0 × 10'0 field centered on Peg III. Large black dots are the stars within an elliptical radius of 2'55, equivalent to 3 half-light radii, of the center of Peg III (red ellipse) whereas the small dots are the stars outside the ellipse but within a circular-radial distance of 2'55 (dashed circle). The red, blue, and orange large dots represent the 12 stars for which we obtained velocity measurements with Keck/DEIMOS, where red (blue) dots identify kinematic members (non-members). The small gray dots are all the rest of stars from our IMACS photometry. The orange large dot is a star whose membership is ambiguous.

Lower left panel: Magellan/IMACS CMD of the stars in the upper panel. The symbols are the same as in the upper panel. The two Dartmouth isochrones (Dotter et al., 2008) of age 13.5 Gyr, [Fe/H]=−2.5 and [α/Fe]=+0.4 (solid) and of age 12 Gyr, [Fe/H]=−1.1 [α/Fe]=+0.2 (dashed) are overplotted at a distance of 215 kpc. The HB fiducial track has been derived from Bernard et al. (2014) by using the observed CMD of the globular cluster M15 ([Fe/H]=−2.42). The blue and red polygons highlight the HB and AGB/RHB candidate stars of Peg III, respectively. Lower right panel: radial velocity distribution of the 12 stars observed with Keck/DEIMOS. The colors are the same as in the upper and the lower left panels. The solid line illustrates the predicted distribution of MW stars from the Besancon model (Robin et al., 2003), within a radius of 5'0, normalized to the number of observed stars.
Chapter 5 A PHOTOMETRIC AND SPECTROSCOPIC STUDY OF THE ULTRA-FAINT MILKY WAY SATELLITE PEGASUS III

5.2 Photometry and Astrometry

We observed Peg III on 2015 July 22nd with the f/4 mode of the Inamori-Magellan Areal Camera & Spectrograph (IMACS) at the Magellan/Baade Telescope in the $g$ and $r$ bands. Magellan/IMACS has eight $2k \times 4k$ CCDs with a total field of view of $15\arcmin 4 \times 15\arcmin 4$ and a pixel scale of $0\farcs2$ pixel$^{-1}$ ($2 \times 2$ binning).

We obtained a series of $17 \times 600s$ dithered exposures in $g$ and $15 \times 600s$ in $r$ together with 20 bias frames, 10 dome flats in each filter taken before the science exposures, and 7 sky flats for each filter taken at the end of our observing night. During the observing run, the weather was clear and seeing ranged from $0\farcs8$ to $1\farcs2$. We produced the master bias and master flats using the zerocombine and flatcombine tasks in IRAF, and then carried out bias subtraction and flat fielding using the imarith task.

To find the astrometric solutions for the reduced science images, we used SCAMP (Bertin, 2006) and the SDSS DR 10 photometry catalog 3. We then combined the reduced images into our final image stacks using SWARP (Bertin et al., 2002).

We performed point-spread function (PSF) photometry on the final image stacks using SExtractor/PSFex (Bertin & Arnouts, 1996; Bertin, 2011). These software programs provide the $\text{SPREAD} \_\text{MODEL}$ parameter that allows morphological star/galaxy separation, for which we set a threshold $|\text{SPREAD} \_\text{MODEL}| < 0.003 + \text{SPREADERR} \_\text{MODEL}$ (see e.g. Desai et

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3http://www.sdss3.org/dr10/
al., 2012; Koposov et al., 2015a). This selection process was applied to the $g$ band image stack, which has a longer total integration time than the $r$ band image stack. After crossmatching the $g$ and $r$ catalogs using STILTS (Taylor, 2005) with a $1''$ tolerance, we converted the instrumental magnitudes of the matched catalog into the SDSS photometric system using unsaturated stars in common with our DECam photometry catalog for Peg III presented in Kim et al. (2015b), via bootstrap sampling with 500 iterations and 3-sigma clipping. Finally, we corrected the calibrated magnitudes for Galactic extinction based on the reddening map by Schlegel et al. (1998) and the correction coefficients from Schlafly & Finkbeiner (2011). In the studied field of view, the typical value of $E(B-V)$ is $\sim 0.124$.

We note that the magnitudes of seven objects in the star catalog were replaced by average measurements from two best-seeing individual exposures as they fell onto the edges or corners of CCD chips in some individual exposures and suffered the extra-widening of the PSF relative to the typical full width half maximum (FWHM) in the process of image stacking. Such stacking-induced degrading of the PSF at CCD chip boundaries becomes more obvious when the individual exposures have a seeing difference as large as the pixel scale. We searched in our sample for stars brighter than $r_0 = 23$ mag that have been affected by the phenomenon, and found seven objects including the stars #1 and #8 in our spectroscopy sample (see Table 5.2). This effectively accounts to $\sim 2\%$ of all objects in that magnitude range. The number of such objects in the fainter magnitude range of $r_0 > 23$ mag where a typical FWHM is not well defined are not precisely determined. This phenomenon is, however, unlikely to significantly affect the rest of our analysis as the portion of the affected stars is small, the resulting magnitude difference smaller than 0.1 mag, and the width of the photometric filtering mask used in Section 3 sufficiently wide to take the effect into account.

We also measured the completeness levels of our photometry as a function of color and magnitudes using artificial stars as described in Kim et al. (2016). At the color $(g-r)_0 = 0.40$, the 90% and 50% completeness levels correspond to $r_0 = 22.65$ and $r_0 = 24.92$, respectively.

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4We found the stars affected by the degrading of PSF in $g$ or $r$ band by crossmatching catalogs from the stacked image and best-seeing individual frames, and filtering the matched catalog with the following criteria:
- $\text{fwhm}_{\text{ind}} < \text{fwhm}_{\text{ind}} + 3\sigma_{\text{fwhm, ind}}$
- $\text{fwhm}_{\text{stack}} > \text{fwhm}_{\text{stack}} + 3\sigma_{\text{fwhm, stack}}$
- $|\text{SPREAD}_{\text{MODEL, ind}}| < 0.003 + \text{SPREADERR}_{\text{MODEL, ind}}$
5.3 Satellite Distance and Stellar Population

The distribution of stars in our IMACS photometry and corresponding color-magnitude diagram are presented in Figure 5.1, reaching \( \sim 3 \) mag fainter than our previous DECam photometry at the same S/N levels. The stars within an elliptical radius of 2′55, equivalent to 3 half-light radii, of the center of Peg III are highlighted with black large dots. The stars outside the 3 half-light radii but within a circular radius of 2′55 are also highlighted with smaller black dots to take into account the large uncertainty of ellipticity derived in Section 4. The large red and blue dots in Figure 5.1 represent kinematically confirmed member and non-member stars respectively (see Section 5 for more details).

We constrain the heliocentric distance of Peg III using the luminosity of its HB and the fiducial HB track of a globular cluster. Since the absolute total luminosity of Peg III was estimated to be \(-4.1 \pm 0.5\) in our previous work, the mean metallicity of the system is expected to be as low as \([\text{Fe/H}] \sim -2.5\) according to the mass-metallicity relation by Kirby et al. (2013). We note that the recent metallicity measurements of the MW satellite dwarf galaxies in the same luminosity range as Peg III, for example Psc II (\([\text{Fe/H}] = -2.45 \pm 0.07; \) Kirby et al., 2015a) and Reticulum II (\([\text{Fe/H}] = -2.65 \pm 0.07; \) Simon et al., 2015) are consistent with the mass-metallicity relation. Accordingly, we adopted the fiducial HB sequence of M15, one of the most metal-poor globular clusters (\([\text{Fe/H}] = -2.42\) ), from Bernard et al. (2014). We converted the fiducial into the SDSS photometric system with the help of transformation equations and coefficients provided by Tonry et al. (2012). We took literature values of \( E(B-V) = 0.11 \) and \((m - M)_0 = 15.25\) (Kraft & Ivans, 2003) to obtain the reddening-corrected fiducial HB sequence. We then expressed this fiducial HB sequence as a function of color \((g - r)_0\) by means of a fifth order polynomial regression, fit this function to the six BHB candidate stars in the blue polygon in the lower left panel of Figure 5.1 with the least-squares method, and derived a distance modulus of \((m - M)_0 = 21.66 \pm 0.12\). For the uncertainty in the final estimate of the distance modulus, we combined in quadrature the uncertainties associated with our calibration to our DECam photometry (< 0.01 mag), the adopted distance modulus of M15 (~ 0.1 mag; Kraft & Ivans, 2003), our fiducial HB sequence fit (0.03 mag, determined by jackknife resampling), and galactic reddening in the \( r \) band (< 0.01 mag). In addition, we took into account the systematic uncertainty associated with the metallicity-luminosity relation, for which our estimate is \( \sim 0.05 \) mag.

In the middle panel, a Dartmouth isochrone (Dotter et al., 2008) for age 13.5 Gyr, \([\text{Fe/H}] = -2.5\), and \([\alpha/\text{Fe}] = +0.4\) (solid curve), an isochrone from the same set but for age 12 Gyr, \([\text{Fe/H}] = -1.1\), \([\alpha/\text{Fe}] = +0.2\) (dashed curve), and the M15 fiducial HB sequence are plotted on the CMD at a distance modulus of \((m - M)_0 = 21.66\), or a heliocentric distance of 215 kpc. The three kinematic member stars in the red polygon appear systematically brighter than the blue horizontal branch (BHB) and bluer than the red giant
Figure 5.3 Convolved density contour map of Peg III candidate stars that pass the photometric filter illustrated in the lower left panel of Figure 5.1. The density map was binned with a pixel size of 10′′ and smoothed with a Gaussian kernel with FWHM of 23′′6. The contours mark the levels of star density in units of the standard deviation above the background (median value). The white dotted ellipse represents 3 half-light radii of the center of Peg III. The left and right arrows point to the nearby outer halo satellite Psc II and the Galactic Center, respectively.

branch (RGB). An excess of such stars relative to the RGB has been noticed in the CMD of the Hercules dwarf galaxy (e.g., Figure 2 in Sand et al., 2009) and the majority of them has been identified as its asymptotic giant branch (AGB) or red horizontal branch (RHB) population by photometric and spectroscopic studies (e.g., Adén et al., 2009; Fabrizio et al., 2014). Most likely the three Peg III member stars in the red polygon are AGB/RHB stars, too. Three of the other four kinematic members of Peg III are consistent with the red giant branch (RGB) while the last one, star #2, is almost 0.1 mag redder. That color difference cannot be explained by photometric uncertainties alone. There are different factors that can cause a color spread in the RGB, including dispersions in metallicity and carbon abundances. The metallicity of stars in MW satellite dwarf galaxies with similar total luminosities to Peg III ranges largely from [Fe/H]=−3.5 up to [Fe/H]=−1.0 dex (e.g., Ursa Major II; Vargas et al., 2013). The red star #2 of Peg III can be indeed fitted with an isochrone for a higher metallicity of [Fe/H]=−1.1 (dashed curve in the middle panel) at the same distance modulus. Carbon stars ([Ca/Fe]≫+1.0) in dwarf galaxies also tend to be redder than carbon-normal RGB stars due to the Bond-Neff effect (Bond & Neff, 1969), as shown for instance in Figure 7 of Kirby et al. (2015c). The possibility of a metallicity and carbon spread among the Peg III stars can be tested once the information on the
chemical abundances of the individual stars becomes available. The low signal-to-noise of our spectra does not permit a detailed analysis for the chemical abundances of the individual targets.

We present a background-subtracted Hess diagram in Figure 5.2, which allows us to qualitatively assess the stellar population of Peg III by means of model isochrone fitting for different properties. The Hess diagram was constructed based on the CMD of all stars within the radial distance of 2′55 and subtracting a control CMD of all stars in an equal area outside 4′0. We overplot Dartmouth isochrones with different ages (8, 10, 12, 13.5 Gyr) and metallicity [F/H] values (-2.5, -2.0, -1.5 dex). The [α/Fe] values for the isochrones are determined based on the [Fe/H]-[α/Fe] relation from Vargas et al. (2013). The distance modulus is fixed at 21.66 mag. The most notable difference among the isochrone fits is found in the main-sequence turnoff region, where the isochrones for metal poor ([Fe/H] ≲ −2.0) and old (≳ 12 Gyr) stellar populations appear to be most consistent. This suggests that Peg III shares similar properties, i.e. low metallicities and old ages, of stellar populations with previously known ultra-faint MW satellite dwarf galaxies (e.g., Brown et al., 2014, and references therein).

5.4 Structural Properties and Absolute Luminosity

Figure 5.3 shows the convolved contour map of the star density centered on Peg III made of stars that passed a photometric filtering mask constructed from the Dartmouth isochrone for age 13.5 Gyr, [Fe/H]=−2.5, and [α/Fe]=+0.4 and the M 15 HB fiducial line, as illustrated with a light-red shadow in Figure 5.1. The width of the mask gradually increases in the faint regime to take into account photometric uncertainties. The shape of the outer isodensity lines still remains irregular in the deep imaging data as previously seen in our DECam data (Kim et al., 2015b), which lends support to the scenario that the observed irregularity reflects the true structure, rather than being a consequence of the limited depth of the previous photometry. Given such a small population of stars in the system, however, assessing the observed irregularity is always subject to small number statistics (see e.g. Martin et al., 2008; Walsh et al., 2008; Sand et al., 2010; Muñoz et al., 2012).

The central coordinates and structural parameters of Peg III were derived using the Maximum Likelihood (ML) routine as described in Kim et al. (2016) based on Martin et al. (2008) using our IMACS photometry catalog and the photometric filtering mask. The upper panels of Figure 5.4 show marginalized PDFs for key structural parameters. In this analysis, Peg III remains elliptical with $\epsilon = 0.38^{+0.22}_{-0.38}$ at a position angle of $\theta = 114^{+19}_{-17}$, but its half-light radius ($r_h = 53 \pm 14$ pc) appears $\sim 32\%$ smaller than the previous estimate ($r_h = 78^{+30}_{-24}$ pc; Kim et al., 2015b). Nevertheless the two values are consistent at
Figure 5.4 Upper panels: marginalized probability distribution functions (PDFs) of the structural parameters of Peg III. Lower panel: radial stellar density profile of Peg III. R is the elliptical radius. Overplotted are the best exponential model based on the parameters in Table 5.1 (dotted line), the contribution of foreground stars (dashed line) and the combined fit (solid line). The error bars were derived from Poisson statistics, i.e. $\sqrt{N/\text{arcmin}^2}$.

We further estimated the absolute luminosity of Peg III using the Dartmouth luminosity function (LF) for age 13.5 Gyr, [Fe/H]=−2.5 and [$\alpha$/Fe]=+0.4 with the mass function by Chabrier (2001) as follows. We first normalized the theoretical LF and multiplied with the photometric completeness function derived in Section 2. We note that the Dartmouth isochrone accounts for RGB and MS stars but not AGB/HB sequences. We then integrated the scaled LF in the magnitude range of $r_0 > 22.0$ mag to calculate the probability density for the number of detected RGB/MS stars fainter than $r_0 = 22$ mag in our IMACS photometry. Accordingly, we repeated the ML routine using the previous filtering mask but excluding the AGB/HB sequences and the RGB sequence brighter than $r_0 = 22.0$ mag to estimate the number of RGB/MS stars fainter than $r_0 = 22.0$ mag that belong to the overdensity $N$ with eq. (5) in Martin et al. (2008). The ratio of the star count $N$ to the probability density allowed us to scale the normalized LF to the observed level. Integrating the up-scaled LF estimates the integrated total luminosity of RGB/MS stars in Peg III as $M_r = -3.2^{+0.3}_{-0.4}$ or
Chapter 5 A PHOTOMETRIC AND SPECTROSCOPIC STUDY OF THE ULTRA-FAINT MILKY WAY SATELLITE PEGASUS III

Table 5.1. Properties of Peg III

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>α(_{J2000})</td>
<td>22 24 24.48</td>
<td>h m s</td>
</tr>
<tr>
<td>δ(_{J2000})</td>
<td>+05 24 18.0</td>
<td>° ′ ″</td>
</tr>
<tr>
<td>l</td>
<td>69.8452</td>
<td>deg</td>
</tr>
<tr>
<td>b</td>
<td>−41.8293</td>
<td>deg</td>
</tr>
<tr>
<td>(m − M)(_{0})</td>
<td>21.66 ± 0.12</td>
<td>mag</td>
</tr>
<tr>
<td>d(_{⊙})</td>
<td>215 ± 12</td>
<td>kpc</td>
</tr>
<tr>
<td>r(_{h})</td>
<td>0.85 ± 0.22</td>
<td>′</td>
</tr>
<tr>
<td>ε</td>
<td>0.38 ± 0.22</td>
<td></td>
</tr>
<tr>
<td>θ</td>
<td>114 ± 10</td>
<td>deg</td>
</tr>
<tr>
<td>M(_{V})</td>
<td>−3.4 ± 0.4</td>
<td>mag</td>
</tr>
<tr>
<td>L(_{V})</td>
<td>1960 ± 720</td>
<td>L(_{⊙})</td>
</tr>
<tr>
<td>(v(_{⊙}))</td>
<td>−222.9 ± 2.6</td>
<td>km s(^{-1})</td>
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<td>v(_{GSR})</td>
<td>−67.6</td>
<td>km s(^{-1})</td>
</tr>
<tr>
<td>σ(_{v})</td>
<td>5.4 ± 3.0</td>
<td>km s(^{-1})</td>
</tr>
<tr>
<td>M(_{1/2})</td>
<td>1.4 ± 3.0</td>
<td>10(^{6})M(_{⊙})</td>
</tr>
<tr>
<td>M/L(_{V})</td>
<td>1470 ± 5660</td>
<td>M(<em>{⊙}/L</em>{⊙})</td>
</tr>
</tbody>
</table>

\(M_V = -3.0^{+0.3}_{-0.4}\) by luminosity-weighted mean color \(V − r = 0.17\) mag for the model LF. Finally, we calculated the flux of AGB/HB candidate stars in the red and blue polygons presented in the lower left panel of Figure 5.1 using the transformation equation by Jordi et al. (2006) to convert their \(g\) and \(r\) magnitudes into \(V\) magnitudes. Their contribution increased the total luminosity in the \(V\) band by 0.4 mag and the uncertainty by 0.1 mag for upper (fainter) limit and by less than 0.1 mag for lower (brighter) limit. Therefore, we adopted \(M_V = −3.4 ± 0.4\) as our final estimate for the total luminosity of Peg III.

All the new estimates for the parameters are consistent with their previous estimates at the 1 \(σ\) level. The new values suggest that Peg III is somewhat smaller and fainter than previously estimated (Kim et al., 2015b). All resulting values presented in this and the next sections are summarized in Table 5.1.

5.5 Spectroscopy

The data were taken with the Keck II 10-m telescope and the DEIMOS spectrograph (Faber et al., 2003). One multislit mask was observed in Peg III on the night of July 17th 2015. We selected 30 targets based on their color-magnitude distribution and distances
from the center of the system using the DECam photometry from Kim et al. (2015b). We assigned priorities to potential RGB, AGB and HB stars selected to follow the best-fitting isochrone to the CMD of Peg III in the DECam data. We used the 1200 line mm$^{-1}$ grating that covers a wavelength range 6400 – 9100Å at the spectral resolution 1.37Å (FWHM, equivalent to 47 km s$^{-1}$ at the Ca II triplet). Slitlets were 0″7 wide. The total exposure time was 2.5 hours.
Table 5.2. Keck/DEIMOS target list

<table>
<thead>
<tr>
<th>Object</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>$(g - r)_0$</th>
<th>$r_0$</th>
<th>$v_\odot$</th>
<th>S/N</th>
<th>Membership</th>
<th>Photometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(deg)</td>
<td>(deg)</td>
<td>(mag)</td>
<td>(mag)</td>
<td>(km s$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>336.17139</td>
<td>5.38661</td>
<td>0.47</td>
<td>22.28</td>
<td>$-165.26 \pm 5.78$</td>
<td>1.89</td>
<td>N</td>
<td>IMACS</td>
</tr>
<tr>
<td>2</td>
<td>336.10198</td>
<td>5.38908</td>
<td>0.77</td>
<td>21.39</td>
<td>$-220.57 \pm 4.71$</td>
<td>5.04</td>
<td>Y</td>
<td>IMACS</td>
</tr>
<tr>
<td>3</td>
<td>336.08657</td>
<td>5.39344</td>
<td>-0.08</td>
<td>22.05</td>
<td>$-193.35 \pm 22.92$</td>
<td>1.43</td>
<td>?</td>
<td>IMACS</td>
</tr>
<tr>
<td>4</td>
<td>336.09530</td>
<td>5.39583</td>
<td>0.37</td>
<td>21.27</td>
<td>$-234.68 \pm 3.84$</td>
<td>4.32</td>
<td>Y</td>
<td>IMACS</td>
</tr>
<tr>
<td>5</td>
<td>336.11372</td>
<td>5.40772</td>
<td>0.49</td>
<td>20.88</td>
<td>$-218.51 \pm 3.64$</td>
<td>7.00</td>
<td>Y</td>
<td>IMACS</td>
</tr>
<tr>
<td>6</td>
<td>336.09952</td>
<td>5.41176</td>
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<td>21.07</td>
<td>$-226.16 \pm 5.04$</td>
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<tr>
<td>7</td>
<td>336.11021</td>
<td>5.41590</td>
<td>0.53</td>
<td>20.94</td>
<td>$-229.45 \pm 5.29$</td>
<td>6.56</td>
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</tr>
<tr>
<td>8</td>
<td>336.07514</td>
<td>5.41965</td>
<td>0.63</td>
<td>21.65</td>
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</tr>
<tr>
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<td>5.42197</td>
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<tr>
<td>10</td>
<td>336.10019</td>
<td>5.42418</td>
<td>0.68</td>
<td>21.07</td>
<td>$-218.26 \pm 3.56$</td>
<td>6.37</td>
<td>Y</td>
<td>IMACS</td>
</tr>
<tr>
<td>11</td>
<td>336.05841</td>
<td>5.43938</td>
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<td>21.71</td>
<td>$-260.11 \pm 9.97$</td>
<td>3.43</td>
<td>N</td>
<td>DECam</td>
</tr>
<tr>
<td>12</td>
<td>336.05740</td>
<td>5.45859</td>
<td>0.42</td>
<td>20.83</td>
<td>$-25.71 \pm 3.06$</td>
<td>6.13</td>
<td>N</td>
<td>IMACS</td>
</tr>
</tbody>
</table>
We reduced the data using a modified version of the DEIMOS spec2d software pipeline (Cooper et al., 2012; Newman et al., 2013). We refer the reader to Simon & Geha (2007) for a more detailed description of the radial velocity measurement method. We measured the spectra of 12 out of the 30 targets, and their median S/N per pixel ranged from 1.4 to 7.0.

The membership of the sample stars was determined based on radial velocity, position in the CMD and distance from the center of the dwarf galaxy. We identify seven secure members shown in red in Figure 1. An eighth member (shown in Figure 1 in orange) is 30 km s$^{-1}$ away from the systemic velocity, but also has very large velocity errors. This star has the colors of a horizontal branch member star, and may be a RR Lyrae star. We do not include this star in the calculations below.

The velocities for all the observed Peg III candidate members are presented in Table 2. We note that the color and magnitude of star #11 was taken from our previous DECam photometry as its PSF on the IMACS images in $g$ band was considerably affected by a saturated object nearby.

### 5.6 Metallicity

Given the low S/N of the spectra, we attempted to measure the spectra-averaged metallicity of the four brightest stars in our sample (#5,6,7,10) using the Ca II triplet lines. The measured strength of the spectral lines for RGB stars can be calibrated to metallicity [Fe/H] based on the empirical relationship between the equivalent width and the luminosity offset from the HB of the system $V_0 - V_{0,HB}$ (e.g., Starkenburg et al., 2010; Da Costa, 2016). The $g_0$ and $r_0$ magnitudes of the stars were converted into $V_0$ magnitudes using the (Jordi et al., 2006) Pop II transformation equations. We calculated the $V_0 - V_{0,HB}$ of the member stars based on the distance moduli for Peg III and M 15 in Section 3, for which we assumed the $V_{HB}$ for M 15 from Harris and E(B$-$V)=0.11 from Kraft & Ivans (2003). After smoothing the observed spectra with a 5-pixel boxcar using splot command in IRAF, we dealt with the spectra in two ways as follows. First, we add them all together in order to increase the S/N. The $\lambda 8542\AA$ and $\lambda 8662\AA$ Ca II line strengths were then measured using the procedure described in Da Costa (2016). The summed equivalent width $\sum W \approx 2.34 \AA$ and the average $V_0 - V_{0,HB} \approx -0.63$ mag give a reduced equivalent width $W'$ of 1.93 $\AA$. Applying the metallicity calibration with Equation (2) in Da Costa (2016) yields [Fe/H]=$-2.40$ dex with an uncertainty of order 0.15 dex. We then added the spectra for stars #6 and #10, and for #5 and #7 together separately. Repeating the above measurement process on these two spectra, we obtained $\sum W \approx 2.72 \AA$ with average $V_0 - V_{0,HB} \approx -0.74$ mag for stars #6 and #10, and $\sum W \approx 1.99 \AA$ with average $V_0 - V_{0,HB} \approx -0.51$ mag for stars #5 and #7. These values transform into [Fe/H]=$-2.24$
dex and \( [\text{Fe/H}] = -2.55 \) dex with uncertainties of order 0.15 dex, respectively. At face value, this is inconsistent with the CMD where the stars \#6 and \#10 appear \( \sim 0.2 \) mag bluer than stars \#5 and \#7 and so should be more metal poor. Stars \#6 and \#10 are, however, possibly AGB stars to which the calibration process strictly may not apply. It must also be kept in mind that the S/N of the summed spectra, even after smoothing, remains low. Nevertheless, this result confirms that Peg III includes stars with metallicity as low as \( [\text{Fe/H}] = -2.55 \pm 0.15 \) dex.

5.7 Kinematics

In order to characterize the kinematics of Peg III, we employed a simple “non-rotation” model based on the method of Drukier et al. (1998). This method assumes that the measured radial velocities have a Gaussian distribution with mean velocity \( \langle v_\odot \rangle \) and dispersion \( \sigma_v \). The likelihood of the \( i \)th measurement \( v_i \pm \delta_i \) is then given by

\[
L_i(v_i|\langle v_\odot \rangle, \sigma_v) = G(v_i|\langle v_\odot \rangle, \sqrt{\sigma_v^2 + \delta_i^2}),
\]

where \( G(x|\mu, \sigma) \) is a Gaussian function of \( x \) with the mean \( \mu \) and the standard deviation \( \sigma \). The likelihood for the available data set \( D \equiv \{v_i\}_{i=1}^N \) is the product of the individual likelihoods:

\[
L(D|\langle v_\odot \rangle, \sigma_v) = \prod_i L_i(v_i|\langle v_\odot \rangle, \sigma_v).
\]

Applying Bayes’s theorem leads to

\[
P(\langle v_\odot \rangle, \sigma_v|D) \propto L(D|\langle v_\odot \rangle, \sigma_v)P(\langle v_\odot \rangle, \sigma_v),
\]

where \( P(\langle v_\odot \rangle, \sigma_v|D) \) is the the posterior probability and \( P(\langle v_\odot \rangle, \sigma_v) \equiv P(\langle v_\odot \rangle)P(\sigma_v) \) is the prior. For the mean velocity, the appropriate prior is a uniform prior \( P(\langle v_\odot \rangle) = C \), for which we have set a finite range between \(-200 \) km s\(^{-1}\) and \(-245 \) km s\(^{-1}\) to make it normalizable. In the case of the velocity dispersion, the appropriate prior is the Jeffreys prior \( P(\sigma_v) \propto \sigma_v^{-1} \) (see, e.g., Drukier et al., 1998, 2007; Koposov et al., 2015b; Torrealba et al., 2016b), which is “non-informative” for a scale parameter such as the dispersion \( \sigma_v \) (see §VII of Jaynes, 1968, for justification). In fact, the choice of the prior has minimal impact on the posterior probability once the data are sufficiently constraining with a large sample size and small measurement errors. Otherwise, a uniform prior leads to a biased estimate.
Figure 5.5 Upper panel: two-dimensional posterior probability distribution for the mean velocity and velocity dispersion of Peg III. Contours outline the $1\sigma - 3\sigma$ confidence levels. In two dimensions, Gaussian densities within 1, 2, and 3$\sigma$ correspond to 39.3%, 86.5%, and 98.9%, respectively. Lower panels: corresponding marginalized PDFs (solid curves). The PDFs for a uniform prior on the velocity dispersion are overplotted for comparison (dotted curves). All the PDFs are normalized such that each PDF covers an equal probability density underneath. The dashed lines correspond to the modal values of the marginalized posterior PDFs. The circle and square with errorbars indicate the typical values and uncertainties determined by the method (a) and (b) in Section 7, respectively.

for a scale parameter (see, e.g., §3.8 of Gregory, 2005; Eriksen et al., 2008). Since the Jeffreys prior $P(\sigma_v) \propto \sigma_v^{-1}$ is also an improper prior, it requires reasonable bounds to turn into a proper prior such that the likelihood distribution is not significantly truncated (see, e.g., §3.3 in Drukier et al., 2007). We have set a finite interval for the prior $\sigma_v \in (1, 30)$ km s$^{-1}$, where the lower bound is $\sim 1/5$ of the typical error on our measurements. We note that the likelihood for $\sigma_v \in (0, 1)$ km s$^{-1}$ is equivalent to only 0.5% of that for $\sigma_v \in (0, 30)$ km s$^{-1}$. 

Figure 5.6 Mass-to-light ratio of Peg III (red) in comparison with other nearby galaxies within 1 Mpc. Mass-to-light ratios were calculated from the velocity dispersion, angular-sizes (half-light radii), heliocentric distances, and absolute magnitudes collected by McConnachie (2012) for consistency with our estimate for Peg III. For the objects given “symmetric” uncertainties on the parameters, the errorbars were determined based on the regular error propagation, and for the rest based on the upper and lower limits of the parameters.

The upper panel of Figure 5.5 shows the resulting posterior probability distribution in two dimensional (2D) space, which appears asymmetric, spreading out toward larger velocity dispersions, most likely due to the small sample size (see, e.g., Figure 2 in Walker et al., 2009). The lower panels show the corresponding marginalized PDFs (solid curves) and also the PDFs constructed with a uniform prior on the velocity dispersion for comparison (dotted curves). Noticeably, the uniform prior favors larger velocity dispersions and displaces the modal value by $+1.2$ km s$^{-1}$. When it comes to determining the typical values and related uncertainties of the parameters, two different methods are commonly used in the literature; (a) find the modal values of the marginalised PDFs and the values that correspond to 61% of the peak probability for the confidence interval (e.g. Martin et al., 2014) or (b) read the 16, 50, and 84 percentiles of the marginalized PDFs (e.g. Walker et al., 2015). The results from each method are: (a) $\langle v_\odot \rangle = -222.9 \pm 2.6$ km s$^{-1}$ and $\sigma_v = 5.4^{+3.0}_{-2.5}$ km s$^{-1}$, and (b) $\langle v_\odot \rangle = -222.8^{+3.0}_{-2.9}$ km s$^{-1}$ and $\sigma_v = 6.2^{+3.7}_{-2.7}$ km s$^{-1}$. We note that the inclusion of the ambiguous star#3 with $v_\odot = -193.35 \pm 22.92$ km s$^{-1}$ in our sample does not make a significant difference in the results as follows: (a) $\langle v_\odot \rangle = -222.5 \pm 2.6$ km s$^{-1}$ and $\sigma_v = 5.4^{+3.1}_{-2.4}$ km s$^{-1}$, and (b) $\langle v_\odot \rangle = -222.3^{+3.1}_{-2.9}$ km s$^{-1}$ and $\sigma_v = 6.3^{+3.8}_{-2.8}$ km s$^{-1}$. On the other hand, the exclusion of star #4 with $v_\odot = -234.68 \pm 3.84$ km s$^{-1}$ from our sample leads to an unresolved solution for the velocity dispersion, no matter which one of the above two priors is used. We noticed the same phenomenon in a test with
the member stars for Psc II reported by Kirby et al. (2015a); removing the star ID10694 with $v_\odot = -232.0 \pm 1.6$ km s$^{-1}$ causes an unresolved solution. In an experiment with the kinematic members of Segue 1 reported by Simon et al. (2011), we found that such an unresolved solution occurs in $\sim 50\%$ of the cases when 6 stars are randomly selected out of 32 stars having comparable measurement errors ($2 < \delta v < 7$ km s$^{-1}$) and Bayesian membership probabilities larger than 90%. This variation is even larger than the $1-\sigma$ uncertainty of the velocity dispersion and the influence of binary stars in the sample ($\sim 0.5$ km s$^{-1}$, see Figure 6 in Simon et al., 2011). This result therefore suggests that the unresolved solutions are most likely a consequence of the small sample size. We will adopt the values and uncertainties obtained from method (a) as our final estimates in Table 5.1 and throughout the text. It is interesting to note that the measured systemic velocity for Peg III is very similar to that found for its neighbouring satellite Psc II ($\langle v_\odot \rangle = -226.5 \pm 2.7$ km s$^{-1}$) independently measured by Kirby et al. (2015a).

Assuming dynamical equilibrium, the mass enclosed within the half-light radius of a stellar system can be accurately measured by the following equation as demonstrated by Wolf et al. (2010)

$$M_{1/2} \simeq \frac{4}{G} \sigma_v^2 r_h M_\odot,$$

(5.4)

where $\sigma_v$ is the line-of-sight velocity dispersion and $r_h$ is the 2-dimensional projected half-light radius. According to this relation, the mass within the elliptical half light radius of Peg III is estimated to be $M_{1/2} = 1.4^{+3.0}_{-1.1} \times 10^6 M_\odot$. The absolute magnitude of Peg III we derived in Section 4, translates into a total luminosity of $1960 \pm 720 L_\odot$, which corresponds to a mass-to-light ratio of $M/L_V = 1470^{+5600}_{-1210} M_\odot/L_\odot$. This value is consistent with the inverse correlation between luminosity and mass-to-light ratio for other nearby dwarf galaxies (see Figure 5.6).

### 5.8 Discussion and Summary

We have obtained Magellan/IMACS photometry and Keck/DEIMOS spectroscopy for Peg III. The deep photometry confirms that Peg III is a faint ($M_V = -3.4 \pm 0.4$), elongated ($\epsilon = 0.38^{+0.22}_{-0.32}$), irregular and distant ($d_\odot = 215 \pm 12$ kpc) stellar system. We measured radial velocities for individual candidate member stars and identified seven, possibly eight member stars in the system based on their radial velocities, where the member stars could be either red giants or AGB stars (red large dots in Figure 5.1). The stellar population of Peg III contains stars with metallicity as low as $[\text{Fe/H}] = -2.55 \pm 0.15$ dex. The velocity dispersion of Peg III ($\sigma_v = 5.4^{+3.0}_{-2.3}$ km s$^{-1}$) significantly exceeds the value expected from
its observed stellar mass alone \((<0.3 \text{ km s}^{-1});\) see Table 5 in Pawlowski et al., 2015), which supports the picture that Peg III is a satellite dwarf galaxy rather than a star cluster.

Peg III and Psc II are approximately 43 kpc away from each other in three dimensions (3D) and their radial velocities in the Galactic standard-of-rest (GSR) frame differ only by \(\sim10 \text{ km s}^{-1} (v_{\text{GSR}} = -67.6 \pm 2.6 \text{ km s}^{-1} \text{ for Peg III and } v_{\text{GSR}} = -79.9 \pm 2.7 \text{ km s}^{-1} \text{ for Psc II}).\) Given that only relatively few distant MW satellite galaxies are presently known, the close spatial proximity of Peg III and Psc II, and their very similar radial velocities, suggest a possible association between them. We note that another companionship of two distant MW satellites has been previously identified, namely the Leo IV - Leo V pair. Despite the difference in their radial velocities in the GSR frame \((\Delta v_{\text{GSR}} \sim 50 \text{ km s}^{-1})\) Simon & Geha, 2007; Belokurov et al., 2008, their close spatial proximity in 3D \((\Delta d_{\text{spatial}} \sim 22 \text{ kpc})\) has led to the hypothesis of a possible physical connection or common origin (e.g. de Jong et al., 2010). Such a companionship of two satellites, as Walker et al. (2009) suggested, may imply a rather circular orbit on which MW tides have a minimum effect. Assuming that the two satellites are currently a bound pair with an equal halo mass and follow a circular orbit on their average Galactocentric distance of \(\sim198 \pm 10 \text{ kpc},\) we have estimated their total halo mass following the method of Evslin (2014). This method estimates the mass of the binary satellite system on the basis of the Virial theorem using the difference in their line-of-sight velocities \((12.3\pm3.7 \text{ km s}^{-1})\) and the separation between its constituents \((d_{\text{spatial}} = 43 \pm 19 \text{ kpc})\) in 3D space. The derived mass of a satellite halo is \(2.3\pm1.7 \times 10^9 M_\odot,\) which yields a tidal radius of \(r_t = 16\pm4 \text{ kpc}.\) The ratio of the separation to the tidal radius is \(d_{\text{spatial}}/r_t = 2.7 \pm 1.0.\) At face value, the tidal radius is smaller than the separation, in which case the binding energy of the two satellites is too low to remain undisrupted in the MW tidal field. This result, however, does not entirely rule out the possibility of physical pair as the tidal radius is comparable to the separation at the 1.7\(\sigma\) level. Information about their tangential velocities and dark-matter halo profiles, as well as more accurate measurements for other parameters, would provide more constraints on this result.

In both our DECam and IMACS photometry, Peg III appears irregular and elongated \((\epsilon=0.38^{+0.22}_{-0.38})\) at 1-\(\sigma\) limit, compared to Psc II that only has an upper limit for its measured ellipticity \((\epsilon < 0.28;\) Sand et al., 2012) with an unconstrained position angle. In fact, a similarity is found with the Leo IV - V pair (see Table 7 in Sand et al., 2012), where Leo V features larger ellipticity \((\epsilon=0.55 \pm 0.22)\) with an unconstrained position angle and lower luminosity \((M_V = -4.4 \pm 0.4)\) than Leo IV \((\epsilon < 0.23, M_V = -5.5 \pm 0.3).\) We consider three possible scenarios for the origin of the ellipticity of Peg III. The first is that it is simply a result of its formation process. The second is that it results from tidal interaction with the Milky Way. Under the assumption that the stars of Peg III are in dynamic equilibrium this seems unlikely, given a) the large velocity dispersion implying a substantial mass,
b) the compact physical size, c) the elongation misaligned with the direction toward the Galactic center, and d) the likelihood that Peg III and Psc II are moving on similar circular or near circular orbits at large Galactocentric distances. On the other hand, if the large velocity dispersion of the Peg III stars reflects a non-equilibrium state or being inflated by unresolved binary stars rather than the presence of a large amount of dark matter, then the system might be a remnant of a dwarf galaxy tidally disrupted by the Milky Way. This would require the orbit of Peg III to be significantly eccentric in order to reach the required smaller Galactocentric distances. In turn, this would make the spatial and velocity agreement with Psc II coincidental, which seems highly unlikely. The third alternative is that the ellipticity of Peg III results from a tidal interaction with Psc II. To test these different ideas will require N-body simulations or full 3D orbit information (i.e. the radial velocities and proper motions of the objects). Much deeper and wider imaging or higher resolution spectroscopy with new forthcoming telescopes such the Wide-Field Infrared Survey Telescope (WFIRST) and the Giant Magellan Telescope (GMT) may provide crucial keys to these questions.
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CHAPTER 6

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


Abstract

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

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

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

In this chapter we report the discovery of a new ultra-faint MW satellite galaxy candidate found in the DES Y1A1 data. We note that this object Horologium II (Hor II) does not

$^1$We note that the satellite reported as Indus I by Koposov et al. (2015a) and as DES J2108.8-5109 by Bechtol et al. (2015) is identical to Kim 2 that was discovered earlier by Kim et al. (2015a).
correspond to any object in the previous studies by Koposov et al. (2015a) and Bechtol et al. (2015) or in catalogs including the NASA/IPAC Extragalactic Database and SIMBAD.

6.2 Data Reduction and Discovery

DES is a deep photometric survey using the wide-field (∼ 3 square degree) Dark Energy Camera (DECam) imager that consists of 62 2k × 4k CCD chips installed at the 4-m Blanco Telescope located at Cerro Tololo Inter-American Observatory (CTIO). DES started operation in August 2013 and will cover ∼ 5000 square degrees of the Southern Sky in the vicinity of the Magellanic Clouds in five photometric bands (grizY) over five years. The data used in this paper is its first year public data set, DESDM Y1A1, collected between August 2013 and February 2014 over approximately 1800 square degrees and released to the public by the NOAO Science archive after a one year proprietary period. This data set includes individual images and corresponding weight-maps processed by the DES data management (DESDM) pipeline. Each image is a 90s single exposure. The instCal images we used for our analysis are bias, dark and flat-field corrected and contain the world coordinate system provided by the DESDM image processing pipeline (see Desai et al., 2012; Mohr et al., 2012, for more details).

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

We then applied our overdensity detection algorithm to the star catalogs to search for MW satellites. Briefly, this algorithm, following the approach by Walsh et al. (2009), involves a photometric filtering process in which an isochrone mask is applied to select a single
Table 6.1. Properties of Horologium II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$\alpha_{J2000}$</td>
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<td>h m s</td>
</tr>
<tr>
<td>$\delta_{J2000}$</td>
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<td>$^\circ$ $^\prime$ $^\prime\prime$</td>
</tr>
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<td>deg</td>
</tr>
<tr>
<td>$b$</td>
<td>-54.137</td>
<td>deg</td>
</tr>
<tr>
<td>$(m - M)$</td>
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<td>mag</td>
</tr>
<tr>
<td>$d_\circ$</td>
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<td>kpc</td>
</tr>
<tr>
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</tr>
<tr>
<td>$\epsilon$</td>
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<td>a pc</td>
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<tr>
<td>$\theta$</td>
<td>127 $^{\pm}11$</td>
<td>deg</td>
</tr>
<tr>
<td>$M_V$</td>
<td>$^{2.6}_{-0.3}$$^{+0.2a}$</td>
<td>mag</td>
</tr>
</tbody>
</table>

$^a$ Adopting a distance of 78 kpc

age/metallicity stellar population at a fixed distance modulus. The density map generated from the selected stars is then convolved with a Gaussian kernel. The significance of local stellar overdensities is measured by comparing their signal-to-noise ratios to the smoothed density map. These steps are repeated shifting the isochrone mask over a range of distance moduli. The detection process is described in more details in Kim & Jerjen (2015). As part of this photometric analysis of the entire 1800 sqrd deg of gr images of the Y1A1 data set, we successfully recovered all the UFD candidates reported by Koposov et al. (2015a) and Bechtol et al. (2015); e.g. Phoenix II (17$\sigma$), Pictoris I (13$\sigma$), Tucana II (11$\sigma$), Eridanus III (10$\sigma$), and Grus I (9$\sigma$). We also found one additional MW satellite candidate in the constellation of Horologium. This new object, Horologium II, was initially detected at the 7-8$\sigma$ significance levels in two separate, but overlapping DECam images. To fill the CCD chip gaps, we combined the photometric catalogs of the two frames and removed duplicates with 1$''$0 tolerance. HorII was then recovered with a significance of 10$\sigma$.

The upper panel of Figure 6.1 presents the density contour map of HorII, made from stars passing the isochrone filter. HorII appears elongated but well defined by high level density contours (> 3$\sigma$). The lower panel shows the corresponding contour map of non-stellar objects in the same field of view.
Figure 6.1 Upper panel: Smoothed density contour map of candidate stars, selected by the photometric filter with a PARSEC isochrone of 13.5 Gyr and [Fe/H] = −2.1 (Bressan et al., 2012) shifted to the distance modulus $(m - M) = 21.56$ magnitudes, centred on Hor II in the $42 \times 42$ square arcmin window. The contours represent the stellar density in units of the standard deviation above the background level. Lower panel: Same as the upper panel but for non-stellar objects, showing no overdensity consistent with Hor II in the upper panel.
Figure 6.2 DECam view of Hor II. Upper panel: distribution of all stars in a 25′ × 25′ field centred on Hor II. The blue and green dots mark the two BHB candidates falling into the blue box in the next panel. The ellipses mark elliptical radii of 6.3′ (∼3r_h), 12.6′ (∼6r_h) and 14.1′ respectively. The red rectangles mark the locations of residual CCD chip gap where none of DES Y1A1 images covers. Lower left panel: CMD of stars lying in the inner ellipse. Overplotted is the best-fitting PARSEC (red dashed lines) isochrone of age 13.5 Gyr and [Fe/H] = -2.1 shifted to the distance modulus of (m - M) = 19.46. Within the isochrone mask (red solid lines) based on photometric uncertainties, there are candidate stars consistently aligned with the isochrone from the RGB to the main sequence turn-off. The two BHB candidates are colored and correspond to those in the Upper panel. Lower middle panel: control CMD of stars falling in the annulus between the two outer ellipses but covering the same on-sky area as in the lower left panel. Lower right panel: differential Hess diagram, the inner CMD minus the control CMD, which exhibits clear excess at the RGB and the main sequence turn-off.
Figure 6.3 Left panels: marginalized probability distribution functions for the the ellipticity ($\epsilon$), the position angle ($\theta$), they half-light radius ($r_h$) and the number of stars in the system for our photometric selection ($N$). The dashed lines mark the modes of the distributions. Right panel: radial density profile of Hor II, constructed on the mode values of each parameter as a function of elliptical radius $R_e$. The error of each data point is based on Poisson statistics, i.e. $\sqrt{N}/\text{arcmin}^2$. The dotted line marks the best-fit exponential model, the dashed line the foreground level and the solid line the combined fit.
6.3 Candidate Properties

The upper panel of Figure 6.2 shows the distribution of all stellar objects in our photometric catalogs within a 25.0′ × 25.0′ window centred on Hor II. The small red rectangles indicate the six locations of residual CCD chip gaps where the two DES images provided no data. In the lower left panel, we present the color-magnitude diagram (CMD) for the stars in the inner circle shown in the upper panel, equal to the dashed circle in the upper panel of Figure 6.1. Overplotted is the PARSEC isochrone (Bressan et al., 2012) of 13.5 Gyr and [Fe/H]=−2.1 shifted to the distance modulus of \((m−M) = 19.46 \pm 0.20\) or a heliocentric distance of 78 ± 8 kpc. Compared to the control CMD established in the same manner as in Belokurov et al. (2006) shown in the lower middle panel, the stars in the vicinity of Hor II consistently trace the old and metal-poor stellar population from the red-giant branch (RGB) down to the main-sequence turn off. Hor II also hosts two potential blue horizontal branch (BHB) stars.

We derived the structural parameters of Hor II using a Maximum Likelihood (ML) algorithm similar to the one described in Martin et al. (2008). The resulting marginalized pdfs for the structural parameters are presented in the left panels of Figure 6.3. The right panel shows the radial density profile with the best-fit exponential profile based on the best parameters; an ellipticity of \(\epsilon = 0.52\), a position angle of \(\theta = 127^\circ\) and a half-light radius of \(r_h = 2.09\). Adopting the heliocentric distance of 78 kpc, the ML-estimated physical size of Hor II is \(r_h = 47 \pm 10 \text{ pc}\).

The total luminosity of Hor II is estimated as follows. Briefly, we use the total number of member stars \(N\) above the photometric threshold \((r_0 \sim 23.5 \text{ mag})\) and its associated uncertainty derived from the ML algorithm run. We then integrate a normalised theoretical luminosity function as a probability density function of magnitude, by the same magnitude limit and use the ratio of the number \(N\) to the probability density to scale the luminosity function up to the observed level. Integrating the scaled luminosity function inclusive of missing flux below the threshold gives the absolute luminosity of Hor II. Using the PARSEC isochrone of 13.5 Gyr and [Fe/H]=−2.1 based on the initial mass function by Kroupa (2001), we obtain \(M_r \sim −2.74\) or \(M_V \sim −2.57\) by the luminosity weighted mean color \(V − r = 0.17\) of the isochrone. We adopt a total luminosity of \(M_V = −2.6^{+0.2}_{−0.3}\) as our final estimate where its uncertainty is derived from the star counts \(N\). All the resulting parameters are summarised in Table 6.1. We note that a heliocentric distance of 78 kpc was assumed in the calculation of physical size and total luminosity, to which the uncertainty on distance was not propagated.
6.4 Discussion and Conclusion

We analysed the first instalment (Y1A1) of the Dark Energy Survey gr imaging data to search for MW satellites, where we recovered all the previously reported systems and also found a new satellite candidate in the constellation of Horologium. The new MW satellite candidate Hor II appears faint ($M_V = -2.6^{+0.2}_{-0.3}$), elongated ($\epsilon = 0.52^{+0.13}_{-0.17}$) and rather extended ($r_h = 47 \pm 10$ pc). On the size luminosity plane, Hor II is placed in the realm of UFDs close to Boötes II. It also features a typically old ($\sim 13.5\text{Gyr}$) and metal-poor ([Fe/H] $\sim -2.1$) stellar population. The best isochrone fit yields a heliocentric distance of $78 \pm 8$ kpc, which is the same as that of a recently discovered neighbour in the DES Y1A1 coverage, Hor I. Compared to the new satellite candidate, Hor I is about twice as luminous ($M_V = -3.4 \pm 0.3$), smaller ($r_h = 30^{+4.4}_{-3.3}$ pc) and more round ($\epsilon < 0.28$), consequently being placed in the somewhat ambiguous region on the size-luminosity plane where UFDs and extended globular clusters overlap (Koposov et al., 2015a). A recent spectroscopic study by Koposov et al. (2015b) has revealed that the dynamical mass-to-light ratio of Hor I reaches $M/L_V = 570^{+1154}_{-112}$ and confirmed that that system is indeed an UFD, possibly (once) associated with the LMC. The pair of UFDs, Hor I and II, are only $\sim 7$ degrees away from each other on the sky, have identical distances and are well aligned with the Vast Polar Structure (Pawlowski et al., 2015). Such UFD pairs have been reported for quite some time e.g. Boötes I - II (Walsh et al., 2007), Leo IV - V (Belokurov et al., 2008) and Pisces II - Pegasus III (Kim et al., 2015b). The tentative link between Hor I and II can be extended further to the Sculptor dwarf spheroidal ($d_\odot \sim 82$ kpc, Weisz et al., 2014) and the UFD Eridanus III ($d_\odot = 87 \pm 8$ kpc). As Sculptor is moving on a retrograde orbit within the Vast Polar Structure when compared to the other classical MW satellite galaxies in the vicinity, including the Magellanic coulds, the hypothesis of a common origin can be tested once proper motion measurements become available. Nevertheless, this alignment is already suggestive of a “layer” of outer halo UFDs parallel to the Magellanic Clouds, possibly associated to the most luminous Sculptor dwarf. Indeed, there is one more object nearby, namely Phe II, that also shares the same distance.
Hunter, J. D. 2007, Computing in Science and Engineering, 9, 90
Jerjen, H. 2010, Advances in Astronomy, 2010, 434390

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CHAPTER 7

DISCOVERY OF A FAINT OUTER HALO MILKY WAY STAR CLUSTER IN THE SOUTHERN SKY


Abstract

We report the discovery of a new, low luminosity star cluster in the outer halo of the Milky Way. High quality $gr$ photometry is presented, from which a color-magnitude diagram is constructed, and estimates of age, [Fe/H], [$\alpha$/Fe], and distance are derived. The star cluster, which we designate as Kim 2, lies at a heliocentric distance of $\sim 105$ kpc. With a half-light radius of $\sim 12.8$ pc and ellipticity of $\epsilon \sim 0.12$, it shares the properties of outer halo GCs, except for the higher metallicity ([Fe/H] $\sim -1.0$) and lower luminosity ($M_V \sim -1.5$). These parameters are similar to those for the globular cluster AM 4, that is considered to be associated with the Sagittarius dwarf spheroidal galaxy. We find evidence of dynamical mass segregation and the presence of extra-tidal stars that suggests Kim 2 is most likely a star cluster. Spectroscopic observations for radial-velocity membership and chemical abundance measurements are needed to further understand the nature of the object.

7.1 Introduction

Globular clusters in the outer halo of the Milky Way (MW) hold important clues to the formation and structure of their host galaxy. Most of these rare distant globular clusters
Chapter 7 DISCOVERY OF A FAINT OUTER HALO MILKY WAY STAR CLUSTER IN THE SOUTHERN SKY

exhibit anomalously red horizontal branch morphology at given metal abundance (Lee et al., 1994), and belong to the so-called “young halo” system (Zinn, 1993a). Young halo objects are hypothesized to have formed in external dwarf galaxies that were accreted into the Galactic potential well and disrupted by the Galactic tidal force (Searle & Zinn, 1978). This scenario has received considerable support by observational results from the MW and M31 (Da Costa & Armandroff, 1995; Marín-Franch et al., 2009; Mackey & Gilmore, 2004; Mackey et al., 2010). Indeed, the young halo clusters resemble the globular clusters located in dwarf galaxies associated with the Milky Way in terms of horizontal branch type (Zinn, 1993b; Smith et al., 1998; Johnson et al., 1999; Harbeck et al., 2001) and other properties such as luminosity, age, and chemical abundance (Da Costa, 2003).

Despite the significant contribution of modern imaging surveys like the Sloan Digital Sky Survey (Ahn et al., 2014) to the discoveries of new Milky Way satellite galaxies (e.g. Willman et al., 2005; Belokurov et al., 2007; Irwin et al., 2007; Walsh et al., 2007) and extended substructures (e.g. Newberg et al., 2003; Grillmair, 2009), only a small number of star clusters have been discovered (Koposov et al., 2007; Belokurov et al., 2010; Balbinot et al., 2013; Kim & Jerjen, 2015), and these are typically located in the inner halo of the Milky Way. A new distant MW halo object at 145 kpc, by the name of PSO J174.0675-10.8774, or Crater, was recently discovered simultaneously in two independent surveys (Laevens et al., 2014; Belokurov et al., 2014). Although this stellar system shares the structural properties of globular clusters in the outer halo of the Galaxy, confirming its true nature still requires additional investigation. Other than PSO J174.0675-10.8774, only six known Milky Way GCs are located at Galactocentric distances larger than 50 kpc, namely AM 1, Eridanus, NGC 2419, Palomar 3, 4, and 14 (see Table 7.1). The Hubble Space Telescope Advanced Camera for Survey photometry of the Galactic GCs (Sarajedini et al., 2007; Dotter et al., 2011) has confirmed that all of the outer halo GCs except for NGC 2419 have a red horizontal branch and young ages relative to the inner halo GCs (Dotter et al., 2010).

In this chapter, we report the discovery of a distant globular cluster in the constellation of Indus. This object was first detected in our on-going southern sky blind survey with the Dark Energy Camera (DECam) at the 4 m Blanco Telescope at Cerro Tololo Inter-American Observatory (CTIO) and confirmed with deep GMOS-S images at the 8.1 m Gemini-South telescope on Cerro Pachón, Chile (Section 2 & 3). The new star cluster, which we designate as Kim2, is at a distance $D_0 \sim 105$ kpc and has a low luminosity of only $M_V \sim -1.5$ and a metallicity of $[\text{Fe/H}] \approx -1.0$, slightly higher than the other young halo clusters (Section 4). In section 5 we discuss the implication of these properties, present evidence for mass segregation in the cluster and discuss its possible origin.
Table 7.1. Properties of the seven most distant Galactic globular clusters known.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AM 1</th>
<th>Pal 3</th>
<th>Pal 4</th>
<th>Pal 14</th>
<th>Eridanus</th>
<th>NGC2419</th>
<th>PSO J174.0675-10.8774a</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{J2000}$</td>
<td>03 55 02.3</td>
<td>10 05 31.9</td>
<td>11 29 16.8</td>
<td>16 11 00.6</td>
<td>04 24 44.5</td>
<td>07 38 08.4</td>
<td>11 36 16.2</td>
<td>h:m:s</td>
</tr>
<tr>
<td>$\delta_{J2000}$</td>
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<td>+00 04 18</td>
<td>+28 58 25</td>
<td>+14 57 28</td>
<td>-21 11 13</td>
<td>+38 52 57</td>
<td>-10 52 39</td>
<td>$^\circ$, ', :</td>
</tr>
<tr>
<td>$l$</td>
<td>258.34</td>
<td>240.15</td>
<td>202.31</td>
<td>28.74</td>
<td>218.10</td>
<td>180.37</td>
<td>274.8</td>
<td>deg</td>
</tr>
<tr>
<td>$b$</td>
<td>-48.47</td>
<td>+41.86</td>
<td>+71.80</td>
<td>+42.19</td>
<td>-41.33</td>
<td>+25.24</td>
<td>+47.8</td>
<td>deg</td>
</tr>
<tr>
<td>$D_{\odot}$</td>
<td>123.3</td>
<td>92.5</td>
<td>108.7</td>
<td>76.5</td>
<td>90.1</td>
<td>82.6</td>
<td>145</td>
<td>kpc</td>
</tr>
<tr>
<td>$D_{gc}$</td>
<td>124.6</td>
<td>95.7</td>
<td>111.2</td>
<td>71.6</td>
<td>95.0</td>
<td>89.9</td>
<td>145</td>
<td>kpc</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>-1.70</td>
<td>-1.63</td>
<td>-1.41</td>
<td>-1.62</td>
<td>-1.43</td>
<td>-2.15</td>
<td>-1.9</td>
<td>dex</td>
</tr>
<tr>
<td>$r_{h}(\text{Plummer})$</td>
<td>15.2</td>
<td>18.0</td>
<td>16.6</td>
<td>28.0</td>
<td>12.4</td>
<td>22.1</td>
<td>22</td>
<td>pc</td>
</tr>
<tr>
<td>$M_{tot,V}$</td>
<td>-4.73</td>
<td>-5.69</td>
<td>-6.01</td>
<td>-4.80</td>
<td>-5.13</td>
<td>-9.42</td>
<td>-4.3</td>
<td>mag</td>
</tr>
</tbody>
</table>


aPSOJ174.0675-10.8774 is not yet unambiguously confirmed as a globular cluster.
Table 7.2. GMOS observing log for the images used in the analysis

<table>
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<tr>
<th>Filter</th>
<th>UT Date</th>
<th>Exposure</th>
<th>Seeing</th>
<th>Airmass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g$</td>
<td>Sep 20 2014</td>
<td>9 $\times$ 292s</td>
<td>0$''$6 - 0$''$9</td>
<td>1.08 - 1.12</td>
</tr>
<tr>
<td>$r$</td>
<td>Oct 29 2014</td>
<td>9 $\times$ 292s</td>
<td>0$''$8 - 0$''$9</td>
<td>1.23 - 1.42</td>
</tr>
</tbody>
</table>

7.2 Discovery

As part of the Stromlo Milky Way Satellite Survey\(^1\) we collected imaging data for $\sim$ 500 sqr deg with the DECam at the 4 m Blanco telescope at CTIO over three photometric nights from 17\(^{th}\) to 19\(^{th}\) July 2014. DECam is an array of sixty-two 2k$\times$4k CCD detectors with a 2.2 deg\(^2\) field of view and a pixel scale of 0$''$27(unbinned). We obtained a series of 3 $\times$ 40 s dithered exposures in the $g$ and $r$ band under photometric conditions. The average seeing was 1$''$0 for both filters each night. The stacked images were reduced via the DECam community pipeline (Valdes et al., 2014). We used WeightWatcher (Marmo & Bertin, 2008) for weight map combination and SExtractor (Bertin & Arnouts, 1996) for source detection and photometry. Sources were morphologically classified as stellar or non-stellar objects. For the photometric calibration, we regularly observed Stripe 82\(^2\) of the Sloan Digital Sky Survey throughout the three nights with 50 s single exposures in each band. To determine zero points and color terms, we matched our instrumental magnitudes with the Stripe 82 stellar catalog to a depth of $\sim$ 23 mag and fit the following equations:

\[
\begin{align*}
g &= g_{\text{instr}} + zp_g + c_g(g_{\text{instr}} - r_{\text{instr}}) - k_g X \tag{7.1} \\
r &= r_{\text{instr}} + zp_r + c_r(g_{\text{instr}} - r_{\text{instr}}) - k_r X \tag{7.2}
\end{align*}
\]

where $zp_g$ and $zp_r$ are the zero points, $c_g$ and $c_r$ are the respective color terms, $k_g$ and $k_r$ are the first order extinctions, and $X$ is the mean airmass.

In the Stripe 82 images we observed right after the Kim 2 field, we found 399 stars with 19 < $r$ < 23 and 0.0 < $g - r$ < 2.0 in the identical CCD chip where the cluster was detected. We restricted the calibration to stars fainter than $r = 19$ mag to avoid the saturation limit of our DECam data. We determined the zero points, color terms and associated uncertainties by bootstrapping with replacements performed 1000 times and

\(^1\)http://www.mso.anu.edu.au/~jerjen/SMS_Survey.html
\(^2\)http://cas.sdss.org/stripe82/en/
Figure 7.1 $4 \times 4$ arcmin$^2$ GMOS cutout g-band image of Kim 2. The cluster is located at the centre of the image. North is up, east is to the left.

using a linear least-squares fit with 3-sigma clipping rejection. Uncertainties in the zero points were measured 0.013 mag in $g$ and 0.010 in $r$, whereas uncertainties in the color terms are 0.011 and 0.009, respectively. The most recent extinction values $k_g$ and $k_r$ for CTIO were obtained from the Dark Energy Survey team. We calibrated our DECam photometry of the Kim 2 field using these coefficients and corrected for exposure time differences.

We employ the same detection algorithm as described in Kim & Jerjen (2015) to search the photometry catalog for stellar overdensities. In essence, we apply a photometric filter in color-magnitude space adopting isochrone masks based on the Dartmouth stellar evolution models (Dotter et al., 2008) to enhance the presence of old and metal-poor stellar populations relative to the Milky Way foreground stars. We then bin the R.A., decl. positions of the stars and convolve the 2-D histogram with a Gaussian kernel. The statistical significance of potential overdensities is measured by comparing their signal to noise ratios (S/Ns) on the density map to those of random clustering in the residual Galactic foreground. This process is repeated for different bin sizes and Gaussian kernels by shifting the isochrone masks over a range of distance moduli ($m - M$) from 16 to 22 magnitudes. We detected the new stellar overdensity with a significance of $\sim 8 \sigma$ relative to the Poisson noise of the Galactic foreground stars. This object that we chose to call Kim 2 was found at 21h08m49.97s, −51d09m48.6s (J2000) in the constellation of Indus.
Chapter 7 DISCOVERY OF A FAINT OUTER HALO MILKY WAY STAR CLUSTER IN THE SOUTHERN SKY

7.3 Follow-up Observations and Data Reduction

To investigate the nature of Kim 2, deep follow-up observations were obtained with the Gemini Multi-Object Spectrograph in imaging mode at the 8.1 m Gemini-South telescope through director’s time (GS-2014B-DD-3) on Sep 20, 21, 22, 30 and Oct 29. Since June 2014, GMOS-S is equipped with a new array of three 2048 \times 4176 \text{ pixel}^2 \text{ Hamamatsu CCDs with a 5.5'} \times 5.5' \text{ field of view and a pixel scale of } 0.08' (\text{unbinned}). To reduce readout time, we employed $2 \times 2$ binning, resulting in a plate scale of $0.16' \text{ pixel}^{-1}$. A series of $17 \times 292$ s dithered exposures in $g'$ and $19 \times 292$ in $r'$ band were observed. These $g'$ and $r'$ filters are similar, but not identical, to the $g$ and $r$ filters used by the SDSS. We chose the nine best images in each band for our photometric analysis. A summary of the selected observations is presented in Table 7.2.

We employed the latest Gemini IRAF package V1.13 (commissioning release)\textsuperscript{3} for data reduction. We applied bias and flat-field images provided by the Gemini science archive for standard GMOS baseline calibration to each exposure using the GIREDUCE task. The three CCD frames of each reduced image were then mosaicked into a single frame using the GMOSAIC task. Figure 7.1 shows a cut out at the centre of a deep $g'$ band image, formed by combining the nine individual mosaicked frames of the passband using the IMCOADD task, in which Kim 2 is visible as a concentration of faint stars.

The photometry of the reduced GMOS images was carried out using the software package kitchen\textunderscore sync presented in Anderson et al. (2008) and modified to work with GMOS-S data. It exploits two distinct methods to measure bright and faint stars. Astrometric and photometric measurements of bright stars have been performed in each mosaicked image, independently, by using appropriate point-spread function (PSF) model, and later combined. To derive the PSF models, we adapted to our data the software as described in (Anderson et al., 2006, see also Bellini et al. 2010). Briefly, we used the most isolated, bright and non-saturated stars in each image to determine a grid of four empirical PSFs. To account for the spatial variation of the PSF across the field of view, we assumed that to each pixel of the image corresponds a PSF that is a bi-linear weighted interpolation of the closest four PSFs of the grid.

Furthermore, the flux and position can also be determined by fitting for each star simultaneously all the pixels in all the exposures. This approach works better for very faint stars, which can not be robustly measured in every individual exposure. We refer the reader to the papers by Anderson et al. (2006) and Anderson et al. (2008) for further details.

\textsuperscript{3}http://www.gemini.edu/node/12227
We then conducted the photometric calibration using 65 stars with $22 < r < 25$ and $0.0 < g - r < 2.0$ we found in the field of view of GMOS. Comparing their instrumental magnitudes to the calibrated magnitudes of our DECam photometry in Section 2, we derived a calibration equation composed of a photometric zero point and a color term from bootstrapping the data 1000 times and performing a least-square fit with 3-sigma clipping rejection. Uncertainties in the zero points are 0.022 mag in the $g$ band and 0.023 mag in $r$. Uncertainties in the color terms are 0.020 and 0.019, respectively.

We performed artificial star tests to determine the completeness level of our photometry. To do this we used the recipe and the software described in detail by Anderson et al. (2008). Briefly, we first generated an input list of artificial stars and placed along the fiducial line of the MS and the RGB of Kim 2, which we have derived by hand. The list includes the coordinates of the stars in the reference frame and the magnitudes in $g$ and $r$ bands. Artificial stars have been placed in each image according to the overall cluster distribution as in Milone et al. (2009).

For each star in the input list, the software by Anderson et al. (2008) adds, in each image, a star with appropriate flux and position and measures it by using the same procedure as for real stars. An artificial star is considered to be detected when the input and the output position differ by less then 0.5 pixel and the input and the output flux by less than 0.75 mag.

The software provides for artificial stars the same diagnostics of the photometric quality as for real star. We applied the same procedure used for real stars to select a sub-sample.
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Figure 7.3 GMOS view of Kim 2. Left panel: Distribution of all objects classified as stars in $2'0 \times 2'0$ field centred on the cluster. The circles mark a radius of $1'3 (\sim 3r_h)$ and $1'8$. Middle panel: CMD of all stars within the inner-most circle marked on the left panel, dominated by the members of the star cluster. Right panel: Comparison CMD of all stars between the inner and the outer circles, showing the foreground stars. The dotted lines mark the 50% completeness level of our photometry. The two best-fitting Dartmouth isochrones with 11.5 Gyr, $[\text{Fe/H}]= -1.0$, $[\alpha/\text{H}]= +0.2$ (solid line), and with 8.0 Gyr, $[\text{Fe/H}]= -0.9$, $[\alpha/\text{H}]= +0.4$ (dashed line) are overplotted at a distance of 105 kpc and 98 kpc, respectively.

of stars with small astrometric errors, and well fitted by the PSF. Figure 7.2 shows the recovery rate of the input stars as a function of the stellar magnitude and the radial distance from the cluster center.

To address the effect of crowding, we measured the completeness not only as a function of the stellar magnitude but also the distance from the cluster center. For the latter, we divided the GMOS field into five concentric annuli, in each of which we measured the completeness in seven magnitude bins, in the interval $-14 < g, r_{\text{instr}} < -5$. Interpolating the recovery rate of the input stars at each of these $7 \times 5$ grid points allows us to estimate the completeness of any star at any position within the cluster as shown in Figure 7.2.

7.4 Candidate Properties

7.4.1 Color-Magnitude Diagram

The left panel of Figure 7.3 shows the RA-Dec distribution of all objects classified as point source by our GMOS photometry centred on Kim 2. The middle panel of Figure 7.3 shows the extinction-corrected CMD of all stars located within $1'3 (\sim 3r_h)$ from the overdensity center. All magnitudes are individually corrected for Galactic reddening by the Schlegel
et al. (1998) maps and the extinction coefficients of Schlafly & Finkbeiner (2011). In Table 7.3, we present our GMOS photometry of all stars brighter than the 50% completeness level, the dotted line in the middle panel of Figure 7.3. For comparison, the right panel shows the CMD of stars in an equal area between the radii $1\,\prime3$ and $1\,\prime8$, the majority of which are expected to be MW field stars.

The subgiant branch and the red giant branch (RGB) of this loose and faint cluster is almost absent, and no hints of an horizontal branch or red giant clump are visible. The main sequence (MS) however is well defined down to $r_0 \approx 26.5$, below which our photometry is affected by incompleteness. There are four possible subgiant branch and MS turn-off stars (red dots in Figure 7.3) consistent with the location of a main-sequence that runs from $r_0 \sim 23.5\,\text{mag}$ down to $26.5\,\text{mag}$. The stars labelled #1 and #2 have small angular distances from the nominal cluster center (see left panel of Figure 7.3). This supports the idea that they are cluster members. If true, we would observe a lack of stars between star #1 and the brightest main sequence stars. Such a gap in the luminosity function is uncommon but not unheard of, for example in Segue 3 (see Fig.2 in Fadely et al., 2011). Overplotted on our CMD are two theoretical isochrones from the Dartmouth data base. They will be discussed in the next section.
Table 7.3. GMOS photometry for stars within 3 $r_h$ from the center of Kim 2

<table>
<thead>
<tr>
<th>$\alpha$ (J2000)</th>
<th>$\delta$ (J2000)</th>
<th>Radial Distance</th>
<th>$r$ (mag)</th>
<th>$g - r$ (mag)</th>
<th>$\alpha$ (J2000)</th>
<th>$\delta$ (J2000)</th>
<th>Radial Distance</th>
<th>$r$ (mag)</th>
<th>$g - r$ (mag)</th>
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<tr>
<td>(h : m : s)</td>
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<td>(mag)</td>
<td>(mag)</td>
<td>(h : m : s)</td>
<td>($^\circ$ : ' : '')</td>
<td>('')</td>
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<td>(mag)</td>
</tr>
<tr>
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<td>24.16</td>
<td>0.37</td>
<td>21:08:46.11</td>
<td>-51:09:52.80</td>
<td>0.608</td>
<td>24.86</td>
<td>1.18</td>
</tr>
<tr>
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<td>0.618</td>
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<td>1.52</td>
</tr>
<tr>
<td>21:08:49.78</td>
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<td>0.620</td>
<td>25.80</td>
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Chapter 7 DISCOVERY OF A FAINT OUTER HALO MILKY WAY STAR CLUSTER IN THE SOUTHERN SKY

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<td>r (mag)</td>
<td>(g − r) (mag)</td>
<td>α (J2000) (h : m : s)</td>
<td>δ (J2000) (° : ′ : ″)</td>
<td>Radial Distance (″)</td>
<td>r (mag)</td>
<td>(g − r) (mag)</td>
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<td>1.256</td>
<td>23.35</td>
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</tr>
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7.4.2 Age and Metallicity

We estimate the age, metallicity, alpha element to iron abundance, and distance of Kim 2 using the maximum likelihood method described in Frayn & Gilmore (2002), Fadely et al. (2011), and Kim & Jerjen (2015). For the analysis we use all stars within a radius of 1′3 around Kim 2, the inner circle in the left panel of Figure 7.3. We calculate the maximum likelihood values \( L_i \), as defined by the Equations 1 and 2 in Fadely et al. (2011), over a grid of Dartmouth model isochrones (Dotter et al., 2008), where \( i \) symbolises the grid points in the multi-dimensional parameter space that covers the age range from 7.0–13.5 Gyr, a metallicity range \(-2.5 \leq [\text{Fe/H}] \leq -0.5 \text{ dex}\), \(-0.2 \leq [\alpha/\text{Fe}] \leq +0.4 \) and a distance range \(19.5 < (m - M) < 20.5 \). Grid steps are 0.5 Gyr, 0.1 dex, 0.2 dex, and 0.05 mag, respectively.

In Figure 7.4, we present the matrix of likelihood values for the sample described above after interpolation and smoothing over two grid points. Depending on the weight given to the two MSTO stars (labelled 1 and 2 in Figure 7.3), we find two slightly different isochrones that fit the data best (center panel of Figure 7.3). If the two stars are given the weights based on their photometric uncertainties, the best-fitting isochrone has an age of 11.5 Gyr and \([\text{Fe/H}] = -1.0 \pm 0.2 \text{ dex}\), \([\alpha/\text{Fe}] = +0.2 \text{ dex}\), with a heliocentric distance of 104.7 kpc \((m - M) = 20.10\), the solid blue line in Figure 7.4. However, if we give extra weight to these stars because they are close to the cluster center we derive a younger age of 8.0
Chapter 7 DISCOVERY OF A FAINT OUTER HALO MILKY WAY STAR CLUSTER IN THE SOUTHERN SKY

Gyr, [Fe/H] = −0.9 dex, [α/Fe] = +0.4, and a distance of 98 kpc ((m − M) = 19.96). The probability that goes with this second solution is 0.9% lower than the first solution. In the following we will adopt the parameters of the first solution. In particular, we use a heliocentric distance of 105 kpc for Kim 2 in the calculation of the physical size and absolute magnitude (Section 4.3). The 68%, 95%, and 99% confidence contours are overplotted in Figure 7.4.

The marginalized uncertainties about this most probable location correspond to an age of 11.5^{+2.0}_{-3.5} Gyr, a metallicity of [Fe/H] = −1.0^{+0.18}_{-0.21} dex, and a distance modulus of (m − M)₀ = 20.10 ± 0.10 (D⊙ = 104.7 ± 4.1 kpc). For the 2nd solution we get: 8.0^{+3.5}_{-2.0} Gyr, [Fe/H] = −0.9^{+0.16}_{-0.19} dex, and (m − M)₀ = 19.96 ± 0.09 (D⊙ = 98.2 ± 4.2 kpc), respectively.

In the discussion about the age and metallicity of Kim 2 it is important to note that a significant fraction of unresolved MS-MS binaries are common among low-mass star clusters. Some low-luminosity clusters in the Milone et al. (2012) sample like E3 have 50% or more binaries (see their Fig. B.4). As we will show in Section 4.3, Kim 2 is among the lowest luminosity (hence lowest mass) star clusters known. If Kim 2 follows the anti-correlation between mass and binary fraction then it would host a large population of binaries. Unfortunately, our photometry does not allow us to distinguish binaries from single MS stars in the CMD, but we know that binaries are located on the red side of the MS. This means that, due to the present of many binaries, the MS we observe would be redder than the MS of single stars. Furthermore, binaries of turn-off stars can be located above the turn-off similar to the observed stars we coloured in red in the CMD. Hence, if Kim 2 has a high binary fraction, we are likely to over-estimate the metallicity by about 0.2-0.4 dex. A detailed study of the binary fraction in Kim 2 shall be the focus of an upcoming study.

Both of our two age/metallicity solutions for Kim 2 are comparable to the observed properties of globular clusters seen in the Galactic halo. A large ensemble of these objects have been studied in detail with the Hubble Space Telescope – see, for example, Figure 13 in Marín-Franch et al. (2009). At [Fe/H] ~ −1.0 and [α/Fe] ~ +0.2 ([M/H]~ −0.86) we find clusters as young as 0.8 times the age of the oldest systems in the Milky Way; an age of 11.5 Gyr would thus be consistent with many other Galactic GCs (albeit lying at smaller Galactocentric radii). Moving to the second solution, at [Fe/H] ~ −0.9 or −0.8 and [α/Fe] ~ +0.4 ([M/H]~ −0.56), there are clearly somewhat younger clusters than at [M/H]~ −0.86, but an age of 8.0 Gyr would be certainly on the younger envelope of the observed distribution (this would correspond to a relative age of about 0.6 or so). Note that by this metallicity the age-metallicity relation for Galactic GCs has clearly bifurcated. Clusters on the upper locus are thought to be accreted objects, and Kim 2 would clearly be part of that ensemble. The other point worth mentioning is that [α/Fe] ~ +0.4 at
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Figure 7.5 Left panel: RA-Dec distribution of GMOS stars centred on Kim 2. The dashed ellipses indicate 0′.4 steps in the elliptical radius of ellipticity $\epsilon = 0.12$ and position angle $\theta = 35$ deg. The solid contours mark the local star density that is 3$\sigma$ to 10$\sigma$ above the background density. Right panel: Radial stellar density profile based on the stellar distribution in the left panel. Open circles represent the star density after subtracting the background contribution. The solid line, dashed line and dotted line show a King profile with a core radius $r_c = 0′.28$ and tidal radius $r_t = 2′.1$, a Plummer profile with a half-light radius $r_h = 0′.42$, and a power law profile with a slope $\gamma = -2.5$ for the extra tidal stars, respectively.

this age and metallicity would be unusually higher than many comparable Galactic GCs. For example, objects with similar ages and metallicities such as Terzan 7 and Pal 12, have $[\alpha/Fe] \sim 0.0$. Higher $[\alpha/Fe]$ would suggest this object came from a relatively massive parent galaxy (perhaps LMC mass or so) where the chemical enrichment proceeded quite quickly, i.e, where the “knee” in the $[\alpha/Fe]$ vs. $[Fe/H]$ plot is at comparatively high $[Fe/H]$. For the older solution $[\alpha/Fe] \sim +0.2$ and $[Fe/H] \sim -1$ would seem to be normal compared to other similar Galactic GCs.

7.4.3 Size, Ellipticity, and Luminosity

The left panel of Figure 7.5 shows the sky distribution of all GMOS stars in the magnitude range $23.5 < r < 26.5$ and $g < 27.0$ in a $0.7^\circ \times 0.7^\circ$ window centred on Kim 2. The solid contours at the centre correspond to 3$\sigma$ to 10$\sigma$ levels above the background density. We derive an ellipticity $\epsilon = 0.12$ and the position angle $\theta = 35$ deg using the fit_bivariate_normal function of the astroML package (VanderPlas et al., 2012). The right panel shows the associated radial profile of the stellar number density, where $R_e$ is the elliptical radius. To estimate the background of field stars, we subtracted from the catalog the stars consistent with the isochrone and counted the remaining stars in the same color-magnitude range, which results in 6.4 stars per sqr arcmin. The error bars were derived based on Poisson
statistics, i.e. $\sqrt{N}/\text{arcmin}^2$. The best-fit King profile based on the innermost four data points gives a core radius of 0'28±0.02 or $r_c = 8.5\pm0.6$ pc, and a tidal radius of 2'10±0.02 or $r_t = 64.0\pm0.6$ pc adopting the distance modulus of 20.1 mag. We note that the observed radial profile exceeds the King model at radii $R_e > 1'$0. Such a departure from the King model at radii considerably less than $r_t$ has been already reported for many other globular clusters and identified as extra-tidal stars that follow a power law density profile (e.g. Grillmair et al., 1995; Carraro et al., 2007; Carraro, 2009). We also estimated a half light radius by means of the best-fitting Plummer profile, which yields 0.42 ± 0.02 arcmin or $r_h = 12.8 \pm 0.6$ pc (dashed line). Above the King and Plummer profiles, we outline the extra-tidal stars using a power law profile with slope $\gamma = -2.5$ (dotted line).

We further derived the total magnitude of Kim 2 as follows. We selected Kim 2 stars by means of a photometric filter based on the best-fitting Dartmouth isochrone and taking into account the uncertainties of our photometry. We then built the observed luminosity function (LF) of Kim 2 by counting the selected stars within $3r_h$ as a function of magnitude from the saturation level $r_0 = 19.5$ to the 50% completeness limit $r_0 = 26.5$. The observed LF was corrected for incompleteness. We then adopted a normalized theoretical LF based on Dartmouth model (Dotter et al., 2008) and scaled it to the observed LF, for which we used two scale factors: (1) the ratio of the integrated number density of the observed LF to the probability density of a normalised theoretical LF between the saturation and the 50% completeness limits and (2) the ratio of the integrated flux of the observed LF to that of the theoretical LF in the same magnitude range. We obtained the total magnitude by integrating the scaled theoretical LF inclusive of the missing flux at $r$ magnitude fainter than 50% completeness limit. Method (1) yields $M_r = -1.74$ and method (2) $M_r = -1.73$. The total V-band luminosity is therefore $M_V = -1.47$ ($V - r = 0.264$, adapted from Dartmouth model for a 11.5 Gyr, $|$Fe/H$| = -1.0$ stellar population). Since we included all stars consistent with the isochrone, the calculated value should be considered an upper limit of the true total V-band luminosity and an exclusion of a single RGB star can change it still by $\sim 0.5$ mag. This result suggests that Kim 2 is among the faintest known Milky Way globular clusters, with a comparable luminosity to Balbinot 1 ($M_V \sim -1.21$; Balbinot et al., 2013), Koposov 1 ($M_V \sim -1.35$), AM4 ($M_V \sim -1.8$). The only MW star clusters with even lower luminosities are Muñoz 1 ($M_V \sim -0.4$; Muñoz et al., 2012), Koposov 2 ($M_V \sim -0.4$; Harris, 1996, and 2010 edition), Segue 3 ($M_V \sim 0.0$; Fadely et al., 2011), and Kim 1 ($M_V \sim 0.3$; Kim & Jerjen, 2015). All derived parameters for Kim 2 are summarised in Table 7.4.
Table 7.4. Properties of Kim 2

<table>
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<th>Value</th>
<th>Unit</th>
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<td>h:m:s</td>
</tr>
<tr>
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<td>°:'&quot;:&quot;</td>
</tr>
<tr>
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<td>deg</td>
</tr>
<tr>
<td>$b$</td>
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<td>deg</td>
</tr>
<tr>
<td>$(m - M)_0$</td>
<td>20.10 ± 0.10</td>
<td>mag</td>
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<tr>
<td>$D_\odot$</td>
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<td>kpc</td>
</tr>
<tr>
<td>$D_{gc}$</td>
<td>99.4 ± 3.9</td>
<td>kpc</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>$-1.0^{+0.18}_{-0.21}$</td>
<td>dex</td>
</tr>
<tr>
<td>[$\alpha$/Fe]</td>
<td>+0.2</td>
<td>dex</td>
</tr>
<tr>
<td>Age</td>
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<td>Gyr</td>
</tr>
<tr>
<td>$r_h$(Plummer)</td>
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<td>pc</td>
</tr>
<tr>
<td>$r_e$(King)</td>
<td>8.5 ± 0.6 a</td>
<td>pc</td>
</tr>
<tr>
<td>$r_t$(King)</td>
<td>64.0 ± 0.6 a</td>
<td>pc</td>
</tr>
<tr>
<td>$\epsilon$</td>
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<td>$\theta$</td>
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<tr>
<td>$M_{tot,V}$</td>
<td>$-1.5 ± 0.5$</td>
<td>mag</td>
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</table>

a Adopting a distance of 104.7 kpc

7.5 Discussion and Conclusion

We report the discovery of a star cluster, Kim 2, in the outer halo of the MW. This object was first detected in our DECam blind field survey data and confirmed by GMOS follow-up observation. We found the cluster distant ($\sim$ 100 kpc), faint ($M_V \sim -1.4$), younger than the oldest GCs ($< 11.5$ Gyr) and more metal-rich ([Fe/H] $\sim -1.0$) than any outer halo GC. Its physical size ($r_h \sim 12.8$ pc) is comparable to that of the other outer halo GCs but with an order of magnitude difference in terms of luminosity (see Figure 8 and 9 in Mackey & van den Bergh, 2005).

7.5.1 Evidence of Mass Loss

Low luminosity globular clusters are expected to be in a mass segregation state as the relaxation time of the clusters is significantly shorter than their respective ages. To estimate the half-mass two-body relaxation time $t_{rh}$ of Kim 2 we used the following equation (Spitzer & Hart, 1971),
where $M$ is the mass of a cluster, $R_h$ is the radius containing half mass of the cluster, $\bar{m}$ is the average mass of the members. Here, we estimated the cluster mass $M \sim 600M_\odot$ and the average stellar mass $\bar{m} \sim 0.3M_\odot$ using an initial mass function by Chabrier (2001) and an isochrone by Bressan et al. (2012). We used the half-light radius of 12.8 pc for $R_h$. Using these numbers gives the relaxation time $t_rh \sim 1.1$ Gyr, which is significantly short relative to the estimated age of the cluster ($\sim 11.5$ Gyr). This result suggests that Kim 2 should have had sufficient time to undergo dynamical mass segregation. To investigate this possibility we show in the upper panel of Figure 7.6 the mass of the stars consistent with the main sequence of Kim 2 in the magnitude range $23.5 < r_0 < 26.5$ as a function of the distance from the center of the cluster. The stellar mass systematically decreases over the radius. The lower panel shows the normalized cumulative distribution function for three different mass intervals ($0.55 < M/M_\odot < 0.65$, $0.65 < M/M_\odot < 0.75$, and $0.75 < M/M_\odot < 0.85$), corrected for incompleteness. The plots clearly show that more massive MS stars preferentially populate the inner part of the cluster.

Figure 7.7 shows the distribution of the potential MS stars and contours of 1$\sigma$ to 6$\sigma$ levels above the background. Although no tail structure of the extra tidal stars at radius $> 1'$ is noticeable, the outer contours are slightly more elliptical in a rather consistent orientation ($\theta \sim 105$ deg). Similar changes of the orientation angle are observed in the cores of other GCs undergoing tidal disruption (e.g. Pal1, Pal 5 and Pal 14 in Niederste-Ostholt et al., 2010; Odenkirchen et al., 2001; Sollima et al., 2011). Considering the low concentration and luminosity of Kim 2, these stars are likely to be loosely bound around the center.

These results suggest that Kim 2 must have experienced substantial mass loss by relaxation and tidal stripping in order to have reached its current physical and dynamic state. With the consistency between the two-body relaxation time and the observed mass segregation, it seems unlikely that Kim 2 contains any significant amount of dark-matter, since otherwise the half-mass radius and the total mass of the system would be much greater than observed leading to a relaxation time comparable to or even exceeding the Hubble time. Accordingly, dynamical mass segregation would be hardly observed in a dark-matter dominated stellar system.

### 7.5.2 Is Kim 2 associated with a MW satellite galaxy or Stream?

Kim 2 has an unusually low luminosity when compared with the other known outer halo GCs (Table 7.1). The significant luminosity difference of at least 3 mag and evidence
Chapter 7 DISCOVERY OF A FAINT OUTER HALO MILKY WAY STAR CLUSTER IN THE SOUTHERN SKY

Figure 7.6 Upper panel: stellar mass of all Kim 2 main sequence stars within $2r_h$ ($\sim 0'.8$) as a function of the distance from the cluster center. Lower panel: Cumulative distribution function of Kim 2 main sequence stars for three different mass intervals.

of extra-tidal stars (Section 4.3) strongly suggests we are seeing an outer halo GC that experienced mass loss due to the MW tidal field, similar to Pal 14 (Sollima et al., 2011). Kim 2 and Pal 14 share low star density and evidence of tidal interaction. As suggested by Sollima et al. (2011), an outer halo GC with such low star density is likely to follow an orbit confined to the outer region of the Galactic halo, and/or to have formed in a dwarf galaxy that was later accreted into the Galactic halo. As a consequence, the cluster could have experienced minor tidal disruption and survived until the present epoch.

Kim 2 also shares properties with AM4 in terms of metallicity, age and luminosity (Carraro, 2009). AM4 is considered to be associated with the Sagittarius (Sgr) dwarf galaxy. Kim 2 is approximately $25^\circ$ away from the orbit of the Sgr tidal stream, and the Law & Majewski (2010) model of the Sgr dwarf galaxy embedded in a triaxial MW halo has only a single
Figure 7.7 Distribution of stars consistent with Kim 2’s main sequence. Contours mark 1.0 – 7.5σ levels above the background, with a step size of 0.5σ.

Sgr Stream particle at a heliocentric distance of 79 kpc within 0.5 sqr deg of Kim 2. This very low particle density and the large line-of-sight distance difference of 26 kpc makes it highly unlikely that Kim 2 originates from the Sgr galaxy.

However, there is still the possibility that Kim 2 is not a genuine MW globular cluster, but was formerly associated with another dwarf galaxy, which deposited it into the Galactic halo. In that context, we note that Kim 2 is relatively close to the vast polar structure (VPOS), a thin (20 kpc) plane perpendicular to the MW disk defined by the 11 brightest Milky Way satellite galaxies (Kroupa et al., 2005; Metz et al., 2007, 2009; Kroupa et al., 2010; Keller et al., 2012; Pawlowski et al., 2012). In the region of Kim 2 VPOS is defined by the SMC, LMC, and Carina. Globular clusters and stellar and gaseous streams appear to preferentially align with the VPOS too (Forbes et al., 2009; Pawlowski et al., 2012). The origin of that plane is still a matter of debate. It could be the result of a major galaxy collision that left debris in form of tidal dwarfs and star clusters along the orbit (Pawlowski & Kroupa, 2013). A more detailed analysis of this matter is beyond the scope of this paper due to the small field of view of GMOS and the shallowness of our more extended DECam photometry.
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CHAPTER 8

KIM 3: AN ULTRA-FAINT STAR CLUSTER IN THE CONSTELLATION OF CENTAURUS


Abstract

We report the discovery of an ultra-faint star cluster in the constellation of Centaurus. This new stellar system, Kim 3, features a half light radius of $r_h = 2.29^{+1.28}_{-0.52}$ pc and a total luminosity of $M_V = +0.7 \pm 0.3$. Approximately 26 stars are identified as candidate member stars down to four magnitudes below the main-sequence turn-off, which makes Kim 3 the least luminous star cluster known to date. The compact physical size and extreme low luminosity place it close to faint star clusters in the size-luminosity plane. The stellar population of Kim 3 appears to be relatively young ($9.5^{+3.0}_{-1.7}$ Gyr) and metal-poor ($[\text{Fe/H}] = -1.6^{+0.45}_{-0.30}$) at a heliocentric distance of $15.14^{+1.00}_{-0.28}$ kpc. The cluster lacks a well-defined center and a small but prominent group of stars consistent with the Kim 3 isochrone is present approximately 9.7 pc in projection south of the cluster center. Both are signs of the cluster being in the final stage of tidal disruption.

8.1 Introduction

The Sloan Digital Sky Survey (SDSS; York et al., 2000) has unveiled a significant number of ultra-faint dwarf galaxies in the Milky Way halo (e.g. Willman et al., 2005; Zucker et al., 2006; Belokurov et al., 2006; Irwin et al., 2007; Walsh et al., 2007; Kim et al.,
Chapter 8 KIM3: AN ULTRA-FAINT STAR CLUSTER IN THE CONSTELLATION OF CENTAURUS

2015b). However, only a small number of new star clusters were found (Koposov et al., 2007; Belokurov et al., 2010; Balbinot et al., 2013; Kim & Jerjen, 2015a), with heliocentric distances 17–50 kpc. These star clusters share both small physical sizes and low luminosities, properties considered to be the consequences of stellar mass loss owing to internal (e.g. dynamic relaxation) and/or external (e.g. tidal stripping, tidal shocking) dynamical evolution processes (Gnedin & Ostriker, 1997; Rosenberg et al., 1998). This picture of the low-luminosity star clusters being strongly dynamically evolved is supported by growing observational evidence such as the presence of extra-tidal stars, flat luminosity functions, and substantial mass segregation (Carraro et al., 2007; Carraro, 2009; Niederste-Ostholt et al., 2010; Fadely et al., 2011; Kim & Jerjen, 2015a; Kim et al., 2015a).

Since the success of SDSS, other blind imaging surveys have continued searching for new stellar systems in the Milky Way halo; the Dark Energy Survey (DES; The Dark Energy Survey Collaboration, 2005), Pan-STARRS 3π survey (K. Chambers et al., in preparation), VST ATLAS survey (Shanks et al., 2015), the Stromlo Milky Way Satellite (SMS) survey (Jerjen, 2010), and the Survey of the Magellanic Stellar History (SMASH; D. Nidever et al., in preparation). These efforts have uncovered more than 20 new satellite candidates up to the present time (Bechtol et al., 2015; Belokurov et al., 2014; Drlica-Wagner et al., 2015; Kim et al., 2015a; Kim & Jerjen, 2015b; Koposov et al., 2015a; Laevens et al., 2014, 2015a,b; Luque et al., 2015; Martin et al., 2015a; Torrealba et al., 2016). Spectroscopic follow-up has revealed the kinematic and chemical characteristics of some of these systems, clarifying their nature (e.g. Simon et al., 2015; Walker et al., 2015a,b; Koposov et al., 2015b; Kirby et al., 2015b; Martin et al., 2015a,b). These ultra-faint stellar systems are rapidly filling the gap between star clusters and dwarf galaxies in the size-luminosity plane, rendering this diagnostic tool less effective (e.g. see discussions in Laevens et al., 2014; Belokurov et al., 2014). Hence, deeper imaging and spectroscopic follow-up are becoming imperative to determine the true nature of the systems and possibly identify star clusters among the new candidates (e.g. Kirby et al., 2015a; Weisz et al., 2015).

In this paper we announce the discovery of a new ultra-faint star cluster, which we designate as Kim3, found in the constellation of Centaurus. This concentration of stars was detected as part of our ongoing imaging survey with the Dark Energy Camera (DECam) on the 4m Blanco telescope at Cerro Tololo in Chile. Section 2 describes the observations and data reduction process, including photometry and star/galaxy separation that led to the discovery of Kim3. We also discuss the photometric calibration and completeness tests. Section 3 contains our analysis of the CMD and describes how we derived the properties of the new star cluster such as age, metallicity, distance, luminosity and structure. We discuss the results and draw our conclusions in section 4.
Figure 8.1 Section of the sky (dashed line), showing the footprint of the ∼ 500 square degree area searched for new ultra-faint Milky Way stellar systems as part of the Stromlo Milky Way Satellite Survey. The Galactic longitude and latitude lines are spaced by 10°. Known satellite galaxies and star clusters in the area are labelled. Black contour lines indicate particle densities for the simulated Sagittarius stream from Law & Majewski (2010). The background image, showing the end of a leading arm of the Magellanic Stream, is by Nidever et al. (2010), NRAO/AUI/NSF and Meilinger, Leiden-Argentina-Bonn Survey, Parkes Observatory, Westerbork Observatory, Arecibo Observatory (see http://www.nrao.edu/pr/2010/magstream/).

8.2 Observation, Data Reduction, and Discovery

As part of the Stromlo Milky Way Satellite (SMS) Survey project we have observed in non-targeted mode ∼ 500 square degrees of sky in the Centaurus region (see Figure 8.1) using the Dark Energy Camera (DECam; Flaugher et al., 2015) of the 4-m Blanco Telescope located at Cerro Tololo Inter-American Observatory (CTIO). The imager consists of 62 2k × 4k CCD chips with a pixel scale of $0\farcs27$, which delivers a ∼ 3 square degree field of view. We obtained images in the g and r bands over two observing runs in July 2014 and June 2015 as part of observing proposals 2014A-0624 and 2015A-0616 (both PI: H. Jerjen). More details on the former observing run can be found in our previous work (Kim et al., 2015a). In the case of the latter session, we set the exposure times to between 100 and 210 s depending on the fraction of moon illumination and the angular distance of the target field from the moon. To fill the inter-chip gaps, we dithered in a diagonal direction by half of a single chip in both x and y for each field, providing two exposures per field per filter. The images were reduced using the DECam community pipeline (Valdes et al., 2014). This
Figure 8.2 $4 \times 4$ arcmin$^2$ DECam cutout $r$-band image of Kim 3 with 210 seconds exposure time. North is up, east is to the left. Circled are all stars fainter than $r_0 = 18.5$ that are within two half-light radii from the adopted center of Kim 3 or within a radius of $0^\prime 15$ from the adopted center of the small group of stars to the south of Kim 3 (see Figure 8.3), and consistent with the best-fitting isochrone (9.5 Gyr, $[\text{Fe/H}] = -1.6$) at a distance of 15.14 kpc.

The process includes bias subtraction, dark and flat-field corrections, and the application of a WCS solution to each image.

We carried out PSF photometry over the pre-processed single exposure images to produce photometric catalogs using SExtractor/PSFEx (Bertin & Arnouts, 1996; Bertin, 2011) on a local 16 node/128 core computer cluster. For the star/galaxy separation we made use of the $\text{SPREAD\_MODEL}$ parameter provided by SExtractor, where the threshold was set $|\text{SPREAD\_MODEL}| < 0.003 + \text{SPREAD\_MODEL}$ as described in Koposov et al. (2015a). This process was applied to the photometric band that exhibited the better defined PSF over the entire field. The $g$ and $r$ band catalogs were crossmatched using STILTS (Taylor, 2005) with a $1^\prime 0$ tolerance. The instrumental magnitudes were then calibrated with respect to the APASS DR 8$^1$ star catalog via bootstrap sampling with 500 iterations and 3-sigma clipping. The number of matched stars in a field ranged between 100–1600. Finally, each calibrated object was corrected for Galactic extinction based on the reddening map by Schlegel et al. (1998) and the correction coefficients from Schlafly & Finkbeiner (2011).

$^1$https://www.aavso.org/apass
We ran our overdensity detection algorithm, which is based on the method of Walsh et al. (2009), over the final point source catalogue that was produced for each field by our photometry pipeline. For more details about the algorithm see Kim & Jerjen (2015a). Briefly, the algorithm enhances the contrast between satellite population and the Milky Way foreground stars by using photometric filters in the color-magnitude space and comparing the integrated signal-to-noise ratios (SNRs) of point-source clusters on a convolved stellar density map in the field of view of DECam. In this search, we recovered the known globular cluster AM4 and detected the new object Kim 3, the SNR of which reached the $10\sigma$ level over the Poisson noise measured in the surrounding point-source distribution.

We performed completeness tests for the photometry as follows. We first created an accurate PSF model image using the PSF task of DAOPHOT in the IRAF environment and then added 100 artificial stars per chip at random pixel coordinates using the ADDSTAR task in IRAF. A series of images were produced for different input magnitudes at 0.5 mag intervals. We then ran our photometry routine and measured the recovery rate, for which we also applied the same star/galaxy separation criteria for more realistic measurements. This procedure was repeated 20 times to obtain reliable statistics. The completeness function for our CMD was then finalised by multiplying the recovery rates in the $g$ and $r$ bands as the two catalogues were cross-matched to generate the CMD. The 90% and 50% levels of our photometry at the color $(g-r) = 0.5$ correspond to $r = 20.74$ and $r = 23.21$ respectively. The 50% completeness level as a function of color and $r$ magnitude is indicated by the dotted lines in Figure 8.4.

Figure 8.2 shows a $r$-band cutout image centred on Kim 3, where the cluster is completely resolved into individual stars. We note that a very bright star to the west of the cluster caused a “blooming” effect across the image, which was automatically corrected via linear interpolation by the NOAO community pipeline. It is possible that some Kim 3 member stars are hidden behind the interpolated region. Another bright star to the south-east of the nominal cluster center could also be hiding stars associated with the cluster.

The left panel of Figure 8.3 shows the R.A.-Dec distribution of all stars that passed the photometric filter based on the main-sequence and its turn off of the best-fitting isochrone. The color of the marker represents the $r_0$ magnitude. The right panel shows the corresponding convolved density map where the contours are in units of the measured standard deviation. The contours reveal an asymmetric feature within high density level isophotes ($> 6\sigma$) and a tail-like structure to the south, which could be evidence of tidal disruption. We note that a similar feature has been found in the case of the dissolving star cluster Kim 1 (see Figure 2 in Kim & Jerjen, 2015a). At the end of that structure a small, but prominent overdensity clearly stands out $\sim 2\arcmin$ below the center of Kim 3.
Figure 8.3 Left panel: distribution of candidate stars that passed the photometric filtering process centred on Kim 3 in the $11 \times 11$ square arcmin window. Right panel: smoothed density contour map corresponding to the left panel. The contour levels mark the stellar density in units of the standard deviation above the background.

This feature further strengthens the impression that the tail is actually the product of the disruption process in the cluster.

8.3 Kim 3 Properties

8.3.1 Color-Magnitude Diagram

The left panel of Figure 8.4 shows all star-like objects from our analysis found in the vicinity of Kim 3 where blue markers represent objects in common in all four exposures, $2 \times 100$ s in $g$ band and $2 \times 210$ s in $r$ band. The next three panels on the right correspond to the CMD of stars within two half-light radii of Kim 3, the control CMD and the differential Hess diagram. We calculated the uncertainty weighted average magnitudes for the overlapping objects so that their photometric uncertainties are $\sim 30\%$ smaller than those with the single measurements. The CMD of Kim 3 possesses stars over $\sim 4$ magnitudes, from the MSTO down to the 50% completeness level, that are consistent with an old (9.5 Gyr) and metal-poor ([Fe/H] = $-1.6$) population at a distance modulus of $(m - M) = 15.90$. Such a tight main-sequence fit has also been noticed in the CMD of Kim1. The CMD of the smaller overdensity nearby Kim 3 also shows a fairly consistent fit to the same isochrone within photometric uncertainties. Its true affiliation to Kim 3 can be determined once spectroscopic data become available.
Figure 8.4 Upper left panel: distribution of all stars in the same window as Figure 8.3. The blue markers represent stars detected in all four exposures taken for the field and thus have two independent photometric measurements per filter. Black markers are stars with one measurement per filter. The three ellipses mark elliptical radii of $1.00$ ($\sim 2r_h$), $3.50$ ($\sim 7r_h$), and $3.54$, respectively, with a position angle of 4 degrees and an ellipticity of 0.17. Upper middle left panel: CMD of stars lying in the inner ellipse of the left panel. Overplotted are the best-fitting Dartmouth (red solid line) isochrone of age 9.5 Gyr and $[\text{Fe/H}]= -1.6$ and the PARSEC (red dashed line) isochrone of the same age and metallicity for comparison, shifted to the distance modulus of $(m-M) = 15.90$. The magnitudes of the stars with two measurements (blue markers) were uncertainty-weighted averaged so that their final uncertainties are $\sim 30\%$ smaller than the stars with one measurement. The dotted line indicates the 50% completeness level of our photometry. Upper middle right panel: control CMD of stars that reside between the two outer ellipses. Upper right panel: the differential Hess diagram, the inner CMD minus the control CMD, for which each CMD was binned onto a grid with intervals of 0.05 mag for $(g-r)_0$ and 0.2 mag for $r_0$. Lower panels: the same as the upper panels but for the small overdensity $\sim 2\prime 2$ south of Kim 3 shown in Figure 8.3. Its central coordinates (J2000) were visually determined as $(\text{RA}, \text{Dec})=(200.696^\circ, -30.637^\circ)$. Its radius was measured $\sim 0\prime 15$. The three circles mark radii of 0\prime 30, 1\prime 05 and 1\prime 09.
Table 8.1. Properties of Kim3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{2000}$</td>
<td>13 22 45.2±2.0</td>
<td>h m s</td>
</tr>
<tr>
<td>$\delta_{2000}$</td>
<td>-30 36 03.6±2.0</td>
<td>° ′ ″</td>
</tr>
<tr>
<td>$l$</td>
<td>310.860</td>
<td>deg</td>
</tr>
<tr>
<td>$b$</td>
<td>31.788</td>
<td>deg</td>
</tr>
<tr>
<td>$(m - M)$</td>
<td>$15.90^{+0.11}_{-0.04}$</td>
<td>mag</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>$-1.6^{+0.05}_{-0.03}$</td>
<td>dex</td>
</tr>
<tr>
<td>$d_{\odot}$</td>
<td>$15.14^{+1.00}_{-0.28}$</td>
<td>kpc</td>
</tr>
<tr>
<td>$d_{gal}$</td>
<td>$12.58^{+0.85}_{-0.23}$</td>
<td>kpc</td>
</tr>
<tr>
<td>$r_h$</td>
<td>$0.52^{+0.11}_{-0.11}$</td>
<td>pc</td>
</tr>
<tr>
<td>$r_h$</td>
<td>$2.29^{+1.28}_{-0.52}$</td>
<td>pc</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>$0.17^{+0.26}_{-0.17}$</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>$4 \pm 24$</td>
<td>deg</td>
</tr>
<tr>
<td>$M_V$</td>
<td>$+0.7 \pm 0.3$</td>
<td>mag</td>
</tr>
<tr>
<td>$E(B - V)^a$</td>
<td>0.061</td>
<td>mag</td>
</tr>
</tbody>
</table>

$a$From Schlafly & Finkbeiner (2011).

8.3.2 Age, Metallicity and Distance Modulus

We estimate the age, metallicity, and distance of Kim3 using the maximum likelihood method described in Frayn & Gilmore (2002), Fadely et al. (2011), and Kim & Jerjen (2015a). For the analysis we use all stars within an elliptical radius of 1.0′ from Kim3, the inner ellipse in the upper left panel of Figure 8.4. We calculate the maximum likelihood values as defined by the Equations 1 and 2 in Fadely et al. (2011), over a grid of Dartmouth model isochrones (Dotter et al., 2008). The grid points in the multi-dimensional parameter space cover the age range from 7.0–13.5 Gyr, a metallicity range $-2.5 \leq [\text{Fe/H}] \leq -0.5$ dex, and a distance range $15.7 < (m - M) < 16.3$. Grid steps are 0.5 Gyr, 0.1 dex, and 0.05 mag, respectively.

Due to the small sample size relative to the number of free parameters, we chose to fix $[\alpha/\text{Fe}]$ in the fit to ensure adequate convergence of the ML algorithm. We tested two scenarios – the first with $[\alpha/\text{Fe}]=+0.4$ to match most known Galactic globular clusters, and the second with $[\alpha/\text{Fe}]=0.0$ to match the small sample of younger globular clusters seen in the MW halo (e.g. Cohen, 2004; Sbordone et al., 2005; Sakari et al., 2011; Villanova et al., 2013). We found a similar age and distance modulus for each scenario, but rather different values of metallicity: $\text{age}= 9.5^{+1.8}_{-1.0}$ Gyr, $(m - M) = 15.93^{+0.11}_{-0.03}$ mag, and $[\text{Fe/H}]= -2.0^{+0.35}_{-0.40}$ for $[\alpha/\text{Fe}]=+0.4$, and $9.5^{+3.0}_{-1.7}$ Gyr, $(m - M) = 15.90^{+0.11}_{-0.04}$, and $[\text{Fe/H}]= -1.6^{+0.45}_{-0.30}$.
Figure 8.5 Smoothed maximum likelihood density map in age-metallicity space for all stars within 2\(r_h\) around Kim 3. 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 with uncertainties are listed in Table 1.

for \([\alpha/\text{Fe}]=0.0\). With the first solution Kim 3 would be a significant outlier in the age-metallicity relationship observed for Galactic globular clusters (see Figure 10 in Dotter et al., 2011), but with the second it would agree much more closely. Given that Kim 3 appears to have a relatively young age, we adopt the solution for \([\alpha/\text{Fe}]=0.0\) as our final estimate for the rest of the paper. However, we will ultimately need spectroscopic follow-up to confirm these results.

In Figure 8.5, we present the matrix of likelihood values for the sample described above after interpolation and smoothing over two grid points. The best-fitting Dartmouth isochrone (red solid line in Figure 8.4) has an age of 9.5 Gyr, \([\text{Fe/H}]= -1.6\) dex, \([\alpha/\text{Fe}]= 0.0\) with a heliocentric distance of 15.14 kpc \((m - M = 15.90)\). These estimates also yield a consistent fit for the PARSEC model isochrones (red dashed line in Figure 8.4). The 68%, 95%, and 99% confidence contours are overplotted in Figure 8.5.

### 8.3.3 Structural Parameters and Luminosity

To determine the central coordinates and structural parameters of Kim 3, we employed the Maximum Likelihood (ML) routine introduced in Martin et al. (2008) using the stars fainter than \(r_0 = 18.5\) mag that passed the photometric filtering process. The upper panels of Figure 8.6 show the resulting marginal probability distribution functions (pdfs) for the structural parameters and the bottom panel shows the radial density profile with the
Figure 8.6 Upper panels: marginalized probability distribution functions for the structural parameters of Kim 3: the ellipticity ($\epsilon$), the position angle ($\theta$), half-light radius ($r_h$) and the number of stars that belong to the cluster in our photometry ($N$). The mode for each parameter is marked by a vertical dashed line. Bottom panel: radial density profile of Kim 3 based on mode values as a function of elliptical radius $R_e$. The dotted, dashed and solid lines correspond to the best-fit exponential model, the foreground level and the combined fit respectively.

exponential profile using the modal values from the ML analysis. Formally, Kim 3 is mildly elliptical with $\epsilon = 0.17^{+0.26}_{-0.17}$ at position angle $\theta = 4 \pm 24$ degrees; however as is evident from the pdfs in Figure 8.5, these quantities are not well constrained by the available data. The physical half-light radius of the cluster is calculated as $r_h = 2.29^{+1.28}_{-0.52}$ pc adopting the heliocentric distance of $15.14^{+1.00}_{-0.28}$ kpc derived in Section 3.2. This shows that Kim 3 is
similar in size to Segue 3 (Fadely et al., 2011). We note that the exclusion of possible member stars obscured by the blooming effect or the bright star near the cluster (see Figure 8.2) could slightly affect the results. The number of stars that belong to the cluster \( N \) was calculated with eq. (5) in Martin et al. (2008).

We estimated the total luminosity of Kim 3 using the star count parameter \( N \) as follows. We first multiplied the normalised theoretical luminosity function (LF) with the completeness function determined in Section 2. We then integrated the LF as a probability density function of magnitude. The ratio of the star count mode \( N = 26 \) to the probability density gives the scale factor to transform the original LF to the observed level. Finally we calculated the weighted integral of flux treating the scaled LF as a weight function. We obtained \( M_V = +0.51^{+0.27}_{-0.29} \) using the Dartmouth luminosity function of 9.5 Gyr and \([\text{Fe}/\text{H}]= -1.6\) with the mass function by Chabrier (2001) and \( M_V = +0.43^{+0.28}_{-0.30} \) using the PARSEC luminosity function of the same age and metallicity with the mass function by Kroupa (2001). The quoted errors include the uncertainties in the star count parameter \( N \) and the distance modulus derived in Section 3.2. For a 9.5 Gyr and \([\text{Fe}/\text{H}]= -1.6\) stellar population, the Dartmouth and PARSEC models have a mean color \( V - r = 0.21 \) and \( V - r = 0.22 \) respectively, which convert both the \( M_r \) magnitudes into \( M_V = +0.7 \pm 0.3 \).

We adopted \( M_V = +0.7 \pm 0.3 \) as our final estimate of the total luminosity of Kim3. All derived parameters presented in this section are summarized in Table 8.1.

### 8.4 Discussion and Conclusion

We report the discovery of the ultra-faint star cluster Kim 3 in the constellation of Centaurus. It is a compact \((r_h = 2.29^{+1.28}_{-0.52})\) and extremely faint \((M_V = +0.7 \pm 0.3)\) star cluster. Although its physical size and ellipticity are comparable to Segue 3 (see Figure 5 in Fadely et al., 2011), Kim 3 is even slightly fainter than Kim1 \((M_V = +0.3 \pm 0.5; \text{Kim \\& Jerjen, 2015a})\), Segue 3 \((M_V = +0.0 \pm 0.8; \text{Fadely et al., 2011})\) and Muñoz 1 \((M_V = -0.4 \pm 0.9 \text{ Muñoz et al., 2012})\) and thus sets a new record in the size luminosity plane. The best-fitting model isochrone in the CMD indicates that the stars of Kim3 are located at a heliocentric distance of \(15.14^{+1.00}_{-0.28}\) kpc, or a Galactocentric distance of \(12.58^{+0.85}_{-0.23}\) kpc, and feature a metallicity \([\text{Fe}/\text{H}]= -1.6^{+0.45}_{-0.30}\) and intermediate age \((9.5^{+3.0}_{-1.7}\) Gyr). At the Galactic latitude of 31.788 deg, Kim3 is located \(\sim 8\) kpc above the Galactic plane and therefore unlikely to be an old open (disk) cluster.

The CMD of Kim3 in Figure 8.4 appears to have a tight main-sequence, which implies the absence of binary stars with large mass ratios. This is in contrast with the observations of a strong anti-correlation between the fraction of binaries and the mass of the cluster (Milone
Figure 8.7 Upper panel: $r_0$ magnitudes of all Kim 3 main sequence stars within $2r_h (\sim 1.0')$ as a function of radial distances from the center of the cluster. Lower panel: completeness-corrected cumulative distribution functions for two different magnitude intervals.

et al., 2012, 2016). Such a low binary fraction is more likely to be observed in the outer region of GCs as the binaries preferentially occupy the central region. Although the lack of a binary sequence in Figure 8.4 might be the consequence of low number statistics, it implies that Kim 3 possibly originated from the outskirts of a more massive GC undergoing tidal disruption in the gravitational field of the Milky Way. High precision photometry and proper-motion measurements will be able to test this hypothesis.

The half-mass relaxation time of Kim 3 is estimated as $\sim 50\text{ Myr}$ based on our measurements of the structural parameters in Section 3.3 and the equation (5) from Spitzer & Hart (1971). As this time scale is significantly shorter than the observed age of Kim 3 ($9.5_{-1.7}^{+3.0} \text{ Gyr}$), it is highly likely that the cluster has been dynamically relaxed for a long time and bears evidence of mass segregation. The left panel of Figure 8.3 already gives an impression of mass segregation in Kim 3 in the way that the majority of bright main-sequence stars between $20.0 < r_0 < 21.5$ preferentially occupy the inner region of the
cluster while the fainter, less massive MS stars mainly comprise the outer part of the cluster. The top panel of Figure 8.7 shows the $r_0$ magnitudes of the 22 stars in the magnitude interval $19.5 < r_0 < 23.5$ consistent with the main-sequence of the best-fit isochrone in the CMD within two half-light radii ($\sim 1.0$) as a function of radial distance from the center of the cluster. The lower panel shows the corresponding cumulative distributions for two different magnitude intervals ($19.5 < r_0 < 21.5$, $21.5 < r_0 < 23.5$), corrected for incompleteness. Although it appears that the brighter (or more massive) main sequence stars are more common in the centre of Kim 3 than in its outskirts, a Kolmogorov-Smirnov (K-S) test implies that this seemingly mass-segregated state is not highly significant, yielding a formal probability of 87 percent that the two groups were sampled from populations with different parent distributions. This is possibly because of the relatively small sample sizes. The lack of a well defined center in the ultra-faint star cluster with an old stellar population also suggests that Kim 3 might have experienced substantial mass loss owing to tidal disruption in the gravitational field of the Milky Way (see, e.g., discussion in Kim & Jerjen, 2015a). The small overdensity 9.7 pc away from Kim 3 to the south, is likely a debris of the tidal disruption. We can use the centers of Kim 3 and the overdensity as reference points to determine the associated great circle. Taking it as an approximation for the orbital path of Kim 3, we find that the two globular clusters $\omega$ Centauri ($d_{gc} = 6.4$ kpc) and NGC5286 ($d_{gc} = 8.4$ kpc), which are $\sim 16.9^\circ$ and $\sim 21.2^\circ$ away from Kim 3, are only $2.5^\circ$ and $0.2^\circ$ away from that great circle. In this context it is further interesting to note that these systems are among the few MW globular clusters showing internal variations in metals (Marino et al., 2015), which led to the hypothesis they are surviving remnants of tidally disrupted dwarf galaxies. Kim 3 may have originated from a more massive stellar system that also hosted NGC5286 or $\omega$ Centauri. Future radial velocity and proper motion measurements will help to test this idea.
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CHAPTER 9

CONCLUDING REMARKS

9.1 Summary

The key results of this PhD research project are summarised below:

- The entire star catalog of the Sloan Digital Sky Survey (SDSS) was re-analysed with a newly developed search algorithm to find previously overlooked Milky Way (MW) satellite candidates. In this search, two promising candidates were detected with statistical significance at the $\sim 7\sigma$ level in the constellation of Pegasus. Deep follow-up imaging with the Dark Energy Camera at the CTIO 4-m Blanco telescope confirmed that they are a previously unseen star cluster and an ultra-faint dwarf galaxy (UFD) in the MW halo, Kim 1 and Pegasus III. Unlike previously known low-luminosity star clusters, Kim 1, located at a heliocentric distance of $19.8 \pm 0.9$ kpc, lacks a well-defined centre but appears elliptical ($\epsilon = 0.42 \pm 0.10$) and rather extended ($r_h = 6.9 \pm 0.6$ pc). This suggests that Kim 1 is most likely a dissolving star cluster being tidally disrupted. Kim 1 is found close to two other extremely faint star clusters with similar age ($\sim 12$ Gyr) and metallicity ([Fe/H] $\sim -1.7$ dex) in the constellation of Pegasus, namely Segue 3 ($d_\odot = 16.9 \pm 0.7$ kpc) and Balbinot 1 ($d_\odot = 31.9^{+1.0}_{-0.6}$ kpc). Given that more than a dozen UFDs but only a few low-luminosity star clusters have been discovered in the SDSS footprint, their proximity and similar properties of the three stellar systems may imply a common origin.

- Pegasus III is one of the most distant ultra-faint MW satellites currently known. It remained undetected until recently most likely due to its large distance modulus ($(m - M)_0 = 21.66 \pm 0.12$), low luminosity ($M_V = -3.4 \pm 0.4$), and large ellipticity ($\epsilon = 0.38^{+0.22}_{-0.38}$). Pegasus III exhibits an old stellar population ($\gtrsim 12$ Gyr) and contains stars with metallicity as low as [Fe/H] $= -2.55 \pm 0.15$ dex. The mass-to-light ratio of Pegasus III inferred from deep photometry and spectroscopy ($M/L_V = 141$...
1470° M⊙/L⊙) confirms that it is a dark matter (DM)-dominated stellar system. These properties are found to be consistent with the metallicity-luminosity and mass-luminosity relations established by previously known Local Group galaxies. Pegasus III and another outer halo satellite dwarf Pisces II are not only spatially close to each other (∆d<sub>spatial</sub> = 43 ± 19 kpc) but also share similar systemic line-of-sight velocities (∆v<sub>GSR</sub> = 12.3 ± 3.7 km s<sup>-1</sup>). Given the very small number of outer halo satellites currently known, the close proximity has led to the speculation about a common origin. Pegasus III is the only UFD detected in the re-analysis of the SDSS and its location is consistent with the satellite plane.

- The re-analysis of the first data release of the Dark Energy Survey (DES) revealed a previously overlooked ultra-faint dwarf galaxy in the constellation of Horologium, Horologium II (M<sub>V</sub> = −2.6<sup>±0.2</sup>_<sub>−0.3</sub>, r<sub>h</sub> = 47 ± 10 pc). The colour-magnitude diagram (CMD) shows that this object features an old (≳ 12 Gyr) and metal-poor ([Fe/H] ≲ −2.0 dex) stellar population at the heliocentric distance of 78 ± 8 kpc. Horologium II falls in the realm of ultra-faint dwarf galaxies on the size-luminosity plane. Horologium II shares the same heliocentric distance with another satellite Horologium I, only ∼ 7 degrees away on the sky, suggesting their possible companionship. This hypothesis of a satellite pair can be tested once their full 3D orbital information (i.e. the radial velocities and proper motions) becomes available. Horologium II is also well aligned with the plane of satellites.

- The two extreme star clusters Kim 2 (M<sub>V</sub> = −1.5 ± 0.5, r<sub>h</sub> = 12.8 ± 0.6) and Kim 3 (M<sub>V</sub> = 0.7 ± 0.3, r<sub>h</sub> = 2.29<sup>±1.28</sup>_<sub>−0.52</sub>) were discovered in the Stromlo Milky Way Satellite (SMS; PI: Helmut Jerjen) survey project using the Dark Energy Camera. Kim 2 is an outer halo stellar system (d<sub>⊙</sub> = 104.7 ± 4.1 kpc) in the constellation of Indus. The extremely low luminosity and a relatively large physical size places Kim 2 in the notional gap between dwarf galaxies and star clusters. Deep imaging with 8-m Gemini/GMOS, however, has revealed evidence of pronounced mass-segregation in Kim 2, which argues in favour of a star cluster-like nature of the object. The extended structure of Kim 2 is thus most likely a consequence of relaxation-driven expansion. Kim 3 is found in the constellation of Centaurus and relatively close to the sun (d<sub>⊙</sub> = 15.1<sup>±1.0</sup>_<sub>−0.3</sub>kpc). Kim 3 also shows evidence of mass segregation. The discovery of Kim 2 and Kim 3 as well as Kim 1 supports the notion that a substantial number of extreme low-luminosity star clusters are likely to have dissolved due to internal and/or external dynamical processes and still remain undetected in the MW halo.
Chapter 9 CONCLUDING REMARKS

9.2 Discussion

9.2.1 Plane Alignment of Milky Way Satellite Galaxies

Until 2010, the population of MW satellites grew rapidly with discoveries in the SDSS data set. The new satellites turned out to be consistent with the plane of satellites previously defined by eleven classical MW satellites, supporting the notion of the “plane of satellites”. The SDSS footprint, however, mainly covered the north Galactic pole region. The SDSS satellites might be thus naturally expected to align with the polar plane structure, although the chance of such tight alignment with the original plane was very low (Pawlowski, 2016). Subsequent wide-field imaging surveys to map the southern sky were holding a key to dismiss or confirm the speculation on the plane of MW satellites.

The present study analysed the SDSS (\(\sim 14000 \text{ deg}^2\)), DES Year 1 (\(\sim 2000 \text{ deg}^2\)), and SMS (\(\sim 1000 \text{ deg}^2\)) data and discovered five new MW companions. Photometric or spectroscopic follow-up studies suggest that two objects are UFDs and the other three are star clusters. Both of the two dwarf galaxies, Pegasus III and Horologium II, are aligned with the plane of satellites (see Figure 1.6 in Chapter 1). Together with findings from other surveys including the Pan-STARRS 3\(\pi\) survey (Laevens et al., 2014, 2015a,b) and DES (e.g., Koposov et al., 2015; Bechtol et al., 2015; Drlica-Wagner et al., 2015), this study has made significant contribution to the census of MW satellites in the southern sky and confirmed...
the presence of the plane of satellites throughout the whole sky (Figure 9.1). Since 2015, nearly twenty new satellites have been reported, only a few of which turned out to be away from the plane of satellites. More surprisingly, the majority of the new satellites in the southern Galactic sky are located in the vicinity of the Magallanic Clouds. This finding alone sufficiently rules out the ΛCDM radial sub-halo distribution (Koposov et al., 2015; Drlica-Wagner et al., 2015).

To date, nearly 50 MW satellites are known. Predicting the total number of MW satellites needs a theoretical model that describes the distribution of satellites even beyond detection limits. Previous studies often assumed an isotropic distribution of DM subhalos (e.g., Diemand et al., 2007) and predicted the total number of satellites based on the number of satellites detected in SDSS and the efficiency of search algorithms in the same data. Although the new algorithm developed for this study has found a few more objects in the SDSS, its prediction on the number of MW satellite galaxies would be consistent with previous ones within the uncertainties, i.e. 200 – 400 within 300 kpc (Tollerud et al., 2008; Walsh et al., 2009), assuming the isotropic distribution of subhalos. Given that this assumption is no longer valid, the range of predictions will instead vary depending on which fraction of satellite galaxies do belong to on- or off-plane satellite populations.

The plane of satellites is not simply a spatial alignment of satellites but a kinematically coherent system. The phase-space coherence was initially determined by the orbital information of 11 classical MW satellites deduced from their proper motions (Pawlowski & Kroupa, 2013). Andromeda (M31) also exhibit a similar satellite alignment (Ibata et al., 2013). It consists of 15 out of 27 currently known M31 satellites and appears edge-on from the Milky Way. The line-of-sight velocities of the M31 satellites on the plane also indicate coherent rotational motion. In order to determine true on-plane and off-plane MW satellite populations, their orbital information is thus required.

Yet, what separates the on-plane and off-plane populations is not fully understood. The on-plane satellites may have a different formation history from that of the off-plane objects. If this were true, it would be reasonable to expect the two different populations to have evolved in different manners. Such different evolution histories of the two populations should be reflected by dynamics, chemical enrichment, and star formation histories. Collins et al. (2015) have assessed this proposition comparing the structural and kinematic properties of twelve on-plane M31 satellites with eighteen off-plane satellites. The authors found that the only observable difference between the two populations is their spatial alignment; they are indistinguishable from one another in terms of their sizes, luminosities, masses, metallicities, and star formation histories. At this stage, one cannot exclude a possibility that the on- and off-plane satellites share the same formation history. When it comes to the MW, it remains to be investigated whether its on-plane and off-plane satellites also
possess such similarities in these perspectives. Since many MW satellite candidates including the ones presented in this thesis were discovered only recently, follow-up studies to accurately constrain their properties are still underway. So far, any distinguishable characteristics between the on- and off-plane MW satellites previously known have not been reported in the literature. Theoretical studies to understand the plane of satellites must account for the observed similarities among the objects in and out of the plane.

There have been speculations on the origin of the observed anisotropic distribution of MW satellites. Lynden-Bell (1976) conjectured that a progenitor, a Greater Magellanic Galaxy, has played a role as a tidally disrupted source of ingredients for smaller satellites. The formation mechanism of the “tidal dwarf” galaxies provides a more natural explanation for the plane distribution and the phase-space coherence of the satellites than the hierarchical formation scenario based on the ΛCDM model (Pawlowski et al., 2011). This idea, however, challenged by the DM contents of the satellites, which is not expected in tidal dwarf galaxies (Barnes & Hernquist, 1992). The large mass-to-light ratios of dSphs inferred from radial velocity measurements are based on the assumption of dynamical equilibrium. Since tidal dwarf satellites are expected to be progressively driven out of equilibrium and undergo a destructive expansion process during interaction with MW disc and hot halo gas (Yang et al., 2014), this scenario could be verified observationally with stellar proper motion measurements from Gaia mission (Gaia Collaboration et al., 2016a). A Magellanic group infall scenario has also emerged as an explanation of the overdensity of satellites in the vicinity of the Magellanic Clouds (e.g., Deason et al., 2015). In fact, nearly half the known DES satellites including Horologium I & II are likely associated to the Large Magellanic Cloud (Jethwa et al., 2016). Yet, such group infall scenarios have been unable to account for the thin polar plane distribution of MW satellites with phase-space coherence as a whole (Pawlowski et al., 2012).

9.2.2 Discovery of Extreme Star Clusters

Kim 1–3 are ranked among the faintest star clusters ever known. Especially Kim 2 has a luminosity at least 3 magnitude lower than that of previously known outer halo GCs ($d_{gc} > 50$ kpc). Until the discovery of Kim 1–3, there were only a handful number of Galactic GCs known with comparably low luminosity e.g., AM 4 ($M_V \sim -1.82$; Carraro, 2009), Segue 3 ($M_V \sim 0.0$; Fadely et al., 2011), Koposov 1 and 2 ($M_V \sim -1.35$ and $M_V \sim -0.35$; Koposov et al., 2007), Balbinot 1 ($M_V \sim -1.21$; Balbinot et al., 2013), and Munoz 1 ($M_V \sim -0.4$; Muñoz et al., 2012). These objects used to form an outlier population on the size-luminosity plane, sharing luminosities at least a factor of three lower than those of the other MW satellites known at the time and half-light radii smaller than 5 pc. Despite such extreme properties, they were often classified as globular clusters.
in the literature because their central surface brightnesses ($\mu \lesssim 26 \text{ mag arcsec}^2$) are higher than those of the known UFDs. Photometric and spectroscopic studies of these objects support their classifications as globular clusters (e.g., Fadely et al., 2011; Muñoz et al., 2012).

Central surface brightness is no longer a direct indicator for the classification of low-luminosity stellar systems. The newly discovered extremely low-mass clusters Kim 1 – 3 share extremely low surface brightnesses comparable to those of MW UFDs. Kim 1 and Kim 3 exhibit the absence of well-defined centers unlike previously known low-luminosity GCs, which make them completely transparent on the sky. Given an ellipticity as large as $\epsilon \sim 0.4$, it would be even incorrect to classify Kim 1 as a “globular” cluster. Since the discovery of Kim 1–3, other wide-field photometric surveys have also reported the detection of stellar overdensities sharing similar extreme properties with Kim 1–3, namely DES 1 (Luque et al., 2016) and SMASH 1 (Martin et al., 2016). These new objects typically exhibit a large ellipticity ($\epsilon \sim 0.7$) and an extended physical size ($r_h \sim 10 \text{ pc}$), with which they considerably resemble Kim 1.

Possibly the low-mass clusters were born with such low masses and have survived to the present time. Another possibility is that these objects are stripped down versions of formally more massive GCs where the currently observed low masses are a consequence of substantial stellar mass loss due to dynamical evolution such as tidal stripping and tidal shocking. There is growing evidence that supports the latter scenario, including mass segregation in Kim 2–3, and the unusually large ellipticity of Kim 1, DES 1, and SMASH 1. These findings are consistent with their observed low mass and short half-mass relaxation time ($t_h < 1 \text{ Gyr}$). Distinguishing between these two different scenarios will provide insight into the formation and evolution of the faintest GC population and the build-up of the MW halo stars.

One of the important aspects of the extremely low-mass star clusters that remain poorly understood is the fraction of binary stars. Previous systematic photometric studies have revealed the anti-correlation between the binary fraction in GCs and the absolute luminosity of the cluster: clusters with lower total luminosity, hence smaller mass, have higher binary fractions in the cluster core (Sollima et al., 2007; Milone et al., 2012). Recent studies of extremely low-mass star clusters using the best ground-based telescopes, however, have challenged the binary fraction-mass anti-correlation. For example, Fadely et al. (2011) investigated the extremely low luminosity star cluster Segue 3 ($M_V = 0.0 \pm 0.8$) and detected only one spectroscopic binary in a sample of 32 analysed stars. This preliminary result can be interpreted that Segue 3 hosts only a small binary population, in contrast to the low-luminosity clusters AM 4 ($M_V = -1.8$), Palomar 13 ($M_V = -3.8$), and E 3 ($M_V = -4.2$), which host a large fraction of binaries up to $\sim 40\%$ in the cluster core (Milone et al., 2016).
The CMDs of Kim 1 ($M_V = 0.3 \pm 0.5$) and Kim 3 ($M_V = 0.7 \pm 0.3$) presented in this thesis also imply the absence of a large binary population in the clusters, although these results remain still inconclusive.

The apparent absence of a large binary population in the CMDs of the currently known clusters with extremely low masses is possibly a consequence of small number statistics and methodological issues such as photometric errors, selection biases, and low detection efficiency. Deep imaging with high precision photometry could reveal the hidden binary stars in the extremely low-mass clusters and lead to a picture that is consistent with previous findings on the anti-correlation between the fraction of binary stars and cluster mass observed for more massive GCs. If confirmed, it will support the ideas that low binary fractions in massive GCs are due to the disruption of soft binaries in the cluster core (Leigh et al., 2015, and references therein) and that the extreme low-mass clusters originally formed as low-mass systems. Conversely, if future observations find the measured binary fractions in the extremely low mass clusters to be indeed very low, the new results will raise the following questions: (i) what is the faintest limit for the validity of the anti-correlation? (ii) what physical process triggers such drastic destruction of binaries at the final stage of the evolution process of star clusters? or otherwise (iii) are the extremely low-mass clusters the remnants of once more massive GCs with a low fraction of binaries? Theoretical simulations will be also required to answer these questions.

It is conceivable that some of the extremely low-mass clusters host a low fraction of binaries, while the others a high fraction as predicted from the anti-correlation. In this case, more than one formation scenario will be required to explain the origin of the extremely low-mass clusters. Investigating the fraction of binaries in them will therefore provide crucial information on the formation and evolution history of GCs in general.

### 9.3 Further Investigation

#### 9.3.1 Mass Segregation: Diagnostics for Classification?

Newly discovered low-luminosity systems are now rapidly filling the notional gap between star clusters and dwarf galaxies in the size-luminosity plane, rendering the size-luminosity based diagnostic tool less effective. The most direct way to determine the type of a stellar system is to conduct a kinematic study with spectroscopy. It is, however, a technical challenge to study more than a handful of stars due to the system’s intrinsic low luminosity and therefore lack of bright giant stars. Another method is to determine the [Fe/H] spread, which also constrains the potential well of a system (Willman & Strader, 2012), but it requires even higher resolution spectroscopy. Deep imaging, on the other hand, can easily
reach magnitudes below their main-sequence turnoff (MSTO). In this context, a diagnostic method using deep photometry could turn out to be a powerful alternative.

We are investigating the presence or absence of mass segregation in nearby low-luminosity stellar systems using deep photometry as a diagnostic test for separating UFDs and low-mass star clusters. This method is based on the fact that star clusters and dwarf galaxies have fundamentally different types of sources for their gravitational fields: a collection of point masses and a smooth distribution of DM, which make them “collisional” and “collisionless” stellar systems, respectively (Binney & Tremaine, 2008). One observed characteristic of star clusters is mass segregation. The origin of mass segregation is either primordial or dynamical. Primordial mass segregation is an outcome of the star formation history at the central region with high collision rate (e.g., competitive accretion of mass and mergers between protostars Baumgardt et al., 2008). Dynamical mass segregation evolves within an initially non-mass-segregated cluster due to two-body relaxations (Meylan & Heggie, 1997; Baumgardt & Makino, 2003a). In either scenario, mass segregation is attributed to N-body encounters and energy equiparition in the clusters. For this reason, mass-segregation is not expected in collisionless systems like DM-dominated dwarf galaxies (see e.g., Mapelli et al., 2007). If a sufficient number of the nearby objects turn out to be consistent with this diagnostic test within certain ranges of parameters, then even more distant systems with similar conditions could be classified by this method, without expensive or infeasible spectroscopic follow-up.

The distribution of stars in a stellar system reflects its dynamical evolution history. For this reason, mass segregation in star clusters has been of great interest in both observational and theoretical studies over decades. Despite the history of the subject, the majority of low-luminosity ($M_V > -3$) clusters still remain largely unexplored in this context. The low-mass star clusters share extremely low density and simple stellar populations, which make them excellent control samples for UFDs. Differences between the radial variations of the mean stellar mass for the dynamically old star clusters and UFDs will reveal the effect of the dynamical component that distinguishes the two types of stellar systems. Although mass segregation in UFDs is not expected within the current DM theory framework, in fact there is very limited observational evidence to support this statement, mostly found in classical dwarf galaxies rather than UFDs (e.g., Mapelli et al., 2007). My future projects will directly investigate the possibility of mass segregation in UFDs for the first time and provide more constraints on the role of DM in the dynamical evolution of dwarf galaxies in general. If evidence of pronounced mass segregation is found in one of UFDs by any chance, it might invoke an exotic evolution scenario for dwarf galaxies.

The accurate classification of extremely low-luminosity stellar systems will have great impact on estimating the true number of MW satellite galaxies and constructing the galaxy
luminosity function at the very faint end. Concretely classified UFDs will provide a reference point for DM indirect detection experiments and studying the formation of the smallest galaxies. The current challenge is that the lack of bright red giant stars in these systems hinders drawing robust classifications from spectroscopic studies alone. Even today, it is uncertain whether some of the most extreme UFDs should be classified as galaxies. Kinematic studies of those UFDs have reached unresolved solutions or large uncertainties for the velocity dispersion of kinematic member stars, due to small number statistics (e.g., Kirby et al., 2013). Consequently, the galaxy luminosity function is not constrained at the faint end. In this sense, having an alternative diagnostic method independent of spectroscopic resources is essential not only for ongoing surveys but also for future surveys like the Large Synoptic Survey Telescope (LSST) survey, which is expected to reveal a great number of extremely low luminosity systems at large distances. Since the stellar systems within the virial radius of the MW ($d_{\odot} \sim 300$ kpc) are close enough for the forthcoming James Webb Space Telescope (JWST) and Giant Magellan Telescope (GMT) to resolve their stellar populations to magnitudes fainter than the MSTO, this new method, once established, will be able to classify even the most distant MW satellites in the low luminosity regime.

9.3.2 Gaia Mission

The Gaia mission (Gaia Collaboration et al., 2016a) provides high-precision astrometric information of every object on the sky brighter than $G \approx 20.5$ mag. Gaia DR 1 became public in late 2016 (Gaia Collaboration et al., 2016b). Since the Gaia data does not contain colour information for point sources, conventional satellite search algorithms cannot make use of photometric filtering process for reducing field contamination. Instead, the source catalog of Gaia provides high quality information on star-galaxy classification based on astrometric behaviours and thus unique capabilities for MW satellite search. Recently, two previously unseen inner-halo star clusters have been discovered in Gaia DR 1 (Koposov et al., 2017), which implies that there are possibly more extreme objects undetected in previous surveys. Proper motion measurements in mas/yr from Gaia will also enable systematic investigations into the orbital motions of relatively luminous or nearby MW satellites. Proper motion information with such high precision was largely unavailable from pre-existing surveys. The orbital information of MW satellites from Gaia will allow establishing their association with the plane of satellites. I will analyse the successive data releases of Gaia to look for new MW UFDs and investigate the proper motions of luminous satellites.
9.4 Future Surveys for Dwarf Satellites

Forthcoming large-scale surveys will revolutionize our view of the MW. The LSST (Ivezic et al., 2008) is a dedicated telescope for optical survey with a wide field of view (≈ 9.6 deg$^2$) and a large collecting area (≈ 8 m in diameter). The LSST will carry out a deep optical survey over the entire southern sky from 2022 over ≈10 years. The LSST will enable searching for MW satellites with luminosity down to $M_V \approx -1$ at distances out to 400 kpc (Tollerud et al., 2008; Bullock et al., 2010) and significantly improve the census of MW satellites in the southern sky. The Wide Field Infrared Survey Telescope (WFIRST) is a 2.4-m space telescope planned to be launched in the mid-2020s that features a resolution comparable to that of Hubble Space Telescope but a much wider field of view, ≈ 0.3 deg$^2$ (Spergel et al., 2013). WFIRST High Latitude Survey will map ≈ 2200 deg$^2$ with an unprecedented photometric depth in near-infrared passbands, which will possibly reveal the faintest and remotest satellites in the MW halo.

Understanding the satellite systems of other galaxies in a variety of environments is also critical for a comprehensive investigation into the small scale problems of the ΛCDM model. There are significant efforts underway to extend the census of low-luminosity satellites in the local universe. The Pan-Andromeda Archaeological Survey (PAndAS; McConnachie et al., 2009) and Panoramic Imaging Survey of Centaurus and Sculptor (PISCeS) are deep wide-field imaging surveys using ground-based telescopes and have revealed a numerous number of satellites and substructures around the nearby (< 4 Mpc) galaxies (Martin et al., 2006, 2009, 2013; Ibata et al., 2007; McConnachie et al., 2008; Richardson et al., 2011; Crnojević et al., 2014, 2016; Sand et al., 2014; Toloba et al., 2016). Due to the limited resolving power of ground-based telescopes, however, the galaxy luminosity function can only be probed down to $M_V \approx -6$. The wide field and high spatial resolution of the WFIRST will enable mapping the stellar halo of such nearby galaxies to large distances and substantially extend the luminosity function, providing constraints on galaxy formation models in the local universe.

Together with JWST and extremely large telescopes being planned such as the GMT, it will be possible to better understand the true nature of extremely faint MW satellites to be discovered in the future surveys. As well as already known MW satellites, those newcomers will be excellent laboratories to probe the cosmic fine-print of DM and galaxy formation.
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