Milky Way Dwarf Galaxies: A Search for Stellar Substructure

by

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A thesis submitted for the degree of Doctor of Philosophy

of the

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October 2016
In memory of my dear friend
“Bec”
Rebecca Patricia Paterson
1987-2015
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 2011 and October 2015 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 three main chapters is therefore a completely self-contained article, which has been published in, or submitted to, a peer-reviewed journal. The thesis has been excellent preparation for post-doctoral research, as the candidate has experienced the full scientific process from planning observations and reducing raw data, through to scientific analysis and producing peer-reviewed publications.

The three papers presented in this thesis use data from the Dark Energy Camera on the 4m Blanco Telescope at Cerro Tololo, Chile. The candidate has written each paper in its entirety, incorporating suggestions and feedback from the co-authors and the referees.

Tammy Ann Roderick
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Abstract

The Milky Way and its satellite population provides the nearest laboratory for the study of galaxy formation and evolution. As a result, it is the subject of detailed analysis, in order to better understand both the formation history of our own galaxy, as well as galaxy formation in the cosmological context. The dwarf galaxy population is of particular interest due to its perceived high dark matter content inferred from velocity dispersion measurements, making the dwarf galaxies candidates for the primordial building blocks of galaxy formation under the ΛCDM cosmological paradigm.

As close as the Milky Way satellite population is, much of it remains a mystery. This is largely due to the difficulty in its observation; not only are the satellites resolved into their individual stars, blending in with the foreground of the Milky Way, they are extremely faint in many cases and require time intensive telescope allocation to obtain science grade data. This has resulted in small-scale, piecemeal observations and varying data sets, making the development of accurate theoretical models difficult. The advent of the digital survey camera era has changed this somewhat, and provides a new opportunity to delve deep into the Milky Way satellite population.

This theses presents homogeneous observations, in the form of deep, wide-field photometry, of three of the Milky Ways satellite dwarf galaxies: Hercules, Sextans and Bootes I. The wide-field nature of these observations enables a thorough search for stellar substructure associated with these dwarfs, in an attempt to better understand their level of tidal interaction with the Milky Way and how this influences our understanding of their role in galaxy formation.

Each of the three dwarfs is found to possess extended stellar substructure, to varying degrees. The brightest, Sextans, demonstrates the least extreme substructure, and potentially has the most circular orbital path. The two fainter dwarfs are more representative of the ultra-faint regime and display more elongated structure, with most extreme of the two, Hercules, most likely to have the minimal peri-galactic distance. Interestingly, Hercules also has the most recent infall time, giving it less time to complete multiple orbits than Sextans or Bootes I. This pattern suggests that while the size and infall of each galaxy is important, it is the orbital eccentricity and peri-galactic distance which play a larger role in the level of tidal influence. It is also important to note that in this sample, the two dwarfs closest to the ultra-faint regime are also the two showing the most extreme structure. If this finding is representative of the rest of the ultra-faint population, it may indicate a need to review mass-to-light ratios which are based on the assumption that the dwarfs are in dynamic equilibrium.
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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

The question of how the Universe came to be has plagued scientists for generations. It has only been in recent history that cosmologists have even come close to having any understanding of an answer. Cosmology has been raised out of its infancy in the last twenty years, however there have been a number of scientific breakthroughs over the last century that served to catalyse its development. In 1920 the Great Debate took place between Shapley and Curtis, where they argued whether spiral nebulae were part of the Milky Way (MW), constituting the entirety of the Universe, or island universes existing outside the MW. The answer became unquestionably clear when Hubble discovered Cepheid variables in the Andromeda nebula (M31), giving it a distance far greater than Shapley’s estimated diameter of the MW (Hubble, 1925a). In the same year Hubble also used Cepheid variables in NGC 6822 to show that the nebula was “definitely assigned to a region outside the galactic system” (Hubble, 1925b). Other significant advances in astronomy followed, including: the discovery of the expanding universe (Hubble, 1929a), the theory that the Universe expanded from a primeval atom or cosmic egg (to become known as the Big Bang Lemaître, 1931), the observation of mass not accounted for by luminous matter (Zwicky, 1933), the chemical equations governing the production of elements in stars (Bethe, 1939; Hoyle, 1946), the idea of hierarchical galaxy formation (Hoyle, 1953), and the concept of cosmic inflation (Guth, 1981). The understanding that came with these advancements eventually led to the development of the modern cosmological paradigm, ΛCDM. This theory describes a universe comprised primarily of cold dark matter (CDM) and a cosmological constant (Λ) (Blumenthal et al., 1984), and has become the prevailing cosmological theory.

Modern technology has made it possible to create relatively complex simulations based on cosmological theory (e.g. Millennium (Springel et al., 2005), Via Lactea, Aquarius

http://www.ucolick.org/~diemand/vl/index.html
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(Springel et al., 2008)), allowing us to watch the Universe evolve from the Big Bang to the present. These models facilitate cosmologically motivated predictions which can be compared to observations as a means of testing the validity of the model. The new era of CCD cameras and wide-field surveys has led to an unprecedented abundance of observational data (e.g. SDSS: Stoughton et al. (2002); Ahn et al. (2014), VHS: McMahon et al. (2013), Gaia-ESO: Randich et al. (2013), and DES: Diehl et al. (2014)), and has provided supporting evidence for ΛCDM cosmology (e.g. Koposov et al., 2009; Kravtsov, 2010; Diemand & Moore, 2011), as well as raised questions about its ability to explain certain observations, particularly with regard to the small scale structure of the Universe and galaxy formation (e.g. de Blok, 2010; Boylan-Kolchin et al., 2012; Pawlowski et al., 2014). With the aid of this new technology and wide-field automated surveys, a new branch of cosmology has developed (near-field cosmology, e.g. Freeman & Bland-Hawthorn, 2002), in an attempt to understand the discrepancies between observation and theory. Observational near-field cosmology makes use of the Galactic neighbourhood, that is the MW and M31, to investigate the process and history of our galaxy’s formation. Although near-field cosmology has only really grown in the digital era, the concept is not new. Pivotal work by Eggen et al. (1962), and Searle & Zinn (1978) pioneered the concept of Galactic archaeology and demonstrated the usefulness of chemical and dynamical information from nearby stellar groups in studying galaxy formation and evolution.

This thesis makes use of a new wide-field CCD camera, known as the Dark Energy Camera (DECam, DePoy et al., 2008; Flaugher et al., 2012, 2015), to build on previous observational data and help further our understanding of galaxy formation and its relationship to cosmology. First a background on the current understanding of galaxy formation is discussed, followed by an overview of current near-field observations. This provides context for the thesis which is outlined at the end of this chapter.

1.1 Hierarchical Galaxy Formation

Under the ΛCDM cosmological paradigm, structure in the Universe formed hierarchically; small filaments of dark matter merged together and coalesced into larger structures, continuing to merge and accrete to form galaxies (Blumenthal et al., 1984; Van Den Bosch et al., 2005; Giocoli et al., 2010). This dark matter substructure has been demonstrated to occur at all scales, resulting in galaxy halos having the appearance of scaled down galaxy clusters (Moore et al., 1999). It follows then, that since galaxy clusters display a merger and accretion history, so too should galaxies like the MW (Diemand et al., 2007). Such evidence has been observed in our own Galactic neighbourhood, with M31 providing a particularly good example, possessing numerous satellite systems and stellar substructure in its halo (McConnachie et al., 2009; Ibata et al., 2014). Our own MW possesses similar features, with a vast system of stellar streams (e.g. Newberg, 2002; Belokurov et al., 2007b;
Grillmair, 2006b, 2014; Newberg et al., 2010; Sesar et al., 2013), and the spectacular Sagittarius dwarf (Ibata et al., 1994) in the midst of being torn apart and consumed by the MW (Majewski et al., 2003; Newby et al., 2013). Perhaps less dramatic, but no less significant, is the satellite population of the MW. This population has been the subject of numerous investigations (notable discussions and census have been provided by Mateo, 1998; Tolstoy et al., 2009; McConnachie, 2012), where in particular, the dwarf galaxy population is seen to be of cosmological origin in the context of ΛCDM.

The dwarf galaxy population of the MW is comprised of various different morphological types, the majority of which are dwarf spheroidals, although dwarf irregulars and transitional type dwarfs are also present (see McConnachie, 2012). Dwarf spheroidals have characteristically old stellar populations and are generally devoid of gas, whereas dwarf irregulars are gas rich and as the name suggests, display an irregular shape (Carraro, 2014). Transitional type dwarfs exhibit characteristics of both populations, leading to suggestions that they represent a transition from dwarf irregular to dwarf spheroidal (Lin & Faber, 1983; Grebel et al., 2003).

The MW dwarf galaxies have been observed to have unusually high velocity dispersions for the amount of visible matter they contain, leading to the interpretation they are dark matter dominated (Simon & Geha, 2007; Martin et al., 2007; Simon et al., 2011; Koposov et al., 2015a; Kirby et al., 2015), providing excellent observational support for their role in cosmology as the building blocks of larger galaxies. However, in some ways, the MW dwarf galaxies have raised more questions than they have answered. A prime example of this is the ‘Missing Satellites’ problem, where simulations indicated the existence of far more satellites than had been observed (Klypin et al., 1999; Moore et al., 1999). Observational selection effects were a very real issue (Jerjen, 2008, 2010; Kravtsov, 2010). By making careful corrections for selection effects and introducing the idea that there is strong suppression of star formation, arguments have been put forward to solve the missing satellites problem (Simon & Geha, 2007; Koposov et al., 2009). However this problem has taken another form, the ‘Too Big To Fail’ problem (Boylan-Kolchin et al., 2011), in which the largest sub-halos found in simulations appear inconsistent with the dynamics of the brightest MW dwarf spheroidals (Boylan-Kolchin et al., 2012). Although attempts have been made to resolve this issue (Wang et al., 2012; Vera-Ciro et al., 2013; Guo et al., 2015), it continues to persist (Jiang & Van Den Bosch, 2015) and has recently been shown to also be a problem for more extreme dwarf galaxies (Papastergis et al., 2015).

Another problem which has arisen from observations of the MW satellites is the ‘Core/-Cusp’ problem. This problem describes a discrepancy between the dark matter profile of galaxies determined from observations (a core-like profile), and the profile expected from simulations (a cusp-like power law behaviour) (Moore, 1994; Flores & Primack, 1994). Various discussions have arisen from this discrepancy (e.g. de Blok et al., 2003; Swaters et al., 2003), and it continues to fuel questions about small scale cosmology (de Blok, 2010).
Recently, it has been posited that the core/cusp problem is related to the too-big-to-fail problem, and that both can be solved through a process of periodic supernova feedback during galaxy formation (Kato et al., 2015).

An issue of a slightly different nature however is the distribution of satellites about the MW. Rather than displaying a relatively homogeneous spatial distribution, it was noted that the satellites were preferentially distributed in a disc-like structure about the MW (Lynden-Bell, 1976; Kroupa et al., 2005). A similar structure has been observed around M31 (Metz et al., 2005, 2007; Ibata et al., 2013; Conn et al., 2013), and in both cases the observed disc shows a high inclination to the plane of the host galaxy. Although it has been shown that the existence of such discs is not in conflict with ΛCDM cosmology (Bahl & Baumgardt, 2014), it has been argued that this is evidence against a cosmological origin for the satellites. An alternative suggestion is that the majority of satellites are of tidal origin (Kroupa et al., 2010; Pawlowski et al., 2011, 2012; Yang et al., 2014; Pawlowski et al., 2015), which would account for the apparently high mass-to-light ratios seen in the dwarf galaxy population (Yang et al., 2014).

The role played by dark matter appears to be an underpinning theme for all of the issues raised by observations of the MW satellites. Despite our best efforts, the nature of the dark matter content in the MW satellites remains a mystery, making them the target of a growing curiosity.

1.2 Dark Matter Content

The existence of dark matter was inferred through observation prior to the development of ΛCDM cosmology (Zwicky, 1933), and it has since been found to constitute over 80% of the mass in the Universe (Ade et al., 2014), based on the ΛCDM paradigm. Using an estimate of mass based on dynamic velocity dispersion measurements in the Coma galaxy cluster, and comparing the estimate to an estimate based on the luminosity of galaxies in the cluster, it was shown that there was not enough luminous matter to account for the total dynamic mass.

This principle can similarly be applied to individual galaxies. An approach to obtaining dynamic mass estimates in large spiral galaxies is to use the internal rotational velocity (Hubble, 1929b). Although conceptually straight forward, it has been shown that this method is complicated by the fact that not all spiral galaxies are axially symmetric (Bosma, 1978). Other considerations have included galaxy morphology (e.g. Rubin et al., 1985), and gas content (e.g. Rubin et al., 1989). A different approach must be adopted for pressure supported systems such as dwarf galaxies. Since these systems are not rotationally dominated (although some have demonstrated a rotational component (Geha et al., 2003)), their dynamic mass can instead be inferred by estimating the gravitational potential from
the observed velocity dispersion (Fish, 1964). In practice, this can be fraught with danger. A key assumption of this method is that the Virial Theorem is applicable. That is, it assumes the system is in dynamic equilibrium and not interacting with its surrounds. This is not necessarily true. Satellite galaxies interacting with their hosts can undergo significant tidal stirring (Lokas et al., 2012), which can potentially lead to the contamination of kinematic samples with unbound stars (Klimentowski et al., 2007). This can cause inflated velocity dispersion measurements and yield higher mass-to-light ratio estimates (e.g. Adén et al., 2009b; Koposov et al., 2011).

Unbound stars are not the only source of kinematic contamination. Other contaminants which can have an effect on velocity dispersion measurements include binary stars and interloper stars (Olszewski et al., 1996). The effect of binary stars on the velocity dispersion of dwarf spheroidals has been determined to be at most 30%, and can be corrected for with multi-epoch observations (Hargreaves et al., 1996). It appears to be more of a problem in ultra-faint dwarfs, but cannot account for observed velocity dispersions much greater than 4.5 km s\(^{-1}\) (McConnachie & Cote, 2010). Interloper stars are stars that do not belong to the system. These are usually foreground stars from the MW, but can also be stars that belong to other satellites in projected proximity to the system. Many can be removed with photometric aid by means of colour and magnitude discrimination (e.g. Adén et al., 2009a). Good discrimination of interloper stars, and an understanding of potential contamination from unbound stars are essential in order to obtain reliable velocity dispersion measurements. This is demonstrated by Koposov et al. (2011) with their re-evaluated velocity dispersion measurement for BoötesI. Not only do they find a significantly lower velocity dispersion, their refined sample also reveals the presence of hot and cold kinematic components.

It is important to note that the presence of unbound stars may not be revealed by a galaxy’s velocity dispersion profile; the velocity dispersion profile of the bound stellar component may remain unchanged even after it has lost 99% of its original stellar population to tidal stripping (Peñarrubia et al., 2008). It is therefore important to obtain as much information as possible about a galaxy, both kinematic and photometric, in order to learn the true nature of its dark matter content. The dominance of dark matter in these galaxies is a leading factor in their support for the ΛCDM cosmological theory. Skepticism as to the true nature of dwarf galaxies has led to the formation of alternative cosmological theories. One such theory, known as Modified Newtonian Dynamics (MOND), has gained some momentum in recent years due to the number of discrepancies between observations of dwarf galaxies and the predictions of ΛCDM.

Modified Newtonian Dynamics was first put forward as an alternative to the existence of dark matter in 1983 (Milgrom, 1983a,b,c). The basic theory introduced a constant, \(a_0\), with dimensions of acceleration, that modified gravity or inertia in the limit of small acceleration, and reproduced the observed rotation velocity curves without the need for large
quantities of dark matter. Although met with a great deal of skepticism from the astronomical community, MOND has gained momentum through the ability to explain observations relating to small scale structure which ΛCDM struggles to account for naturally. Examples include Renzo’s rule (Sancisi, 2004), and the baryonic Tully-Fisher relation (BTFR, Tully & Fisher, 1977). Renzo’s rule describes the existence of features in a rotation curve corresponding to features in the luminosity profile, implying gravitational dominance of baryonic matter. The BTFR describes a relationship between a galaxy’s rotational velocity and its mass (a similar relation exists between the mass and velocity dispersion for elliptical galaxies; Faber & Jackson, 1976), but has been refined more recently to show a specific relationship to the total baryonic mass (both luminous and gaseous), which can be understood in terms of MOND (McGaugh, 2005; McGaugh & Wolf, 2010). Despite the elegance of MOND in these situations, it lacks a generally accepted physical theory and therefore a cosmological connection, making it a less appealing theory in the scientific community (Sanders, 2015). In contrast, ΛCDM has been successful at reproducing large-scale cosmological observables, despite its shortcomings on small scales, and provides a physical theory that has generally been embraced by the scientific community. The conflicts between MOND and ΛCDM serve to demonstrate the need for improved observational data in order to better constrain our theories.

1.3 Galactic Archaeology

Galactic archaeology and near-field cosmology are strongly intertwined. Where near-field cosmology aims to understand the observed small-scale structure of the Universe in a cosmological context, Galactic archaeology aims to piece together the formation history of our local Universe based on the fossil record that has been left behind. The process of galaxy formation should leave behind imprints in the spatial, kinematical, age and chemical distribution of stars, and the Galactic halo should possess some of the best preserved fossils of our galaxy’s formation (e.g. Helmi, 2008).

This fossil record presents itself in many forms, including the stellar halo of the MW, its multitude of stellar streams, and numerous subsystems of globular clusters and dwarf galaxies. Many theories have been put forward to describe the development of these features, but it can be argued that there are two traditional models which most formation scenarios conform to (Helmi, 2008). One describes a dissipative process where the oldest stars were formed from the collapse of gas falling toward the Galactic centre (Eggen et al., 1962). The other is much closer to the hierarchical scenario described by ΛCDM, where stars formed in a number of proto-galaxies (Searle & Zinn, 1978). It has been shown that both scenarios can reproduce the shape and density profile of the inner stellar halo (Samland & Gerhard, 2003; De Lucia & Helmi, 2008), however the observed substructure in the outer halo would appear to provide stronger support for a hierarchical scenario.
rather than a dissipative process (Helmi, 2008; Belokurov, 2013); from a cosmological standpoint, the dwarf galaxy population represents what remains of the dark matter halos accreted by the MW (Bullock & Johnston, 2005).

The extent to which accreted dwarf galaxies might have contributed to the build-up of the MW halo may be tested using the chemical signature of stars in our galaxy to trace its formation history (e.g. Freeman & Bland-Hawthorn, 2002). While some subset of halo stars do appear to show abundance patterns consistent with those observed in present-day dwarf galaxies (Nissen & Schuster, 1997, 2010), the majority of halo stars are quite distinct from stars observed in the large classical dwarf satellites of the MW (e.g. Venn et al., 2004). This indicates that the halo cannot be predominantly composed of stars from this type of system; any such accretion activity must have occurred at early epochs, before the putative dwarf progenitors of the halo had time to chemically evolve. More recently, it has been shown that the observed disc of satellites around the MW is consistent with a merger event between M31 and the MW (Yang et al., 2014), raising further questions about the role of the satellites in the formation of the MW. The current kinematics of the satellites can be used to model their orbits, and to develop an understanding of their infall times (Rocha et al., 2012). This provides an important link between Galactic archaeology and cosmology, however, the difficulty in obtaining proper motions for all of the satellites makes it difficult to develop accurate models. Detailed study of the tidal tails in some systems, as well as modelling of tidally disrupting systems, suggests the potential to obtain orbital information about a satellite from the spatial distribution of any tidal debris it may be associated with (Küpper et al., 2015). This will provide more precise comparison for simulations, and also has the potential to reveal information about underlying dark matter distributions (Errani et al., 2015). Developing a broader census of the spatial distribution of the satellites will also provide a more methodical approach to obtaining wide-field spectroscopic follow-up.

1.4 The Milky Way Satellites

The MW, and by extension M31, is a well established treasure trove of information in regard to galaxy formation and evolution (Mateo, 1998; Grebel et al., 2003; Tolstoy et al., 2009). The MW satellites are close enough that they can be resolved into their individual stars. While this causes problems in disentangling them from the MW foreground, it enables detailed observation of their stellar populations.

The existence of the MW dwarf galaxies has been known for some time, however the era of the digital all-sky survey (e.g. SDSS (York et al., 2000), Pan-STARRS (Kaiser et al., 2002), DES (Flaugher, 2005), Southern Sky Survey (Keller et al., 2007)) has led to an explosion of discoveries of increasingly low luminosity objects. Those first dwarfs found prior to the digital survey era are now referred to as the ‘classical’ dwarf galaxies, and belong to a
class of brighter satellites (Sculptor, \(M_v = -11.1\) (Shapley, 1938b), Fornax, \(M_v = -13.4\) (Shapley, 1938a), Leo I, \(M_v = -12.0\), and Leo II, \(M_v = -9.8\) (Harrington & Wilson, 1950), Draco, \(M_v = -8.8\), and Ursa Minor, \(M_v = -8.8\) (Wilson, 1955), Carina, \(M_v = -9.1\) (Cannon et al., 1977), Sextans, \(M_v = -9.3\) (Irwin et al., 1990)). The abundance of newly detected low surface brightness objects has led to a new class of satellites, known as the ultra-faint dwarfs (e.g. Walsh et al., 2007; Belokurov et al., 2007a). The search for new MW satellites has probed so far down the luminosity function that the distinction between dwarf galaxy and star cluster has become extremely difficult (Willman & Strader, 2012). Some objects are so faint and diffuse it is difficult to learn much about them at all (e.g. Kim et al., 2015b; Kim & Jerjen, 2015b).

This in some sense serves as motivation to study the brighter dwarfs in as much detail as possible, particularly in respect to kinematics. For example: if the majority of MW dwarfs are experiencing tidal perturbations, this should naturally extend to the ultra-faint population since they must surely undergo similar, or more extreme effects from the potential of the MW. Many of the MW dwarfs do show signs of tidal interaction with the MW (e.g. Ursa Minor (Palma et al., 2003), Ursa Major II (Simon & Geha, 2007), Carina (Battaglia et al., 2012)), or possibly between each other (e.g. Fornax, Coleman et al., 2004; Coleman & Da Costa, 2005; Yozin & Bekki, 2012). These features are not confined to just the dwarfs; many MW globular clusters also show evidence of tidal structure (see Grillmair et al., 1995; Leon et al., 2000; Majewski et al., 2012). In some cases the effects are extreme (e.g. Sagittarius (Ibata et al., 1994; Majewski et al., 2003; Newby et al., 2013), Pal 5 (Odenkirchen et al., 2001b; Carlberg et al., 2012; Kuzma et al., 2015)), and result in vast stellar streams littering the halo of the MW (Newberg, 2002; Peñarrubia et al., 2004; Grillmair, 2006a; Belokurov et al., 2007b; Newberg et al., 2010). The existence of a disc of satellites (Pawlowski et al., 2012, 2013) also serves as motivation for the tidal origin of many of the satellites orbiting the MW, and the cosmological implications have made this a controversial topic.

In contrast, some of the satellites appear almost pristine (e.g. Draco, Ségall et al., 2007), while others are more ambiguous (e.g. Sculptor Coleman et al., 2005; Westfall et al., 2006). In order to resolve the issues regarding the origin of the satellites, each one requires detailed study. This is a massive undertaking, and due to limited telescope time and narrow fields-of-view, has resulted in piecemeal data which typically concentrate on the central regions of these galaxies. The hierarchical nature of galaxy formation suggests that any evidence of tidal interaction will most likely be present in the outskirts of a system, making wide-field observations a necessity in the search for answers.
1.5 Thesis Outline

The era of the wide-field CCD camera presents the opportunity to peer into the extended outskirts of the MW satellites and search for substructure and tidal features previously undetectable. The body of work in this thesis employs the wide-field observational capability of DECam on the 4m Blanco telescope, at Cerro Tololo in Chile, to present a set of deep, uniform, observations focussing on three of the MW dwarf galaxies. This study lays the foundation for a deep, homogeneous survey of the MW dwarf galaxy population in order to better understand the nature and degree to which the dwarf galaxies are influenced by the MW tidal forces. Although there have been recent in-depth observations taken for some of the MW dwarf galaxies (e.g. Battaglia et al., 2012; McMonigal et al., 2014), few dwarfs have been observed on such scale accessible to DECam, and there is no uniform data set to enable comparisons.

Potential targets for this thesis were chosen from the catalogue compiled by McConnachie (2012). All nearby dwarf galaxies were considered, with the final targets chosen to fit the following criteria:

- Distance of no more than 500 kpc (twice the MW virial radius);
- Small enough to be easily surveyed (excludes Sagittarius and Magellanic Clouds);
- Luminous enough to have sufficient RGB stars for suitable measurements to be done (excludes most ultra-faint dwarfs);
- Visible during allocated telescope time.

The following chapters present a detailed analysis of the substructure in each of the dwarf galaxies: Hercules, Sextans and Boötes I. These three galaxies represent a variety of the MW dwarfs. While Sextans is considered a classical dwarf, Hercules and Boötes I are much closer to the ultra-faint regime. The three galaxies lie at varying heliocentric distances of 132 kpc, 86 kpc and 65 kpc for Hercules, Sextans and Boötes I respectively. Note that each chapter presents an independent, original journal publication in its entirety, and is formatted accordingly with an abstract, introduction and summary.

In Chapter 2, the analysis is presented for the Hercules dwarf. Since this chapter was the first to be published, the techniques developed for the analysis are discussed in detail. This includes the photometric process and star/galaxy separation, as well as a technique for the more flexible selection of stars from the colour-magnitude diagram. This chapter also develops the statistical analysis which is applied to later chapters. Chapters 3 and 4 present the analyses for Sextans and Boötes I, respectively. All three chapters present discussions on their individual results.
This thesis concludes in Chapter 5 with a discussion placing the results in context with the larger picture of galaxy formation in the MW, demonstrating the usefulness of wide-field photometric observations of this scale. The future potential for this work is also be presented, and tables providing weighted candidate stars for each statistically significant over-density mentioned in the thesis body are provided as an appendix (tables in the appendix are abbreviated for printed form, but provided in full as digital supplements).
CHAPTER 2

Stellar Substructures around the Hercules Dwarf Spheroidal Galaxy

This chapter has previously been published as “Stellar substructures around the Hercules dwarf spheroidal galaxy”, Roderick, T.A. et al., 2015. ApJ, 804(2), pp.112.

2.1 Abstract

We present deep $g,i$-band DECam stellar photometry of the Hercules Milky Way satellite galaxy, and its surrounding field, out to a radial distance of 5.4 times the tidal radius. We have identified nine extended stellar substructures associated with the dwarf; preferentially distributed along the major axis of the galaxy. Two significant over-densities lie outside the 95% confidence band for the likely orbital path of the galaxy and appear to be free-floating tidal debris. We estimate the luminosity of the new stellar substructures, and find that approximately the same amount of stellar flux is lying in these extended structures as inside the main body of Hercules. We also analyse the distribution of candidate blue-horizontal-branch stars and find agreement with the alignment of the substructures at a confidence level greater than 98%. Our analysis provides a quantitative demonstration that Hercules is a strongly tidally disrupted system, with noticeable stellar features at least 1.9 kpc away from the galaxy.

2.2 Introduction

Ultra-faint Milky Way (MW) satellite galaxies are the most dark matter dominated stellar systems in the Universe (Mateo, 1998; Simon & Geha, 2007; McConnachie, 2012). The high mass-to-light ratios seen in these pressure-dominated systems are determined from their velocity dispersion, which assumes that the underlying stellar populations are in dynamic-equilibrium. However, satellite galaxies interacting with their hosts can undergo significant
tidal stirring (Lokas et al., 2012), leaving kinematic samples potentially contaminated by unbound stars (Klimentowski et al., 2007). In the case where a galaxy is being tidally disrupted, the mass-to-light ratio can be overestimated, and this may not be apparent in the galaxy’s dispersion profile (Peñarrubia et al., 2008). It is also possible for a galaxy that has undergone tidal disruption to retain its spherical shape (Muñoz et al., 2008).

The dynamical state of a satellite galaxy is thus a highly relevant question. For that reason it is important to search for signs of tidal disruption not only in the central region of these galaxies, but in the vicinity around them where tidal debris may be present. The MW satellites provide an excellent opportunity for this type of investigation, as they are close enough to be resolved into individual stars and can be studied in great detail (see Tolstoy et al., 2009; McConnachie, 2012; Jerjen, 2012, for a discussion and census of local satellites).

Comprehensive studies of the MW satellite galaxies have led to numerous investigations of their role in galaxy formation. In the ΛCDM cosmological paradigm, galaxies form hierarchically through merger and accretion of smaller structures (Blumenthal et al., 1984; Van Den Bosch et al., 2005; Giocoli et al., 2010). Moore et al. (1999) demonstrated that dark matter sub-structure occurs on galactic scales, resulting in galaxy halos appearing as scaled versions of galaxy clusters. Mergers and accretion are a feature of galaxy clusters, therefore the outskirts of larger galaxies should also show signs of merger and accretion events (Diemand et al., 2007). A rather striking example in this context is Andromeda (M31), which possesses numerous satellite systems and copious substructure in its stellar halo (McConnachie et al., 2009; Ibata et al., 2014). Substructures are also observed in our own Milky Way in the form of stellar streams (e.g. Newberg, 2002; Belokurov et al., 2007b; Grillmair, 2006b; Newberg et al., 2010; Sesar et al., 2013; Grillmair, 2014), with perhaps the quintessential example being the Sagittarius dwarf (Ibata et al., 1994), and its great tidal tails strewn across the sky (Majewski et al., 2003; Newby et al., 2013).

Contrary to the predictions of ΛCDM, Kroupa et al. (2005) demonstrated that the distribution of the MW satellite population is inconsistent with that of a dwarf galaxy population drawn from cosmological sub-structure. Further investigation of the satellite populations of both the MW and M31 has found, in both cases, that the satellites have a disc-like distribution with high inclination to the plane of the host galaxy (Metz et al., 2005, 2007, 2009; Pawlowski et al., 2013; Ibata et al., 2013; Conn et al., 2013). This has led to the alternative picture that a significant fraction of the currently known MW satellite galaxies is of tidal origin (Kroupa et al., 2010; Pawlowski et al., 2014); forming from a major collision of the MW and another galaxy. This theory accounts for many of the observed features of the dwarf galaxy population, including the high mass-to-light ratios (explained as systems driven out of equilibrium (Yang et al., 2014)).

Learning whether or not the dwarf population is largely comprised of systems driven out of equilibrium, or shows signs more indicative of hierarchical build-up, may be a key
factor in determining the origin of the population as a whole. Most of the research into the MW dwarf galaxy population to date has been restricted to the main stellar body of each dwarf. However, it is in the outer regions where we expect to see more subtle signs of tidal disruption. The obvious example is Sagittarius (Ibata et al., 1994; Newby et al., 2013), however, Ursa Minor (Palma et al., 2003), Ursa Major II (Simon & Geha, 2007), Carina (Battaglia et al., 2012; McMonigal et al., 2014), and Fornax (Coleman et al., 2004) all display stellar substructure in their outer regions, suggesting that they are not dynamically pristine stellar systems.

The need for wide-field studies of the dwarf galaxy population is a recurring theme. Given recent advances in large-mosaic CCD cameras, a logical next step is to choose a target and explore its surrounding area in detail. The Hercules dwarf spheroidal galaxy (Table 2.1) detected in the Sloan Digital Sky Survey (Belokurov et al., 2007a) is, in this context, particularly interesting. It is the most elongated of the MW dwarfs (see Coleman et al., 2007; Sand et al., 2009; Deason et al., 2012), which has led to suggestions of tidal disruption and interaction with the MW. Coleman et al. (2007) noted that, given the large heliocentric distance of Hercules at 132 kpc, in order for it to be tidally disrupted, it must be on a highly elliptical orbit about the MW; consistent with the best model value for the perigalactic distance of \( r_p = 18.5 \text{kpc} \) (Adén et al., 2009b). Sand et al. (2009) suggested that Hercules may be embedded in a stellar stream, finding a stellar extension to the northwest of Hercules, and several associated stellar over-densities along the major axis out to \( \sim 35' \) (1.4 kpc). Martin & Jin (2010) further developed the idea that Hercules is part of a stream, and suggested that a progenitor on its orbit may have been taken close enough to the MW to induce disruption from a bound dwarf galaxy into a stellar stream. They present a viable scenario in which this is the case, where the orbital path of Hercules is aligned with its direction of elongation. The Hercules stellar population is old (>12 Gyr) and metal poor ([Fe/H]=-2.41) (Coleman et al., 2007; Kirby et al., 2008; Adén et al., 2011; Fabrizio et al., 2014), and displays a spread in [Fe/H] of more than 0.5 dex (Adén et al., 2011; Kirby et al., 2011). It has also been shown to have a high level of \( \alpha \)-enhancement (Koch et al., 2008; Adén et al., 2011; Koch et al., 2012), suggesting a large chemical enrichment contribution from TypeII supernovae progenitors. More recently, Koch et al. (2013) reported a significant deficiency in neutron-capture elements and suggested that the chemical enrichment of Hercules was governed by massive stars, coupled with a low star formation efficiency. All of this indicates Hercules has a rather colourful star formation history.

With the exception of Sand et al. (2009), and more recently Fabrizio et al. (2014), all observations of Hercules have focussed on its main stellar body (e.g. Coleman et al., 2007; Adén et al., 2009a, 2011). Sand et al. (2009) made observations along the semi-major axis, with five 23'× 23' fields, and Fabrizio et al. (2014) made similar observations with a 2 × 2 arrangement of 23'× 23' fields centred on Hercules. In this paper, we make use of the large field-of-view afforded by the Dark Energy Camera (DECam) on the 4m Blanco...
Table 2.1: Fundamental Parameters of Hercules

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morphological type</td>
<td>dSph</td>
<td>(1)</td>
</tr>
<tr>
<td>RA (J2000)</td>
<td>16:31:02</td>
<td>(1)</td>
</tr>
<tr>
<td>DEC (J2000)</td>
<td>+12:47:30</td>
<td>(1)</td>
</tr>
<tr>
<td>$l$</td>
<td>$28.7^\circ$</td>
<td>(1)</td>
</tr>
<tr>
<td>$b$</td>
<td>$36.9^\circ$</td>
<td>(1)</td>
</tr>
<tr>
<td>$D_{\odot}$</td>
<td>$132 \pm 12$ kpc</td>
<td>(2)</td>
</tr>
<tr>
<td>$M_V$</td>
<td>$-6.6 \pm 0.4$</td>
<td>(3)</td>
</tr>
<tr>
<td>$(m-M)_0$</td>
<td>$20.6 \pm 0.2$</td>
<td>(2)</td>
</tr>
<tr>
<td>$v_{\odot}$</td>
<td>$45.2 \pm 1.1$ km s$^{-1}$</td>
<td>(4)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$3.7 \pm 0.9$ km s$^{-1}$</td>
<td>(4)</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>$0.63 \pm 0.02$</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>$113.8 \pm 0.6^\circ$</td>
<td></td>
</tr>
<tr>
<td>$r_h$</td>
<td>$330$ pc</td>
<td>(3)</td>
</tr>
<tr>
<td>$[Fe/H]$</td>
<td>$-2.41 \pm 0.04$</td>
<td>(5)</td>
</tr>
<tr>
<td>Stellar mass (dynamic)</td>
<td>$2.6 \times 10^6 M_{\odot}$</td>
<td>(6)</td>
</tr>
<tr>
<td>Mean age</td>
<td>$&gt;12$ Gyr</td>
<td>(6)</td>
</tr>
<tr>
<td>Mass-to-Light ratio</td>
<td>$103^{+53}_{-43}$</td>
<td>(7)</td>
</tr>
<tr>
<td>$r_{tidal}$ (theoretical)</td>
<td>$485$ pc</td>
<td>(7)</td>
</tr>
</tbody>
</table>


Telescope at Cerro Tololo in Chile. We present wide-field observations (see Figure 2.1) in order to determine the true nature of Hercules’ elongated shape; including how far it extends into its surrounds, both parallel and perpendicular to the major axis. In Section 2.3, we describe the observations and data reduction process, including photometry and star/galaxy separation. We also discuss photometric calibration and completeness. In section 2.4, we describe the process of discriminating between Hercules and MW foreground stars via model isochrone selection. Section 2.5 contains our analysis of the shape of Hercules and the identification of statistically significant over-densities, while in Section 2.6 we investigate the luminosity of these over-densities and perform a further test of significance using blue-horizontal-branch star candidates as tracers. In section 2.7, we discuss these results in relation to the tidal disruption of Hercules, and summarise our findings.
2.3 Observations and Data Reduction

Observations were carried out over two nights on 2013 July 12 and July 13, using DECam at the CTIO 4m Blanco telescope, as part of observing proposal 2013A-0617 (PI: D. Mackey). DECam is comprised of a hexagonally shaped mosaic of 62 2K × 4K CCDs, each with a pixel scale of 0\arcsec 27/pix, providing a total field-of-view of 3 square degrees.

The data set is composed of a single DECam pointing, encompassing more than five times the estimated tidal radius of Hercules (485 pc or 12\arcmin 6, Coleman et al., 2007; Adén et al., 2009b), with 2 sets of 4× 900s exposures in $g$, and 1 set of 11× 600s exposures in $i$. Relatively poorer seeing in the initial set of $g$-band images resulted in a second set of exposures being taken to obtain appropriate photometric depth, thus giving total integration times of 7200s and 6600s in $g$ and $i$ respectively. A box shape dither pattern was used for exposures in both filters. This was to fill in the inter-chip gaps on the focal plane, and to avoid stars repeatedly falling on the same pixels (reducing the effect of bad pixel columns and CCD edge pixels).

The images were reduced using the DECam community pipeline\footnote{http://www.ctio.noao.edu/noao/content/Dark-Energy-Camera-DECam} (Valdes et al., 2014). This process included the application of a WCS solution to each image, the subtraction of sky-background, and the co-addition of images into a single image stack for each filter. The final product is a multi-extension FITS file, containing the stacked image-mosaic sliced into 9 separate tiles; one tile per FITS extension. The combined images for the Hercules data set have an average seeing across the field-of-view of 1\arcsec 49 for $g$ and 1\arcsec 09 for $i$. 

Figure 2.1: Field-of-view of our DECam observation (showing a smoothed representation of our complete catalogue from Section 2.3). The ellipse in the centre delineates the orientation and half light radius of Hercules (McConnachie, 2012). Outlines for the five fields from Sand et al. (2009) are superimposed in black, while the four fields from Fabrizio et al. (2014) are shown as a dashed outline.
The full-frame subtraction of the sky background from the hexagonal DECam images resulted in the corners of the final stacked FITS image containing no science data, but having non-zero pixel values. During preliminary photometry, this was found to cause problems with the background mapping for the corner tiles, where as much as 50% of the tile contained non-science pixels. In order to overcome this issue, WeightWatcher\(^2\) (Marmo & Bertin, 2008) was used, in conjunction with the weight maps produced by the community pipeline, to mask out the non-science pixels. By using these weight maps, the background map was weighted to reflect the presence of bright stars and the different levels of exposure created by dithering the CCD mosaic, producing an optimised background map for conducting photometry.

2.3.1 Photometry

Aperture photometry was performed on each of the nine tiles of the \(g\) and \(i\) images using the program Source Extractor\(^3\) (Bertin & Arnouts, 1996). Each of the corresponding masked weight maps from WeightWatcher were used by Source Extractor to produce the background map before source detection and photometry were carried out. The extraction process was run in two passes for each tile. A shallow first pass determined the average FWHM (\(\bar{F}\)) value for point sources in the image, where point sources were defined to be bright, circular detections with a Source Extractor ‘internal flag’ of 0 indicating isolation from near neighbours or image edges. This information served as input for the second, deeper pass, where aperture photometry was measured within \(1 \times \bar{F}\) and \(2 \times \bar{F}\). Using this method separately on each of the nine tiles also ensured that the aperture size was allowed to reflect variations in the point spread function (PSF) across the large field-of-view.

Spurious and non-stellar detections were eliminated from the Source Extractor catalogues by discarding objects whose light profile appeared significantly different to the point-like sources in the catalogue. Different types of objects were identified by examining the difference in instrument magnitude, \(m_2 - m_1\) (where \(m_1\) and \(m_2\) correspond to aperture sizes of \(1 \times \bar{F}\) and \(2 \times \bar{F}\) respectively). Stars with a well defined PSF populate a narrow range of negative \(m_2 - m_1\) values. Background galaxies however, are more extended and have a larger relative flux encompassed in the \(m_2\) aperture than the \(m_1\) aperture. Objects with \(m_2 - m_1 \geq 0\) represent cosmic rays, or other spurious objects which were instantly discarded. Figure 2.2 shows \(m_2 - m_1\) against instrumental magnitude for a single image tile in the \(i\)-band. Note that saturation occurs at an instrumental magnitude of \(\simeq -12\), and therefore detections brighter that this were excluded from analysis. The stars are the main vertical distribution of points (centred at \(m_2 - m_1 \simeq -0.68\)), flaring out at the faint end. Extended sources appear as a plume to the left of this population. The boundaries of the main stellar distribution were modelled with an exponential function to create a region

\(^2\)http://www.astromatic.net/software/weightwatcher
\(^3\)http://www.astromatic.net/software/sextractor
Chapter 2 Stellar Substructures around the Hercules Dwarf Spheroidal Galaxy

Figure 2.2: Example of the star/galaxy separation method used, where objects are distinguished by their light profile. $m_1$ corresponds to flux measured inside an aperture of $1 \times F$ and similarly, $m_2$ an aperture of $2 \times F$. Background galaxies are seen as a plume to the left of the vertical column of stellar objects.

Objects that fell outside this region were excluded from the catalogue. Our own star/galaxy separation method was accompanied by a cut based on the Source Extractor star/galaxy flag. A loose cut was made with objects accepted as stars if the flag was $> 0.35$. This method of combining the light profile and Source Extractor flag was adopted in order to retain more stellar objects at fainter magnitudes. The Source Extractor classification flag becomes less reliable at faint magnitudes due to the ambiguity in determining the shape of objects at this level; experimentation revealed that adopting this combined methodology gained at least a magnitude in depth with relatively little cost or contamination.

The star/galaxy separation was performed only on the $i$ band image, due to the significantly poorer seeing in the $g$ band. The results of this process were applied to the $g$ band during the following cross matching step.

The last step in creating the final catalogue of stellar sources was to cross reference the WCS solution coordinates, applied during the community pipeline processing, between the $g$ and $i$ catalogues. The cross referencing was carried out using the Stilts command line
package (Taylor, 2011). Only stars detected in both filters, and passed through the $i$ band star/galaxy separation, were included.

Once the complete catalogue of 87,000 stellar sources was established, it was calibrated onto the standard SDSS photometric system. This was achieved by first matching objects from the Hercules catalogue to stars from SDSS data release 10 (SDSS DR10: Ahn et al., 2014). The photometric zero points ($Z$), and colour terms ($c$), where colour is defined as $g_{\text{inst}} - i_{\text{inst}}$, were determined by comparing the SDSS magnitude to the instrumental magnitude of the $2 \times$ FWHM aperture for each star. Figure 2.3 shows this comparison for each filter (each point on the plot represents the mean of 10 stars, first sorted by colour and then grouped into tens). The following values were determined for $g$ and $i$, using a least-squares fit:

$$Z_g = 32.347 \pm 0.002, c_g = 0.042 \pm 0.002$$

$$Z_i = 32.067 \pm 0.002, c_i = 0.054 \pm 0.002$$
Chapter 2 Stellar Substructures around the Hercules Dwarf Spheroidal Galaxy

Figure 2.4: Map of Galactic extinction ($A_g$) used for each star in the Hercules catalogue. Correction values used are those from the SDSS photometry, based on Schlegel et al. (1998).

The large field-of-view afforded by DECam begets a significant variation in Galactic extinction across the field. It was, therefore, deemed inappropriate to use a single correction value for the whole Hercules catalogue. Instead, the extinction correction values ($A_g$ and $A_i$) from SDSS DR10, based on Schlegel et al. (1998), were applied to the calibrated Hercules photometry. The specific coefficients used were $A_g = 3.793E(B - V)$ and $A_i = 2.086E(B - V)$ (Stoughton et al., 2002). The values were applied by matching each star in the catalogue to its nearest SDSS neighbour, and using the corresponding extinction value. Figure 2.4 illustrates the extinction variation $0.165 < A_g < 0.280$ (a variation of approximately 5% in apparent luminosity) across the field, and corresponds to the extinction maps of Schlegel et al. (1998) in the direction of Hercules. The final, fully calibrated and extinction corrected catalogue was used as the reference for the following analysis.

2.3.2 Completeness

Artificial star tests were carried out in order to estimate the photometric depth of the data set, and determine the photometric accuracy. The IRAF `addstar` task was used to add stars of random R.A. and Dec. to each image tile; 40 stars each in 0.5 mag intervals between 20.5 and 27.0 mag. The previously described photometry pipeline was then run on each tile to recover the artificial stars. This process was repeated 30 times, to determine the mean recovery rate for each image tile. The completeness level of the whole image was estimated by taking the average over the nine tiles. The 50% completeness limit was ascertained by fitting the interpolation function described by Fleming et al. (1995) to the distribution of recovered artificial stars (shown in Figure 2.5), and determined to be 25.11 in $g$ and 24.70 in $i$, respectively.
Figure 2.5: Black points show recovered artificial stars for each 0.5 magnitude bin averaged across the field (in $g$ and $i$). The dashed lines show the best-fitting relation of the form described by Fleming et al. (1995), which was used to determine the 50% completeness levels.

The photometric accuracy was determined by measuring the variation in recovered magnitudes for each input magnitude. An exponential was fit to these measurements and used as a function for determining the photometric uncertainty for individual stars in the catalogue. This procedure was completed separately for each photometric band.

2.4 Foreground Discrimination

In order to detect stellar over-densities related to the Hercules dwarf galaxy, it is essential to disentangle its stellar population from that of the MW foreground. Selecting stars based on their position in the colour-magnitude diagram (CMD) is a useful way of performing such discrimination, and a model isochrone provides an excellent aid.

To that end, the best-fitting model isochrone and known distance to Hercules were used to produce a mask, separating MW foreground stars from Hercules stars in the CMD. Considering the old (> 12 Gyr), metal poor ($\approx -2.41$), population of Hercules, an isochrone of age 15 Gyr, [Fe/H] = -2.49 dex and [$\alpha$/Fe]=0.6 dex from the Dartmouth Stellar Evolution
Figure 2.6: Left: Colour-magnitude diagram of stars within the half-light radius of Hercules. Centre: Hess diagram of the same region as left, with 15 Gyr model isochrone from the Dartmouth Stellar Evolution Database (Dotter et al., 2008) overlaid. Right: Isochrone mask based on the model isochrone. The mask provides weights to the Hercules catalog based on proximity; stars closer to the isochrone are weighted more heavily. Note that the tip of the red giant branch is not visible due to the saturation point of the data.

Database (Dotter et al., 2008) was used (see Figure 2.6). Rather than applying a straight cut along the isochrone, a graduated mask was applied, comprised of weights varying with proximity to the isochrone. This was done to make allowances for photometric uncertainties, and provide a more rigorous method of discrimination than a straight cut selection box. Note that although a horizontal branch is clearly visible in the CMD in Figure 2.6, it is not included in the mask. These stars are used as individual tracers of the Hercules population later in the analysis. The tip of the red giant branch (RGB) is not visible due to the saturation point of the data. However, based on the luminosity function of the model isochrone, there are relatively few member stars populating this part of the CMD and the extra signal this would provide against the foreground would be minimal.

In order to create the mask, the isochrone was binned into 0.02 mag increments in $g$, and a Gaussian function was calculated along the colour range for each bin, with the width determined by the colour uncertainty, and an amplitude of 1. This gave stars lying on the isochrone the highest weight. The mask is shown in the right panel of Figure 2.6. The shape of the mask reflects the change in photometric uncertainty with magnitude, and encompasses the stellar population seen within the half-light radius of Hercules.

Once complete, the mask was applied to all stars in the CMD, assigning each star a weight, $w$, between 0 and 1. This immediately enabled the selection of the more likely Hercules stars, by employing a cutoff at any chosen weight. By lowering the cutoff weight, the selection region about the isochrone could be widened, and similarly the region could be narrowed by choosing a more strict cutoff. This provided a flexible means by which to analyse the Hercules population.
Figure 2.7: Demonstration of the binning and smoothing process. Left: 2D histogram of stars in the DECam field consistent with Hercules $w \geq 0.2$. Centre: the complement of the left histogram ($w < 0.2$) forming a ‘foreground map’. Right: difference of the two histograms, smoothed with a Gaussian filter of 3 pixel (120") kernel size.

2.5 Analysis

The search for over-densities was undertaken in two main steps: the detection and formal identification of potential over-densities, followed by a comparison of each detection to a control region to quantify its significance. Sections 2.5.1 and 2.5.2 describe these procedures in detail.

2.5.1 Detecting Over-Densities

In order to detect over-densities of Hercules stars in the DECam field, the distribution of stars in our catalogue was binned into a normalised 2D histogram of R.A. and DEC. Using $40'' \times 40''$ bins, an image of $200 \times 177$ pixels was created, where the pixel values reflected $\text{count}_{\text{bin}}/\text{count}_{\text{sample}}/\text{area}_{\text{bin}}$. To maximise the contrast between the Galactic foreground and Hercules stars, two separate histograms were created (see Figure 2.7) using the weights described in Section 2.4. The first contained only stars close to the model isochrone ($w \geq 0.2$), and the second contained everything else. By subtracting this ‘foreground’ map from the isochrone based histogram, artificial structures and foreground fluctuations were removed, leaving a well defined outline of Hercules and several potential over-densities (right panel in Figure 2.7). This residual image was then convolved with a Gaussian filter of varying kernel size (3, 5, and 7 pixels; smoothing over 120", 200", and 280" respectively), in order to identify features on different scales.

The stellar features detected in this final smoothed histogram were formally identified and labelled using the Python package scipy.ndimage. This package considers all pixels in an image above a specified threshold, and defines individual ‘segments’ based on adjoining pixels. Each segment was given a label for identification and later analysis.

\footnote{http://docs.scipy.org/doc/scipy/reference/ndimage.html}
We performed some experimentation in order to select a suitable threshold for the analysis. We calculated the mean and standard deviation of the pixel values in the smoothed histogram, and applied threshold values as some multiple of this standard deviation ($\sigma_t$). If the threshold was set too low, it was found that the algorithm returned many detections that were subsequently determined not to be significant; conversely, if the threshold was set too high then the algorithm found only the central body of Hercules. Thresholds of $1\sigma_t$ and $1.5\sigma_t$ struck an acceptable balance between these two extremes, and we performed the segmentation process twice with these two different thresholds in order to probe the extent of each detected over-density. Pixels with values $> 4\sigma_t$ above the mean were considered part of the main body of Hercules and excluded from labelling (this region was slightly larger than the area contained inside the half-light radius). We also performed the segmentation process using a threshold of $0.5\sigma_t$ in order to explore the very low-level structure of the central over-density surrounding the main body of Hercules. Although we do not report the results at this threshold in the same detail as for the other two thresholds (in order to maintain the clarity of the paper), we return to this calculation in Section 5.

Using this regime, individual features were identified as ‘segments’ and labelled. As the kernel increased from 120'' to 200'' and 280'', the smaller details disappeared and only the larger features remained apparent. As a check, this process was also performed with a 60'' kernel, at which point the level of detection ‘noise’ became too large. The results from the 120'' kernel are therefore presented here as it represents the best compromise between detail and noise. Figure 2.8 shows the over-densities for the two thresholds, smoothed with the 120'' kernel. Note that the labelling based on the $1\sigma_t$ threshold was adopted for the $1.5\sigma_t$ threshold, in order to compare similar over-densities (e.g. OD 13 surrounding the main body of Hercules at the $1\sigma_t$ threshold, decomposes into three segments at $1.5\sigma_t$, labelled OD 13.1, OD 13.2, and OD 13.3 respectively).

During the segmentation process, a control region was also defined for use in later analysis, consisting of all pixels in the 2D-histogram with a value less than the detection threshold. This ensured that no over-density was used in the control sample, and the sample was evenly distributed across the DECam field.

Once the identification and labelling of segments were complete, the stars which fell inside the segment boundaries were extracted from the catalogue, regardless of their isochrone weight. This ensured that the significance of each feature was analysed indiscriminately. Similarly, all stars corresponding to the control region were extracted, forming a sample for significance testing.

### 2.5.2 Significance of Detections

Once the stars of each over-density had been extracted, the significance of each feature was tested relative to the model isochrone. As well as this, a brief test was conducted
to check if extinction or variations in completeness across the field could be responsible for the over-densities detected. The location of the over-densities was compared to the extinction map from section 2.3.1 to check for correlations. It was found that the peak-to-peak amplitude of the extinction had to be increased by a factor of three before there were even hints of a correlation. As this equates to approximately five times the variation in the derived 50% completeness level across the field, it was deemed that these factors do not play a significant role in our detection of over-densities.

A feature was determined to be significant if a notable number of its stars are close to the isochrone in the CMD, i.e. $w \geq 0.8$. The number of stars with $w \geq 0.8$ ($N_{w \geq 0.8}$) was counted and recorded for each segment. The value of $N_{w \geq 0.8}$ for each detection was then tested against the control sample defined in Section 2.5.1. In order to carry out this test, a sub-sample of stars from the control sample was drawn randomly such that the number of stars in the sub-sample was equal to the number of stars in a given segment. $N_{w \geq 0.8}$ was counted and recorded for this control sub-sample, similarly to the segment. This process was repeated 10,000 times. The resulting frequency distribution was then compared to the value recorded for the segment. Figure 2.9 illustrates the results for two of the over-densities detected (OD 13 and OD 22). The frequency distribution of the control sampling is displayed as a histogram, with a box and whisker plot showing the range of possible values the control samples could take. The value of $N_{w \geq 0.8}$ recorded for the segment is marked with a black dashed line. The result for OD 13 (top) represents a significant

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Labelling of segments from the segmentation process for the 3 pixel (120''') kernel smoothed image. $1\sigma_t$ threshold detections are in grey, and $1.5\sigma_t$ threshold detections are in black. The labelling scheme is such that the label of the $1.5\sigma_t$ threshold detections take on the label of their $1\sigma_t$ threshold counter-parts. Where there is more than one corresponding segment, labelling takes a decimal form (e.g. Segments 13.1, 13.2, and 13.3 are the $1.5\sigma_t$ threshold counter-parts to segment 13). Note that the very centre of Hercules is excluded from segmentation.}
\end{figure}
Figure 2.9: Results of the control sampling process for two over-density detections (Top: OD 13, Bottom: OD 22). The histograms represent the frequency distribution of $N_{w \geq 0.8}$ values from the 10,000 control sub-samples taken for each over-density. The black dashed lines represents $N_{w \geq 0.8}$ for each over-density. The solid grey lines show a Gaussian fit to each frequency distribution. The box plot represents the median and 25th/75th percentiles of the distribution, with the whiskers showing the most extreme data points not considered outliers, and the filled circles representing the outliers. Note that the outliers are shown at 50% opacity so underlying points may be seen.

detection, where $N_{w \geq 0.8}$ for the over-density is greater than the range of values found for the control samples. The result for OD 22 (bottom), on the other hand, suggests that this over-density could be explained as a random fluctuation in the foreground population, with $N_{w \geq 0.8}$ for the over-density being quite close to the mean control sample value.

A ‘significance value’ ($\zeta$) was determined for each test result, as a means of identifying the most significant detections, and comparing these results to the null hypothesis. The value of $\zeta$ was generated by calculating how far $N_{w \geq 0.8}$ was away from the mean of the control sample ($\langle N_{w \geq 0.8}(CS) \rangle$). This was achieved by fitting a Gaussian to the frequency
distribution of $N_{w \geq 0.8}$ values for the control samples (see Figure 2.9), and expressing the distance in units of the standard deviation ($\sigma$):

$$\zeta = \frac{N_{w \geq 0.8}(OD) - \langle N_{w \geq 0.8}(CS) \rangle}{\sigma}$$

A detection was considered significant if $\zeta \geq 2.0$. The results of this analysis are summarised in Tables 2.2 and 2.3, and presented graphically in Figure 2.10. Diamonds and circles in this figure represent detections based on the $1\sigma_t$ and $1.5\sigma_t$ thresholds respectively. There are nine over-densities that are significant. Several of these are sufficiently large that they appear significant in the larger 5 pixel and 7 pixel convolutions. These will be discussed in more detail later.

In order to test the null hypothesis, the significance analysis, as described in section 2.5.2, was repeated for 300 randomly selected segments from the control region, varying in size between 4 - 18 sqr arcmin. Figure 2.11 shows the resulting frequency distribution of $\zeta$ values for the 300 segments. The mean and standard deviation are computed as -0.30 and 0.89, respectively, further supporting the significance of detections with $\zeta \geq 2.0$.

The significance test was also performed on the ‘nuggets’ reported by Sand et al. (2009) (see their Figure 9). The majority of these nuggets appear quite small, varying from less than an arcminute to a few arcminutes in size. Using the coordinates of the nuggets from this figure as centre, two different sized boxes of $3'$ and $6'$ width were defined for each nugget in order to examine their extent, and ensure a large enough sample of stars in the nuggets for our statistical analysis. The segmentation and significance testing was performed for each box size, mimicking the process used for detecting our over-densities. The results are summarised in Tables 2.4 and 2.5, and Figure 2.12. Only one of these
Table 2.2: Significance values for the $1\sigma$ detected Hercules over-densities, where segment labelling corresponds to the grey outlines in Figure 2.8.

<table>
<thead>
<tr>
<th>Segment</th>
<th>$N_+$</th>
<th>$N_{w \geq 0.8} (OD)$</th>
<th>$\langle N_{w \geq 0.8} (CS) \rangle$</th>
<th>$\zeta$</th>
</tr>
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<tr>
<td>OD 1</td>
<td>18</td>
<td>4</td>
<td>1</td>
<td>1.93</td>
</tr>
<tr>
<td>OD 2</td>
<td>136</td>
<td>17</td>
<td>12</td>
<td>1.52</td>
</tr>
<tr>
<td>OD 3</td>
<td>65</td>
<td>10</td>
<td>6</td>
<td>1.75</td>
</tr>
<tr>
<td>OD 4</td>
<td>74</td>
<td>10</td>
<td>7</td>
<td>1.42</td>
</tr>
<tr>
<td>OD 5</td>
<td>16</td>
<td>2</td>
<td>1</td>
<td>0.73</td>
</tr>
<tr>
<td>OD 6</td>
<td>309</td>
<td>44</td>
<td>28</td>
<td>3.18</td>
</tr>
<tr>
<td>OD 7</td>
<td>21</td>
<td>1</td>
<td>2</td>
<td>0.13</td>
</tr>
<tr>
<td>OD 8</td>
<td>377</td>
<td>48</td>
<td>34</td>
<td>2.50</td>
</tr>
<tr>
<td>OD 9</td>
<td>530</td>
<td>64</td>
<td>48</td>
<td>2.45</td>
</tr>
<tr>
<td>OD 10</td>
<td>55</td>
<td>6</td>
<td>5</td>
<td>0.62</td>
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<td>3</td>
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<td>1.15</td>
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<tr>
<td>OD 12</td>
<td>89</td>
<td>9</td>
<td>8</td>
<td>0.59</td>
</tr>
<tr>
<td>OD 13</td>
<td>2468</td>
<td>316</td>
<td>224</td>
<td>6.47</td>
</tr>
<tr>
<td>OD 14</td>
<td>39</td>
<td>8</td>
<td>3</td>
<td>2.39</td>
</tr>
<tr>
<td>OD 15</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0.35</td>
</tr>
<tr>
<td>OD 16</td>
<td>908</td>
<td>123</td>
<td>82</td>
<td>4.75</td>
</tr>
<tr>
<td>OD 17</td>
<td>20</td>
<td>3</td>
<td>2</td>
<td>1.10</td>
</tr>
<tr>
<td>OD 18</td>
<td>53</td>
<td>8</td>
<td>5</td>
<td>1.60</td>
</tr>
<tr>
<td>OD 19</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0.14</td>
</tr>
<tr>
<td>OD 20</td>
<td>257</td>
<td>36</td>
<td>23</td>
<td>2.78</td>
</tr>
<tr>
<td>OD 21</td>
<td>53</td>
<td>8</td>
<td>5</td>
<td>1.56</td>
</tr>
<tr>
<td>OD 22</td>
<td>150</td>
<td>16</td>
<td>13</td>
<td>0.74</td>
</tr>
<tr>
<td>OD 23</td>
<td>226</td>
<td>35</td>
<td>20</td>
<td>3.41</td>
</tr>
<tr>
<td>OD 24</td>
<td>21</td>
<td>5</td>
<td>2</td>
<td>2.30</td>
</tr>
</tbody>
</table>

Figure 2.11: Histogram of possible values of $\zeta$ for 300 blind segments taken from regions of the Hercules field devoid of over-density detections.
Table 2.3: Significance values for the 1.5σ <i>t</i> detected Hercules over-densities, where segment labelling corresponds to the black outlines in Figure 2.8.

<table>
<thead>
<tr>
<th>Segment</th>
<th>( N_\ast )</th>
<th>( N_{\omega \geq 0.6}(OD) )</th>
<th>( \langle N_{\omega \geq 0.6}(CS) \rangle )</th>
<th>( \zeta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD 6</td>
<td>207</td>
<td>34</td>
<td>19</td>
<td>3.74</td>
</tr>
<tr>
<td>OD 8</td>
<td>183</td>
<td>27</td>
<td>17</td>
<td>2.73</td>
</tr>
<tr>
<td>OD 9</td>
<td>282</td>
<td>37</td>
<td>26</td>
<td>2.34</td>
</tr>
<tr>
<td>OD 13.1</td>
<td>1019</td>
<td>144</td>
<td>93</td>
<td>5.51</td>
</tr>
<tr>
<td>OD 13.2</td>
<td>255</td>
<td>33</td>
<td>23</td>
<td>2.11</td>
</tr>
<tr>
<td>OD 13.3</td>
<td>16</td>
<td>2</td>
<td>1</td>
<td>0.74</td>
</tr>
<tr>
<td>OD 16.1</td>
<td>104</td>
<td>18</td>
<td>9</td>
<td>3.00</td>
</tr>
<tr>
<td>OD 16.2</td>
<td>168</td>
<td>20</td>
<td>15</td>
<td>1.29</td>
</tr>
<tr>
<td>OD 20</td>
<td>170</td>
<td>24</td>
<td>16</td>
<td>2.26</td>
</tr>
<tr>
<td>OD 23</td>
<td>144</td>
<td>24</td>
<td>13</td>
<td>3.15</td>
</tr>
<tr>
<td>OD 24</td>
<td>13</td>
<td>2</td>
<td>1</td>
<td>0.99</td>
</tr>
</tbody>
</table>

nuggets coincides with an over-density in our list: NGT 9 (NGT 9.2 at 3′ width) showed \( \zeta = 2.21 \), while our corresponding over-density (OD 13.2) showed \( \zeta = 2.11 \). All other nugget segments have significance values considerably below our \( \zeta = 2 \) limit. Since their data was somewhat deeper than ours, it is unsurprising that we may not detect all of the nuggets they did. It should be noted that with the exception of OD 13, there is little overlap between our over-densities and the fields observed by Sand et al. (2009). Several of our less significant detections (\( \zeta < 2.0 \)) have very small amounts of overlap with these fields. Since these detections are not strong, it is unlikely that partial coverage would yield a detection. There is however, partial overlap with OD 9 and OD 16, which we find to be significant. These over-densities appear less significant at the 1.5σ <i>t</i> threshold, indicating they are extremely diffuse. Partial coverage of such diffuse over-densities may cause them to go unnoticed, even in a deeper data set. With regard to the main halo-like body of OD 13, there is remarkable correlation with the contours in Figure 9 from Sand et al. (2009) (upper central panel).

### 2.6 Results

Further to the investigation of the spatial distribution of the over-densities detected, we tried to estimate the luminosity of these new over-densities. For that purpose, the over-densities were subdivided into four regions. The first region was Hercules itself, as defined during the segmentation process. It covers about 1.75 times the area of the half-light ellipse and was excluded from our analysis. The second was the over-density surrounding Hercules, OD 13. The third was all other over-densities with \( \zeta \geq 3.0 \), and the fourth
Table 2.4: Significance values for ‘nuggets’ depicted by Sand et al. (2009), using a 6′ × 6′ box for segmentation. The segments are shown in Figure 2.13.

<table>
<thead>
<tr>
<th>Segment</th>
<th>(N_e)</th>
<th>(N_{w \geq 0.8}(NGT))</th>
<th>(\langle N_{w \geq 0.8}(CS)\rangle)</th>
<th>(\zeta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGT 1</td>
<td>321</td>
<td>32</td>
<td>29</td>
<td>0.57</td>
</tr>
<tr>
<td>NGT 2</td>
<td>1022</td>
<td>84</td>
<td>93</td>
<td>-0.92</td>
</tr>
<tr>
<td>NGT 3</td>
<td>248</td>
<td>28</td>
<td>22</td>
<td>1.25</td>
</tr>
<tr>
<td>NGT 4</td>
<td>570</td>
<td>53</td>
<td>52</td>
<td>0.21</td>
</tr>
<tr>
<td>NGT 5</td>
<td>248</td>
<td>23</td>
<td>22</td>
<td>0.14</td>
</tr>
<tr>
<td>NGT 6</td>
<td>651</td>
<td>52</td>
<td>59</td>
<td>-0.93</td>
</tr>
<tr>
<td>NGT 7</td>
<td>260</td>
<td>23</td>
<td>23</td>
<td>-0.07</td>
</tr>
<tr>
<td>NGT 8</td>
<td>278</td>
<td>30</td>
<td>25</td>
<td>1.03</td>
</tr>
<tr>
<td>NGT 9</td>
<td>717</td>
<td>82</td>
<td>65</td>
<td>2.21</td>
</tr>
<tr>
<td>NGT 10</td>
<td>308</td>
<td>16</td>
<td>28</td>
<td>-2.31</td>
</tr>
<tr>
<td>NGT 11</td>
<td>291</td>
<td>27</td>
<td>26</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 2.5: Significance values for ‘nuggets’ depicted by Sand et al. (2009), using a 3′ × 3′ box for segmentation. The segments are shown in Figure 2.13.

<table>
<thead>
<tr>
<th>Segment</th>
<th>(N_e)</th>
<th>(N_{w \geq 0.8}(NGT))</th>
<th>(\langle N_{w \geq 0.8}(CS)\rangle)</th>
<th>(\zeta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGT 1</td>
<td>94</td>
<td>11</td>
<td>8</td>
<td>0.98</td>
</tr>
<tr>
<td>NGT 2.1</td>
<td>353</td>
<td>32</td>
<td>32</td>
<td>0.03</td>
</tr>
<tr>
<td>NGT 2.2</td>
<td>68</td>
<td>2</td>
<td>6</td>
<td>-1.32</td>
</tr>
<tr>
<td>NGT 3</td>
<td>87</td>
<td>8</td>
<td>8</td>
<td>0.16</td>
</tr>
<tr>
<td>NGT 4.1</td>
<td>74</td>
<td>8</td>
<td>7</td>
<td>0.69</td>
</tr>
<tr>
<td>NGT 4.2</td>
<td>107</td>
<td>12</td>
<td>10</td>
<td>0.83</td>
</tr>
<tr>
<td>NGT 5</td>
<td>84</td>
<td>6</td>
<td>7</td>
<td>-0.31</td>
</tr>
<tr>
<td>NGT 6.1</td>
<td>84</td>
<td>6</td>
<td>7</td>
<td>-0.30</td>
</tr>
<tr>
<td>NGT 6.2</td>
<td>164</td>
<td>11</td>
<td>15</td>
<td>-0.98</td>
</tr>
<tr>
<td>NGT 7</td>
<td>101</td>
<td>8</td>
<td>9</td>
<td>-0.33</td>
</tr>
<tr>
<td>NGT 8</td>
<td>84</td>
<td>10</td>
<td>7</td>
<td>1.02</td>
</tr>
<tr>
<td>NGT 9.1</td>
<td>189</td>
<td>20</td>
<td>17</td>
<td>0.78</td>
</tr>
<tr>
<td>NGT 9.2</td>
<td>95</td>
<td>13</td>
<td>8</td>
<td>1.64</td>
</tr>
<tr>
<td>NGT 10</td>
<td>106</td>
<td>7</td>
<td>10</td>
<td>-0.84</td>
</tr>
<tr>
<td>NGT 11</td>
<td>95</td>
<td>8</td>
<td>8</td>
<td>-0.12</td>
</tr>
</tbody>
</table>
region included those over-densities with $2.0 \leq \zeta < 3.0$. For each region, the combined flux of all stars with $w \geq 0.8$ was calculated. An estimate of the foreground flux was made by summing the flux from stars with $w \geq 0.8$ for fields drawn randomly from the control region, equal in area to each of the over-density regions. This was performed 1000 times for each of the four over-density regions, in order to build up a frequency distribution for which a statistically robust mean and standard deviation could be determined. The mean value for each was taken to represent the foreground over that area of sky, and subtracted from the flux counted for the corresponding over-density region. The remaining flux was considered to represent an upper limit for the luminosity of the over-density regions. The extended region 2, surrounding the main body of Hercules (region 1), was calculated to have $52 \pm 12\%$ of the flux of region 1, spread over approximately 2.7 times the area. Similarly, Region 3 contains $42 \pm 9\%$ as much flux as region 1, spread over approximately 1.4 times the area. Region 4 contains $25 \pm 8\%$ as much flux as region 1 spread over approximately 1.2 times the area. In total, the combined flux found in all significant over-densities (regions 2, 3, and 4) is of the same order ($119 \pm 29\%$) as the flux of Hercules itself, thus a significant portion of Hercules’ stellar population has been tidally disrupted.

The summary of our analysis is illustrated in Figure 2.13. The new over-densities are colour-coded according to their significance, with the $1.5\sigma_t$ detections laid over the $1\sigma_t$ detections. We have also over-laid the outline of those $0.5\sigma_t$ detections with $\zeta > 2.0$, in order to provide the broadest illustration of Hercules. The segmentation of the nuggets from Sand et al. (2009) is shown as an overlay of black outlined boxes. Stars consistent with the blue horizontal branch (BHB) of Hercules ($21.0 < g_0 < 21.2 , -0.40 < (g-i)_0 < -0.15$), are shown as open black stars. The elongation of Hercules and the postulated orbital path from Martin & Jin (2010) are demonstrated by a grey ellipse and black solid line respectively. We note that the orbital path presented by Martin & Jin (2010) represents a viable scenario in which Hercules has had a close encounter with the MW, and the orbital path was assumed to be aligned with the direction of elongation of Hercules. This is consistent with the idea that Hercules has very recently passed peri-galacticon, not yet
having flipped its tidal tails in an orientation toward the MW (Klimentowski et al., 2009). Small grey-filled stars represent stars identified as potential Hercules members, by means of relative proper motions, from Table 2 of Fabrizio et al. (2014). This table includes all 528 of the initial proper motion candidates identified by Fabrizio et al. (2014), which they state contains a level of remaining field contamination. In order to reduce the number of contaminants in the sample, we preferentially selected stars sitting closest to the red-giant and horizontal branches in the CMD. The distribution of these 239 proper motion, CMD, selected stars shows a remarkable correlation with the outline of the extended body of Hercules.

The overall distribution of the over-densities detected appears roughly aligned with the major axis of Hercules. However, two of the significant detections (OD 6 and OD 23) lie at notably different orientation angles to the major axis. These over-densities could be free-floating tidal debris following Hercules on slightly different orbits. As a means of further investigation, the astroML\(^5\) (VanderPlas et al., 2012) machine learning package was employed to determine the ellipticity and angular orientation of Hercules in our data set. Taking the central 9\(\prime\)\(\times\)9\(\prime\) (containing the half-light radius of Hercules), a maximum likelihood bivariate normal fit was performed. An ellipticity of \(\epsilon = 0.63 \pm 0.02\) was found, which is in agreement with the published value of 0.68 \(\pm\) 0.08 (McConnachie, 2012). An orientation angle of 113.8 \(\pm\) 0.6\(\degree\) was found, which is slightly steeper than the published value of 102\(\degree\) \(\pm\) 4\(\degree\) (McConnachie, 2012). In the scenario from McConnachie (2012), where the orbital path is aligned with the position angle of the major axis of Hercules, this would indicate a steeper orbital path as plotted with the dash-dot line in Figure 2.13. This path lies closer to several of the leading and trailing over-densities. To test the correlation between the properties of the main stellar body of Hercules and the distribution of the newly identified stellar over-densities, we fit a line to the positions of all of the over-densities, using the \(\zeta\) values as weights for the fit. This line is shown in Figure 2.13 as the dash-dot-dot line. Confidence bands for this fit at the 68\% and 95\% level are shown by the dashed and dotted grey lines respectively. Both the orbital path from Martin & Jin (2010), and our revised orientation of the major axis of Hercules, fall inside the 68\% confidence band.

A clear trend is also detected in the distribution of the BHB star candidates, following the elongation of Hercules. Since these are BHB star candidates (as photometrically defined by the black box in the CMD in Figure 2.6), the expectation is that they belong to Hercules, and therefore provide a good tracer of its stellar population. Tests were performed to see if the distribution of BHB stars could be reproduced with a random selection of stars from across the field. There are 21 BHB star candidates, however, the seven stars within the half-light radius were excluded from testing due to the high probability of membership. Thus, 14 stars remained in the outer regions. Of these, six appear to coincide with (or sit on top of) the detected over-densities; in addition, six are observed to sit within the 68\% confidence band.

\(^5\)http://www.astroml.org/
Figure 2.13: Summary figure displaying compiled results from this analysis. The significance of $1\sigma_t$ and $1.5\sigma_t$ detections are colour coded according to $\zeta$ ($1.5\sigma_t$ detections appear ‘inside’ the $1\sigma_t$ detections). Coloured contours reflect those over-densities detected at the $0.5\sigma_t$ threshold with $\zeta \geq 2.0$. Our segmentation of the nuggets from Sand et al. (2009) is shown as an overlay of black outlined boxes. Candidate blue horizontal branch stars, selected from the CMD (see Figure 2.6), are shown as open black stars. The elongation of Hercules and the orbital path proposed by Martin & Jin (2010) are demonstrated by a black solid line and grey ellipse. Small grey-filled stars represent stars identified as potential Hercules members, through relative proper motions, from Table 2 of Fabrizio et al. (2014). The dash-dot line represents the inclination of Hercules in this data set based on a maximum likelihood bivariate normal fit to stars inside the central $9' \times 9'$. The dash-dot-dot line represents a weighted least squares fit to the position of the over-densities, using $\zeta$ as weights. Confidence intervals for this fit at the 68 and 95 percentile limits are shown by the dashed and dotted grey lines respectively.

It was found that, drawing a random sample of 14 stars from anywhere in the field, six or more coincided with an over-density 1364 times out of $10^7$ trials (0.01%). A similar test was performed to assess the likelihood of stars falling inside the 68% and 95% confidence bands. It was found that six or more out of 14 stars lie inside the 68% interval 0.09% of the time (out of $10^7$ trials). Similarly, 11 or more out of 14 stars fall inside the 95% confidence band 2% of the time (out of $10^7$ trials). This shows that the distribution of BHB candidates we detect beyond Hercules’ radius is in agreement with the alignment of the substructures at a confidence level greater than 98%.
2.7 Summary

The tidal disruption of the Hercules dwarf galaxy has been alluded to for some time (Coleman et al., 2007; Adén et al., 2009b; Sand et al., 2009; Martin & Jin, 2010), however the full extent to which it occurs was not easy to quantify due to technical limitations. Our deep, photometric analysis of 3 sqr deg around Hercules, with the Dark Energy Camera, reveals that this dwarf galaxy has undergone significant tidal disruption, with nine statistically significant over-densities extending to more than 2 kpc from its centre. Most over-densities are distributed along the major axis, with all but two falling inside the 95% confidence band of the likely orbital path. We estimated the combined luminosity of these over-densities relative to the Hercules galaxy itself. The total number of stars in these over-densities is of the same order as the total number of stars in the main body of Hercules, highlighting the severe tidal disruption this dwarf galaxy has experienced in the tidal field of the Milky Way.

Although we find little correlation with the nuggets reported by Sand et al. (2009) (with the exception of the shape of the extended region surrounding the main body of Hercules), we find excellent correlation with the proper-motion identified stars from Table 2 of Fabrizio et al. (2014). Given the distinctly different method used by Fabrizio et al. (2014), the correlation of these results with our own provides extra confidence in the position of our over-densities, and encourages the use of relative proper motion as a means of identifying membership.

Our results provide useful new observational constraints for theoretical modelling. Recent work by Blaña et al. (2015) raises questions about the current picture of the orbit of Hercules, and suggests that a path aligned along the major axis of the dwarf may not necessarily be correct. Our results are consistent with the orbital path proposed by Martin & Jin (2010), although both the position angle of the major axis, and the alignment of the substructures suggest a slightly steeper orientation. Interestingly, the position angle of the major axis that we determine does not line up perfectly with the alignment of the substructures (although the two are consistent within the 68% confidence band). This suggests a picture similar to that for the globular cluster Palomar 5, where the orbital path is not quite aligned with the leading and trailing tidal arms (Dehnen et al., 2004; Odenkirchen et al., 2009). It may also be an indication that the tidal tails are transitioning to an orientation aligned towards the Milky Way as the dwarf approaches apo-galacticon (Klimentowski et al., 2009). Finally, two of the significant over-densities we detect sit outside the confidence bands of the substructure alignment. This may suggest that Hercules has made more than one peri-galactic pass, and is accompanied by free-floating debris. This would be consistent with infall timescales of 2-5 Gyr found in the literature (Rocha et al., 2012; Blaña et al., 2015), and the destructive peri-galactic passage described by Martin & Jin (2010).
The identification of statistically significant over-densities provides new opportunities for spectroscopic follow up and further analysis in the ELT era, as well as new data that can be added to test and calibrate theoretical models.
CHAPTER 3

Structural analysis of the Sextans dwarf spheroidal galaxy

This chapter has previously been published as “Structural analysis of the Sextans dwarf spheroidal galaxy”, Roderick, T.A. et al., 2016. MNRAS, 460 (1) pp. 30-43.

3.1 Abstract

We present wide-field $g$ and $i$ band stellar photometry of the Sextans dwarf spheroidal galaxy and its surrounding area out to four times its half-light radius ($r_h = 695$ pc), based on images obtained with the Dark Energy Camera at the 4-m Blanco telescope at CTIO. We find clear evidence of stellar substructure associated with the galaxy, extending to a distance of 82′ (2 kpc) from its centre. We perform a statistical analysis of the overdensities and find three distinct features, as well as an extended halo-like structure, to be significant at the 99.7% confidence level or higher. Unlike the extremely elongated and extended substructures surrounding the Hercules dwarf spheroidal galaxy, the overdensities seen around Sextans are distributed evenly about its centre, and do not appear to form noticeable tidal tails. Fitting a King model to the radial distribution of Sextans stars yields a tidal radius $r_t = 83.2′ ± 7.1′$ (2.08±0.18 kpc), which implies the majority of detected substructure is gravitationally bound to the galaxy. This finding suggests that Sextans is not undergoing significant tidal disruption from the Milky Way, supporting the scenario in which the orbit of Sextans has a low eccentricity.

3.2 Introduction

The dawn of the survey telescope era has led to a rapid increase in discoveries of Milky Way (MW) satellite galaxies (most recently: Laevens et al., 2014; Koposov et al., 2015a; Kim & Jerjen, 2015a; Bechtol et al., 2015; Kim et al., 2015b; Laevens et al., 2015; Drlica-Wagner et al., 2015), spurring a flurry of research into low mass galaxy formation and testing of the
Kinematic studies of the MW satellites have revealed them to have a high dark matter content (most particularly the ultra-faint systems) (e.g. Simon & Geha, 2007; Martin et al., 2007; Simon et al., 2011; Koposov et al., 2015a; Kirby et al., 2015). The velocity dispersion measured in these pressure-dominated systems suggests they are more massive than the visible baryonic matter can account for. However, this assumes the systems are in dynamic equilibrium. Where a system is interacting with its host, it can undergo significant tidal stirring (Lokas et al., 2012) resulting in kinematic samples being contaminated by unbound stars (Klimentowski et al., 2007). Many of the MW satellites possess substructure indicative of tidal stirring, and in some cases extreme tidal stripping, for example: Sagittarius (Ibata et al., 1994; Newby et al., 2013), Ursa Minor (Palma et al., 2003), Ursa Major II (Simon & Geha, 2007), Carina (Battaglia et al., 2012; McMonigal et al., 2014), and Fornax (Coleman et al., 2004). If the majority of MW satellite galaxies are undergoing some form of tidal interaction, their kinematic samples may well be affected and it will be necessary to review the estimates of their dark matter content.

Recently, the Hercules dwarf spheroidal has been demonstrated to possess extended stellar substructure, with over-densities found out to 5.8 times the half-light radius from the galaxy’s centre (Roderick et al., 2015). Previous studies of this satellite have suggested that tidal disruption is a likely scenario (Coleman et al., 2007; Sand et al., 2009; Deason et al., 2012), however the full extent of the stellar debris around the galaxy had not been realised. In addition to the discovery of these distant stellar over-densities, a strong correlation was noted between the position of the over-densities, the position of blue horizontal branch (BHB) stars, and the orbital path suggested by Martin & Jin (2010). This study illustrates the usefulness of new generation wide-field imaging to scrutinise the outskirts of known MW satellite galaxies, in order to better understand the extent and nature of their stellar structure.

Following this line of reasoning, we present results of a large scale photometric study of the Sextans dwarf spheroidal galaxy. Sextans (see Table 3.1), discovered by Irwin et al. (1990), was the eighth MW dwarf satellite galaxy to be found. Like a typical MW dwarf, Sextans is old (12 Gyr, Mateo et al., 1991) and metal poor ([Fe/H] ≃ −1.9, Kirby et al. (2011)), with a high mass-to-light ratio (M/L ≈ 97, Lokas, 2009)). Tidal stirring has been suggested as a possible cause of the large observed velocity dispersion (Hargreaves et al., 1994). There has also been discussion on whether or not there are substructures at the centre of Sextans, with the observation of kinematically cold structures in the galaxy’s centre (Kleyna et al., 2004; Walker et al., 2006; Battaglia et al., 2011), and the suggestion
of a dissolved star cluster at its core (Karlsson et al., 2012). The Sextans dwarf also contains a substantial population of blue straggler stars (BSS) (or possibly intermediate age main sequence stars formed 2-6 Gyr ago, Lee et al., 2003), with the brighter stars being more centrally concentrated than the fainter part of the population (Lee et al., 2003). An extensive study performed by Lee et al. (2009) revealed that, although the majority of star formation in Sextans occurred $>$ 11 Gyr ago, there are slight differences in the star formation history between the different regions identified in Sextans (especially between inner and outer populations). Their conclusion was that the primary driver for the radial stellar population gradient seen in this galaxy is the star formation history.

Given the interesting kinematic features and star formation history of Sextans, we have performed a wide-field photometric study in order to gain a better understanding of what is happening in the outskirts of this galaxy. Our data set consists of five fields taken with the Dark Energy Camera (DECam) on the 4m Blanco telescope, at Cerro Tololo in Chile. We perform our analysis with the intention of investigating the nature of Sextans stellar structure, and ascertaining the extent to which this system is being tidally perturbed by the MW potential. Section 3.3 details our observations as well as the data reduction and photometric process. In Section 3.4 we illustrate our method for discriminating between Sextans stars and the MW halo stars, and we describe our method for creating a spatial map in Section 3.5. In Section 3.6 we perform an analysis of the structural parameters of Sextans. Our main analysis of the structure of Sextans is detailed in Section 3.7, using techniques analogous to those of Roderick et al. (2015). This section also includes a brief analysis of the centre of Sextans. Finally in Section 3.8 we discuss our results and summarise our findings.

3.3 Observations and Data Reduction

Observations were conducted on 2013 February 15 using DECam at the CTIO 4m Blanco telescope, as part of observing proposal 2013A-0617 (PI: D. Mackey). The total DECam field-of-view is 3 square degrees, formed by a hexagonal mosaic of 62 2K×4K CCDs, each with a pixel scale of 0′′27/pix.

The data set consists of five separate DECam pointings: one centred on Sextans itself (CEN) and four arranged symmetrically about the centre (P1-P4). The central coordinates for each of the outer fields are offset from the central coordinates of the centre field by 1° in each R.A. and Dec. (see Figure 3.1). This configuration encompasses four times the half-light radius of Sextans (27.6′, Irwin & Hatzidimitriou, 1995), and provides over-lapping regions between each of the outer fields and the centre for photometric calibration. Each field was imaged $3 \times 300$ s in $g$-band and $i$-band filters, providing total integration times of 900s in each filter for each field. Table 3.2 details the central coordinates and average seeing for each field.
Table 3.1: Fundamental Parameters of Sextans

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
<td>10:13:03.0</td>
<td>1</td>
</tr>
<tr>
<td>DEC (J2000)</td>
<td>−1:36:53</td>
<td>1</td>
</tr>
<tr>
<td>l</td>
<td>243.5°</td>
<td>1</td>
</tr>
<tr>
<td>b</td>
<td>42.3°</td>
<td>1</td>
</tr>
<tr>
<td>$D_\odot$</td>
<td>86 ± 4 kpc</td>
<td>2</td>
</tr>
<tr>
<td>$(m - M)_0$</td>
<td>19.67 ± 0.1</td>
<td>2</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>7.9 ± 1.3 km s$^{-1}$</td>
<td>3</td>
</tr>
<tr>
<td>$v_\odot$</td>
<td>224.3 ± 0.1 km s$^{-1}$</td>
<td>3</td>
</tr>
<tr>
<td>$r_h$</td>
<td>695 pc</td>
<td>4</td>
</tr>
<tr>
<td>$M_V$</td>
<td>−9.3 ± 0.5 mag</td>
<td>4</td>
</tr>
<tr>
<td>$[\text{Fe/H}]$</td>
<td>−1.93 ± 0.01 dex</td>
<td>5</td>
</tr>
<tr>
<td>$\theta$</td>
<td>56.7° ± 2.8°</td>
<td>6</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.29 ± 0.03</td>
<td>6</td>
</tr>
</tbody>
</table>

References: (1) Irwin et al. (1990), (2) Lee et al. (2009), (3) Walker et al. (2009), (4) Irwin & Hatzidimitriou (1995), (5) Kirby et al. (2011), (6) This work

Figure 3.1: Stellar distribution in five separate DECam pointings around the Sextans dwarf spheroidal galaxy. The grey ellipse outlines the orientation and half-light radius of the galaxy. Pointings are labelled CEN to P4 (outlined in light grey), and correspond to Table 3.2. The slight tile pattern visible here is a result of the inter-chip gaps in the CCD mosaic. Several CCDs in the mosaic were not functioning properly at the time of observation and have been masked out of the data set. These are visible as irregular white gaps in the hexagonal pattern.
Table 3.2: Properties of observations of Sextans taken as part of observing proposal 2013A-0617.

<table>
<thead>
<tr>
<th>Field</th>
<th>Coordinates (J2000)</th>
<th>Filter</th>
<th>Average Seeing ($''$)</th>
<th>(90%) Completeness (%)</th>
<th>Zero Point (ZP)</th>
<th>Colour Term (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEN</td>
<td>10:13:03.0 -01:31:53</td>
<td>g</td>
<td>1.07</td>
<td>24.75</td>
<td>24.97</td>
<td>31.177</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i</td>
<td>0.97</td>
<td>24.01</td>
<td>24.26</td>
<td>31.109</td>
</tr>
<tr>
<td>P1</td>
<td>10:09:03.0 -00:31:53</td>
<td>g</td>
<td>1.16</td>
<td>24.65</td>
<td>24.85</td>
<td>31.248</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i</td>
<td>1.10</td>
<td>23.82</td>
<td>24.11</td>
<td>31.161</td>
</tr>
<tr>
<td>P2</td>
<td>10:17:03.0 -00:31:53</td>
<td>g</td>
<td>1.25</td>
<td>24.60</td>
<td>24.78</td>
<td>31.145</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i</td>
<td>1.11</td>
<td>23.81</td>
<td>24.09</td>
<td>31.450</td>
</tr>
<tr>
<td>P3</td>
<td>10:09:02.8 -02:31:53</td>
<td>g</td>
<td>1.33</td>
<td>24.52</td>
<td>24.73</td>
<td>31.243</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i</td>
<td>1.38</td>
<td>23.50</td>
<td>23.78</td>
<td>31.003</td>
</tr>
<tr>
<td>P4</td>
<td>10:17:03.3 -02:31:53</td>
<td>g</td>
<td>1.43</td>
<td>24.39</td>
<td>24.59</td>
<td>31.136</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i</td>
<td>1.33</td>
<td>23.50</td>
<td>23.80</td>
<td>31.246</td>
</tr>
</tbody>
</table>

The images were processed using the DECam community pipeline\(^1\) (Valdes et al., 2014), which included sky-background subtraction, WCS solution fitting and the co-addition of images into a single deep frame. The final product was a multi-extension FITS file for each filter of each field, containing the processed and co-added image-stacks sliced into nine separate extensions or tiles.

### 3.3.1 Photometry and Star/Galaxy Separation

Photometry and star/galaxy separation were conducted with the same pipeline used by Roderick et al. (2015). WeightWatcher\(^2\) (Marmo & Bertin, 2008) was used in conjunction with the weight maps produced by the community pipeline to mask out non-science pixels in preparation for aperture photometry to be performed using Source Extractor\(^3\) (Bertin & Arnouts, 1996).

Source Extractor was run in two passes on each image. An initial shallow pass was performed to estimate the average FWHM ($F$) of bright point-like sources in the field, where a point-like source was defined as being circular and away from other sources and CCD edges. This information then provided the input for a second deeper pass, where aperture photometry was carried out within $1 \times F$ and $2 \times F$. Performing the photometry separately on each of the nine tiles across all five fields allowed the apertures to vary with changes in the point-spread-function across the large field-of-view.

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\(^1\)http://www.ctio.noao.edu/noao/content/Dark-Energy-Camera-DECam
\(^2\)http://www.astromatic.net/software/weightwatcher
\(^3\)http://www.astromatic.net/software/sextractor
Star/galaxy separation was performed on the $i$-band image catalogues in the same manner as Roderick et al. (2015). Due to the variation in seeing between fields, the Source Extractor star/galaxy flag proved unreliable; some objects in fields of poorer seeing were unambiguously classified as stars, while in the overlapping region of the central field with best seeing, the same objects were unambiguously classified as galaxies. The aperture magnitude-difference method described by Roderick et al. (2015) was adopted instead, since investigation of the overlapping regions between fields showed that it was able to consistently classify stellar objects. As demonstrated in Figure 3.2, stars show a consistent flux ratio when measured by different sized apertures, enabling them to be separated from non-stellar objects. For each field, the stellar locus was modelled with an exponential which was reflected and shifted to encompass and select objects in the locus. Note that the shape of the exponential allows for increasing photometric uncertainties at faint magnitudes. The resulting stellar catalogue for each field was then cross-matched according to the WCS sky coordinates with the corresponding $g$-band catalogue, using the Stilts command line package (Taylor, 2011). This produced one catalogue of stellar sources for each of the five fields. As a further step to ensure the consistency of star/galaxy classification between fields, this process was performed iteratively by checking the overlapping regions for consistent numbers of stars. The 90% photometric completeness level (discussed later) of the poorest quality field was adopted as the magnitude limit for the entire stellar catalogue, to ensure even depth across fields, and a comparison made between the overlapping regions of each outer field with the central field. The selection region encompassing the stellar locus in Figure 3.2 was adjusted until the star counts in the overlapping regions were consistent to within poisson noise. This ensured a smooth transition between fields with consistent star/galaxy separation optimised for the quality of each image.

### 3.3.2 Photometric Calibration and Completeness

Once each catalogue was complete, it was individually calibrated to the SDSS photometric system. This was achieved by matching objects from the catalogue to stars from SDSS data release 10 (SDSS DR10: Ahn et al., 2014). By comparing the SDSS magnitude of each star to its instrumental magnitude within the $2 \times F_\text{aperture}$, photometric zero points ($ZP$) and colour terms ($c$) were determined using a least-squares fit; colour defined as $(g - i)_{\text{inst}}$. The zero points and colour terms for each catalogue are summarised in Table 3.2.

Once each catalogue had been calibrated to the SDSS photometric system, the outer fields were calibrated to the central field using stars in the overlapping regions between fields. The stars in each of the overlapping regions have been extracted and measured separately for each image, and thus provide two measurements which can be used for calibration. This was performed in the same manner as the SDSS calibration, with the central field serving as the reference to calibrate from. The stars in each of the overlapping regions were matched according to their sky coordinates, and each outer field then calibrated to
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Figure 3.2: Graphical interpretation of our star/galaxy separation process using the difference of magnitude between apertures for objects detected in P1. This figure shows the stellar locus, as well as a flare or plume of galaxies to the left and other spurious detections. The solid black lines denote the region inside which objects were classified as stars. They are catalogued and coordinate matched to their corresponding $g$-band counterpart.

The central field in each filter. A check of the calibrations was then performed for each field as follows. Again using the overlapping regions, the magnitude difference between measurements of stars in the outer field and the central field were compared in each filter as a function of magnitudes measured in the central field. The frequency distribution that resulted was also considered. A consistent calibration would show a small scatter and no systematic offset. Some inconsistencies were noticed, particularly in the $i$-band images with poorest seeing. Closer investigation revealed that the anomalous measurements came from stars which lacked coverage by one or more images in the co-added stack. These stars were removed from the catalogue using the exposure maps generated by the DECam community pipeline. To ensure accurate photometry, only stars with coverage from all three images in the stack for both filters were retained. The calibration process was repeated and checked again. The plots in Figure 3.3 illustrate the calibration check, and show, as expected, that the magnitude difference is distributed about zero in each field (and filter) and flares out as magnitudes become fainter and measurement uncertainties increase.
Figure 3.3: Demonstration of the calibration check between fields, using overlapping regions. Each plot shows the difference in measured magnitude for each star in the overlapping regions between the central (CEN) and outer (P1-P4) fields. The grey dashed line represents the median difference in each and is expected to be close to zero. A histogram shows the frequency distribution for each overlap region. Figures on the left represent $g$, while figures on the right represent $i$.

Once satisfied that each of the outer fields had been accurately calibrated to the centre, a correction for Galactic extinction was applied. The large DECam field of view affords noticeable variation in Galactic extinction. The greatest variation is seen in the $g$-band, being $0.092 < A_g < 0.250$ (a differential variation of approximately 8% in magnitude). In order to correct for this variation, and given the photometry has been calibrated in the SDSS photometric system, the extinction values used by SDSS in the direction of Sextans were adopted for our data set. Although newer coefficients exist (Schlafly et al., 2010; Schlafly & Finkbeiner, 2011), the coefficients used to obtain the SDSS corrections were $A_g = 3.793E(B-V)$ and $A_i = 2.086E(B-V)$ (Stoughton et al., 2002), based on the extinction maps of Schlegel et al. (1998). Each star in each of our catalogues was matched to its nearest SDSS neighbour, and the corresponding extinction value applied.

The final step in the photometric process was to perform completeness tests. These were carried out separately in each filter for each field, in order to determine photometric depth and accuracy. The IRAF addstar task was used to add artificial stars to each image in random R.A. and Dec. Stars were added in magnitude bins, 1 mag apart at the bright end and decreasing to 0.25 mag apart at the faint end in the range between 20 and 26 mag, to best sample the completeness drop-off. The image was then run through the photometry pipeline and the artificial stars recovered. This process was completed 15 times for each image to build up a statistically robust sample, with $\simeq 58,000$ stars added in total to each
image in each filter. The 50% completeness level was determined by fitting the relation described by Fleming et al. (1995) to the fraction of recovered stars. The results of the completeness test for each field are shown in Figure 3.4 and summarised in Table 3.2. The completeness across all fields is relatively consistent, with the exception of P3 and P4 in the $i$-band, which are approximately 0.5 mag shallower than the deepest field (CEN) due to slightly poorer seeing.

Photometric accuracy was determined by comparing the input magnitude to the measured magnitude of each artificial star recovered. An exponential function was fit to these results and used as a reference for determining the uncertainty of each individual star in each catalogue. This was performed separately for each image, in each photometric band.

3.4 Foreground Discrimination

Clean discrimination between stars belonging to the Sextans dwarf and stars belonging to the MW halo is of paramount importance for the identification and characterisation
of extended stellar substructure associated with the dwarf. Selection of stars based on their position in the colour-magnitude diagram (CMD) aids greatly in achieving such discrimination. This forms the basis for a technique often referred to as matched filtering. In this context, the colour-magnitude information of a stellar catalogue is used to create a filter for investigating its spatial distribution, and has proved to be a highly successful means for investigating stellar substructure in a low signal to noise environment (e.g. Rockosi et al., 2002; Odenkirchen et al., 2001b; McMonigal et al., 2014; Küpper et al., 2015). Adopting this philosophy, we created a weight mask for our stellar catalogue, to assign each star a weight based on its position in the CMD.

We followed the methodology used by Roderick et al. (2015) for creating a graduated mask based on an isochrone that best describes the stellar population. However, rather than using a model isochrone, we determined the locus of the Sextans stellar population empirically. This approach was possible because Sextans has a much more densely populated CMD than that of Hercules analysed by Roderick et al. (2015). The empirical fit was determined using a CMD of stars inside the half-light radius of Sextans, but having had the horizontal branch removed to ensure that only the main sequence, sub-giant and giant branch were present. The horizontal branch and blue straggler populations contain fewer stars and will be used during the analysis for a consistency check. Consequently they should not be used to identify potential over-densities. The remaining CMD was binned down the magnitude axis \((g)\), in increments of 0.002, and the median colour-value determined for each bin. Thus, for each bin in \(g\), the colour \((g - i)\) corresponding to the most well populated part of the CMD was known. These values were then used as the basis for a second binning process with larger bin size in \(g\), and the corresponding colour values determined for the new bins. This iterative process was continued with increasing bin size, until the ridge line of the Sextans isochrone emerged. The final isochrone model was obtained by performing a cubic interpolation over the result of the iterative process.

Once the empirical model had been determined, it was used to create a mask for weighting stars in each of the five catalogues of our fields, similar to that of Roderick et al. (2015). The mask was created by first binning the isochrone in 0.02 mag increments down the \(g\) magnitude axis. A Gaussian profile along the colour range was calculated for each bin, centred on the Sextans stellar locus given by the empirical model. The width of each Gaussian was determined by the photometric uncertainty of \(g - i\), and the amplitude set to 1. Thus stars could be assigned a weight, \(w\), between 0 and 1 according their proximity to the stellar locus. The mask for the central field is shown in the right panel of Figure 3.5. The shape of the mask reflects the photometric uncertainties, and is based on the stellar population within the half-light radius of Sextans. Note that the areas of the CMD corresponding to potential horizontal branch or blue straggler stars have been been assigned ‘nan’ values to ensure they are omitted from the over-density identification process to follow.
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Figure 3.5: Left: CMD of all stars within the central half-light radius of Sextans. Blue and red boxes denote regions of candidate BSS and BHB stars respectively. Centre: 2D histogram of the complete Sextans catalogue, showing considerable contamination from MW halo stars. Right: Contour plot of the weight mask created from an empirically derived model of the Sextans isochrone. Mask width increases with photometric uncertainty. The colour bar represents the contour values.

A separate mask was made for each field using the same empirical isochrone model. However, the width of the Gaussian profile calculated along the colour range for each mask varied according to the photometric uncertainties in each individual field. This allowed the weighting to reflect the varying uncertainties in the photometry caused by the variation in seeing between the different images. Each mask was applied to its corresponding catalogue, with stars weighted according to their proximity to the ridge line of the empirical isochrone as described above.

Once the membership weights were applied, the five separate catalogues were merged into a single catalogue. Where there were duplicate measurements of stars from the overlapping regions, the measurement from the image with the better seeing was retained, and the other discarded. Finally, the combined catalogue was cut at the 90% completeness level of the shallowest field ($g = 24.39$), to ensure even depth across the entire observed field-of-view. This final catalogue contained more than 46,000 stars, reaching a photometric depth approximately 1 mag below the main sequence turn off.

3.5 Spatial Mapping

Having weighted each star in the catalogue according to colour and magnitude, we used the weights to create a map of the spatial distribution of Sextans stars. The weights were used to subdivide the catalogue into two groups, a foreground catalogue and a Sextans member catalogue, similar to the method used by Roderick et al. (2015). This then provides a catalogue which can be used to create a map of the foreground which can then be subtracted from the map of Sextans members to reveal substructure in the surrounding region, similar to Küpper et al. (2015).
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Figure 3.6: Each step in the process of creating the detection map. Left: smoothed 2D histogram of Sextans members. Centre: smoothed 2D histogram of ‘foreground’. Right: final flat fielded, foreground subtracted detection map. The colour scale increases from blue to red, and is the same for left and centre panels, but differs in the right panel to make the features of each visually clear.

To create the maps, each catalogue was binned into a normalised 2D histogram of R.A. and Dec. with equal bin sizes of \(30'' \times 30''\), which we will refer to as pixels. Each histogram was smoothed with a Gaussian kernel, to create a density map. The normalised foreground map (centre panel of Figure 3.6) was then used as a form of flat field (such that the average pixel value across the field was equal to one), and divided through the Sextans map (left panel of Figure 3.6). Finally, the foreground map was subtracted from this flat-fielded map in order to reveal substructures present in the field (right panel of Figure 3.6). We note that, as a result of the large smoothing kernel used, this final ‘foreground’ corrected image is free from the pattern created by the inter-chip gaps between the CCDs.

Several different cut-off weights were tested in order to find the optimal value for our density maps. Varying the cut-off weight effectively changes the width of the selection region around the empirical isochrone, including more or less of the Sextans stellar population. A weight \(w = 0.3\) was determined as the optimal cut-off point since this encompasses the body of Sextans stars in the CMD, without cutting too many away or including a large fraction of Galactic foreground stars (refer to right-hand panel in Figure 3.5).

Varying the size of the Gaussian kernel changes the scale of the detected over-densities. In order to find an appropriate smoothing factor, kernels of 3, 5, and 7 pixels (corresponding to \(90''\), \(150''\) and \(210''\)), were tested. A kernel smoothing of 7 pixels was chosen since it provided the most detail with the least amount of noise in the detections. While the 3, and 5 pixel kernels revealed similar over-all structures, they also provided a large amount of ‘noisy’ detections. The detection maps shown in Figure 3.6 demonstrate the 7 pixel (\(210''\)) smoothing kernel.

Finally, with the detection of over-densities in the outskirts of the galaxy in mind, we define a detection threshold in terms of the mean pixel value in the outer regions of the smoothed, foreground subtracted map. Since the signal from the centre of Sextans is so
Figure 3.7: Contour map of the foreground subtracted spatial distribution of Sextans. Contours represent 2,3,4,5,10,15,20,25,30 times $\sigma_t$ above the mean pixel value, where the mean pixel value is determined from the region outside three times the half-light radius of Sextans and taken to represent the average field value. Red dashed and dotted lines represent the core and tidal radii respectively.

strong, we consider all pixels in the map outside of three times the half-light radius (27.8, Irwin & Hatzidimitriou, 1995), corresponding approximately to the furthermost half of each of the outer four fields. We then define contours in terms of the standard deviation, $\sigma_t$ (where $t$ is a reminder that this is used to determine the detection threshold), above the mean pixel value, with the lowest threshold corresponding to 2$\sigma_t$ above the mean. Figure 3.7 shows the full map with contours at 2,3,4,5,10,15,20,25,30 times $\sigma_t$.

3.6 Structural Parameters

Using the spatial map created in the previous section, we determined the orientation angle, $\theta$, and ellipticity, $\epsilon$, of Sextans.

We determined $\theta$, and $\epsilon$ for each of the contours in our spatial map, averaging the results and using the variation between measurements to estimate more robust uncertainties, similarly to McConnachie & Irwin (2006). This takes into account the variation in shape and orientation with radius of the galaxy, giving a more independent measurement of the
parameters. A maximum-likelihood bivariate-normal-fit from the astroML\(^4\) (VanderPlas et al., 2012) machine learning package was used to determine \(\theta\) and \(\epsilon\), as well as the centroid for the spatial distribution in each case. The results of our analysis show \(\theta = 57.5^\circ \pm 5.3^\circ\), \(\epsilon = 0.29 \pm 0.03\) and a centroid offset in degrees from the central R.A. and Dec of 0.014\(\pm\)0.003 and 0.002\(\pm\)0.008 respectively. Our results for \(\theta\) and \(\epsilon\), and the centre of Sextans, are consistent with the values from Irwin & Hatzidimitriou (\(\theta = 56^\circ \pm 5^\circ\), \(\epsilon = 0.35 \pm 0.05\), 1995).

We also produced a radial profile based on the foreground subtracted map. Using the values determined in the previous paragraph, we placed logarithmically spaced, concentric, elliptical annuli about the centre of Sextans out to a major axis distance of 100\('\). This major axis length was chosen since it encompasses as much of the data set as possible, without meeting the edge of our fields. The stellar number density was noted for each annulus. The results are shown in Figure 3.8, with the error-bars reflecting the measurement uncertainties in the counts, based on Poisson statistics, as well as the uncertainty in the foreground map. A King profile (King, 1962) was fit to these measurements, as well as an exponential profile, similar to Irwin & Hatzidimitriou (1995). Figure 3.8 shows both profiles, the King profile (left), and the exponential profile (right). We note that although Irwin & Hatzidimitriou (1995) found a similarly good fit for the exponential profile as the King profile, we see a better fit for the King profile than the exponential. Consequently, we also fit a Plummer profile (Plummer, 1911), also shown in the right panel of Figure 3.8, which shows an improved fit. The fit for the King profile yielded a core radius of \(r_c = 26.8' \pm 1.2'\), and a tidal radius of \(r_t = 83.2' \pm 7.1'\), compared to Irwin & Hatzidimitriou \((r_c = 16.6' \pm 1.2', r_t = 160' \pm 50', 1995)\), and Irwin et al. \((r_c = 15', r_t = 90', 1990)\). Comparatively, the fit for the Plummer profile yielded a core radius of \(r_c = 23.0' \pm 0.4'\). Although the agreement between the data and the best fitting King model is not particularly good at large radii, there is only tentative evidence for a break radius to indicate extra-tidal features. This will be discussed further in Section 3.8.

### 3.7 Substructure Analysis

We follow the methodology of Roderick et al. (2015) to conduct our substructure analysis. The procedure is similar in nature to that of Küpper et al. (2015), however rather than determining a significance statistic for each pixel in our foreground subtracted map and then searching for substructure, we use the contour levels across our full map and assess the significance of each structure after it is identified.

We use the Python package `scipy.ndimage`\(^5\) to identify and label each individual overdensity. This package looks for groups of adjoining pixels in an image, and labels each

\(^4\)http://www.astroml.org/
\(^5\)http://docs.scipy.org/doc/scipy/reference/ndimage.html
Chapter 3 Structural analysis of the Sextans dwarf spheroidal galaxy

Figure 3.8: Radial profile of Sextans showing number density of stars vs. major axis distance from centre. Markers show the profile using our own values for $\theta$ and $\epsilon$ determined by the astroML machine learning package. Error bars are given by Poisson statistics. The dashed line in each plot indicates the tidal radius determined by fitting a King profile. The dotted line in each plot shows the average background density. Left: Solid black line shows the King profile fit. Right: Dashed black line shows the exponential profile fit, solid black line shows the Plummer profile. Tidal and core radii determined from fitting the King profile are given by $r_t = 83.2' \pm 7.1'$ and $r_c = 26.8' \pm 1.2'$ respectively. The core radius determined by the Plummer profile is given by $r_c = 23.0' \pm 0.4'$

Before assessing the significance of each segment, or over-density, a control region was determined for testing and calibrating against. Ideally, the significance of an over-density is determined by comparing it to a sample of the foreground. This is difficult since the body of Sextans takes up a large portion of our field-of-view. During the detection of over-densities we consider anything above the detection threshold as being a potential over-density, we therefore consider anything below the detection threshold as part of the foreground. Thus, we define a control region for testing by taking the region of sky below the detection threshold. Having determined the segmentation of the detected over-densities, as well as appropriate regions from which to take a control sample, all the corresponding stars from the catalogue were separated into their relevant groups for the significance testing. When separated into their relevant groups, stars from the complete catalogue were included regardless of their weight. This was to ensure an indiscriminate analysis of the significance of each detection.
We determine a value for the significance of each over-density, \( \zeta \), in the manner described by Roderick et al. (2015). This \( \zeta \) value is obtained by counting how many stars are in close proximity to the isochrone for each over-density, compared to the control region. A star with close proximity to the isochrone is defined as having \( w \geq 0.9 \). The number of stars in an over-density that fit this criteria is given by the quantity \( N_{w \geq 0.9}(OD) \). Note that since the main body of Sextans forms part of this analysis, we have excluded stars inside the region defined by the 15\( \sigma \) threshold. This was done in order to obtain a significance value that reflected the star content in the extremities of Sextans, rather than the centre. For each over-density, the control region was randomly sampled 10,000 times, selecting a number of stars equal to the over-density being tested and counting those with \( w \geq 0.9 \). A frequency distribution was built from these values, and a Gaussian fit to determine the mean, \( \langle N_{w \geq 0.9}(CS) \rangle \), and standard deviation, \( \sigma \). The significance, \( \zeta \), was then determined as the distance of \( N_{w \geq 0.9}(OD) \) from \( \langle N_{w \geq 0.9}(CS) \rangle \) in units of the standard deviation:

\[
\zeta = \frac{N_{w \geq 0.9}(OD) - \langle N_{w \geq 0.9}(CS) \rangle}{\sigma}
\]

In order to understand the confidence of our \( \zeta \) values, we performed a test of the null hypothesis. Our significance test was performed on 400 randomly chosen segments (varying in size from 4 to 360 square arcminutes) created from the control region. Since these segments are dominated by foreground, the expectation is that a frequency distribution of the \( \zeta \) values obtained should be centred approximately at \( \zeta = 0 \). Figure 3.9 shows this distribution. A Gaussian function modelling this distribution yields a mean of -0.6, and a standard deviation of 1.04. Choosing significant values of \( \zeta \) to be three standard deviations above the mean, we consider over-densities with \( \zeta \geq 2.52 \) to be statistically significant. The results of this test for all the segments identified are shown in Figure 3.11. The test results for those over-densities deemed significant are summarised in Table 3.3. Since the segments at each high detection threshold are also found at the lower detection threshold, the labelling used at the lowest threshold (2\( \sigma \)) was adopted for all thresholds. Where an over-density broke into multiple detections at a higher threshold, a decimal labelling system was used (e.g. OD 7 contains OD 7.1, OD 7.2 and OD 7.3). Figure 3.10 illustrates the labels discussed in the text.

To further illustrate the significance of the detections with \( \zeta \geq 2.52 \), colour-magnitude diagrams of over-densities with \( \zeta \geq 2.52 \) have been included in Figure 3.12. A population of stars belonging to Sextans is evident in the main region surrounding the body of the dwarf (OD 7, OD 7.1 at the different detection thresholds). Horizontal branch and blue straggler stars are apparent in these CMDs as well. OD 20 also displays features of the Sextans population including horizontal branch stars (at the 3\( \sigma \) threshold). OD 7.2 and OD 7.3 and OD 19 contain fewer stars, however a statistically significant fraction of them are consistent with the Sextans empirical isochrone. The bottom row of CMDs in Figure
Figure 3.9: Frequency distribution of $\zeta$ values obtained testing the null hypothesis (grey line). A Gaussian model (dashed line) yields a mean of -0.6, and a standard deviation of 1.04. Values above three standard deviations from the mean are considered statistically significant (dotted line).

Figure 3.10: Labelling convention used for over-densities discussed in the text. Labels also correspond to Table 3.3 and Figures 3.11 and 3.12.

3.12 are from detections with $\zeta < 2.52$. These diagrams show more obvious foreground stars relative to the number of stars with $w > 0.9$.

As a final test of our detections, we investigated the distribution of background galaxies across the field. While apparent over-densities were detected, they were found to have no correspondence to any of the features discussed above. Furthermore, assessing their significance in the same way as our stellar over-densities yielded no significant $\zeta$ values, supporting the robustness of the star/galaxy separation and indicating that the substructure detected about Sextans is most certainly stellar.

A summary of the stellar over-densities which were determined to be significant is shown spatially in Figure 3.13. This figure is discussed in more detail in Section 3.8. We also
Figure 3.11: The significance value ($\zeta$) for each segment, or over-density identified by the segmentation process. Note the bottom panel is a close up of the corresponding region in the top panel (for visual clarity). Circles, diamonds, squares and stars and hexagons represent thresholds $2\sigma_t$ to $10\sigma_t$ respectively. The grey dashed line is at $\zeta = 2.52$, above which detections are considered significant.

Table 3.3: Results for the over-densities with $\zeta \geq 2.52$. Each horizontal line divides the group by detection threshold, with the top group found at $2\sigma_t$ and the bottom at $10\sigma_t$.

<table>
<thead>
<tr>
<th>Segment</th>
<th>$N_*$</th>
<th>$N_{w \geq 0.9}(OD)$</th>
<th>$\langle N_{w \geq 0.9}(CS) \rangle$</th>
<th>$\zeta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD 7.0</td>
<td>1303</td>
<td>190</td>
<td>101</td>
<td>9.21</td>
</tr>
<tr>
<td>OD 23.0</td>
<td>14</td>
<td>4</td>
<td>1</td>
<td>2.64</td>
</tr>
<tr>
<td>OD 7.1</td>
<td>825</td>
<td>144</td>
<td>64</td>
<td>10.38</td>
</tr>
<tr>
<td>OD 7.2</td>
<td>38</td>
<td>9</td>
<td>2</td>
<td>3.25</td>
</tr>
<tr>
<td>OD 7.3</td>
<td>42</td>
<td>8</td>
<td>3</td>
<td>2.55</td>
</tr>
<tr>
<td>OD 19</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>2.60</td>
</tr>
<tr>
<td>OD 20</td>
<td>50</td>
<td>9</td>
<td>3</td>
<td>2.54</td>
</tr>
<tr>
<td>OD 7.1</td>
<td>549</td>
<td>95</td>
<td>42</td>
<td>8.56</td>
</tr>
<tr>
<td>OD 20</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>3.53</td>
</tr>
<tr>
<td>OD 7.1</td>
<td>1915</td>
<td>447</td>
<td>148</td>
<td>26.39</td>
</tr>
<tr>
<td>OD 7.1</td>
<td>1433</td>
<td>377</td>
<td>111</td>
<td>26.94</td>
</tr>
</tbody>
</table>
include a catalogue of all stars corresponding to the spatial distribution of over-densities in Figure 3.13 as supplementary online data.

### 3.7.1 The Centre of Sextans

Although the focus of this paper is to look for substructure in the outskirts of Sextans, there have been interesting discussions on kinematic substructure more centrally located (see Kleyna et al., 2004; Walker et al., 2006; Battaglia et al., 2011; Karlsson et al., 2012). Here we present a brief analysis of this inner region of our Sextans field. Using our smoothed foreground subtracted map, we focus on the central region with contours representing 40, 50 and 60 times $\sigma_t$. It is important to note that this region will be more sensitive to any member stars that may have fallen into the foreground map, compared to the outskirts. However, the weight mask was applied carefully to minimise these effects. Also note that the contours do not represent the presence of the candidate BSS and HB star populations. These are investigated separately.

Figure 3.14 displays the results of this analysis, with contours displayed at 20, 30, 40, 50 and 60 times $\sigma_t$ making comparison to the full map straight forward. The contours are shown in increasing shades of grey to black, and show that the densest part of Sextans is not actually at its centre, defined by Irwin & Hatzidimitriou (1995), but slightly toward the North-East of its centre. This is the same direction as the offset in coordinates found in Section 3.6. It is interesting to note that this is close to the kinematically cold region, marked with a red star in Figure 3.14, detected by Walker et al. (2006). Figure 3.14 also shows confirmed red giant branch stars from Battaglia et al. (2011). The colour scale represents the [Fe/H] value determined by Battaglia et al. (2011) for each of these stars. They find nine stars inside a radius of 13.2' from Sextan’s centre with similar kinematics to each other, and a metallicity within a scatter of 0.15 dex from [Fe/H] = −2.6. Pointing out that the average error in metallicity on these stars is 0.29 dex, they suggest that these stars once belonged to a single stellar population.

Given the differences noted in the distribution of the various stellar populations within Sextans (Lee et al., 2003), we have also performed a brief investigation into the distribution of candidate BSS and BHB stars in our field. We investigated the cumulative distribution function (CDF) of the radial distribution of the two groups (Figure 3.15). First, we estimate $\theta$, $\epsilon$ for the two groups, as well as their centroid. For the BHB candidates we find $\theta = 72^\circ \pm 15^\circ$ and $\epsilon = 0.20 \pm 0.06$, and for the BSS candidates $\theta = 40.9^\circ \pm 5.4^\circ$ and $\epsilon = 0.36 \pm 0.02$. The centroids for each group are $-0.086 \pm 0.009, 0.045 \pm 0.006$ and $0.02 \pm 0.01, -0.004 \pm 0.002$ respectively, measured in degrees from the centre of Sextans. The high uncertainty associated with $\theta$ for the BHB candidates is most likely due to the low number density. However within combined uncertainties, the BSS and BHB populations are largely consistent with the full Sextans sample. Concentric elliptical annuli were placed...
Figure 3.12: Top three rows show CMDs for all detections with $\zeta \geq 2.52$ (listed in Table 3.3), bottom row shows examples of detections with $\zeta < 2.52$. The detection threshold is labelled on each plot. Marker fill-colour correlates with mask weight (where 1 is black and 0 is white). Note horizontal branch features in OD 20, as well as the main region surrounding Sextans (OD 7, OD 7.1).
at evenly spaced intervals of 3' about each group, and the number of stars inside each annulus counted. This was then used to create the CDF for each population of stars. A Kolmogorov-Smirnoff (K-S) test was performed to test the likelihood of the two groups being drawn from the same distribution. With a $p$-value of 0.38, it is possible the two groups come from separate distributions.

We also looked specifically at the BSS population. Lee et al. (2003) noticed that brighter ($V < 22.3$) stars appeared more centrally concentrated. We split our BSS population into two at $g = 22.3$, plotting the CDF and performing a K-S test. With a $p$-value of 0.998, it is highly likely that the two groups belong to the same distribution.
Figure 3.14: Contour plot of central region of Sextans. Contours representing 15, 20, 25, 30, 35 and 40 times $\sigma_1$ are shown in increasing shades of grey to black. A red star represents the location of a kinematically cold region detected by Walker et al. (2006) at the 95% confidence level. Coloured points represent red giant branch members identified by Battaglia et al. (2011), with the colour scale showing [Fe/H]. Note that the coverage by Battaglia et al. (2011) is not uniform, and therefore the lack of stars South-East of centre is a selection effect.

Figure 3.15: Cumulative distribution functions for the BHB and BSS populations (defined in Figure 3.5). The BSS population is also split into bright and faint groups at $g = 22.3$. The grey dash-dot line represents the core radius.
3.8 Discussion and Summary

The observation of kinematically cold structures in the centre of Sextans (Kleyna et al., 2004; Walker et al., 2006; Battaglia et al., 2011), as well as the suggestion of a dissolved star cluster at its core (Karlsson et al., 2012), has led to some discussion on whether or not this galaxy is undergoing tidal disruption. Our analysis of the field surrounding Sextans has revealed significant extended halo-like substructure, extending to a distance of up to 82′ (2kpc). Much of this structure appears to be highly statistically significant, with over-densities having \( \zeta \) values as high as 26.94, and clear signs of Sextans’s stellar population in the colour-magnitude diagram. We note however, that unlike Hercules (Roderick et al., 2015), the substructure surrounding Sextans appears to be both aligned with, and perpendicular to the major axis. Figure 3.13 shows a summary of our results. The distribution of over-densities is shown, colour-coded according to significance. Different line-widths represent the different detection thresholds, with the fill colour corresponding to the \( \zeta \) value at that threshold. The direction of proper motion of Sextans (Walker et al., 2008) is shown by a black arrow.

We have shown the candidate BSS population in Figure 3.13 with size correlated to brightness; brighter stars appear as larger points. Previous work has shown that the brighter part of this population is more centrally concentrated than the faint part inside a radius of 22.5′ (Lee et al., 2003). Our analysis shows that both the bright and faint components of this population are likely to be drawn from the same distribution at the 99.8% confidence level. We also find that the BSS population is more centrally concentrated than the BHB population, in agreement with Lee et al. (2003). This fits the idea of Lee et al. (2009) that the star formation history of Sextans varies slightly according to location within the galaxy.

A brief analysis of the central region of Sextans has revealed an over-dense region approximately 9′ to the North-East of the galaxy’s centre. Interestingly, this is close to a kinematically cold region detected by Walker et al. (2006). Sextans is not the first MW dwarf to show such a feature. The Ursa Minor dwarf shows two apparent ‘clumps’ of stars (Olszewski & Aaronson, 1985; Irwin & Hatzidimitriou, 1995), of which the one furthest from centre has been associated with a kinematically cold region (Kleyna et al., 2003). It has been suggested that this is a primordial artefact rather than some form of transient substructure, and incompatible with a cusped dark matter halo (Kleyna et al., 2003). This has interesting repercussions for \( \Lambda \)CDM; the appearance of such a feature in Sextans provides an excellent opportunity for further investigation.

The radial profile of Sextans is well described by a King model, and shows only tentative evidence of a break radius indicating extra tidal stars. This is similar to the case of Draco (Odenkirchen et al., 2001a; Ségall et al., 2007), however it is possible that extra tidal features may become apparent further outside the tidal radius; see for example Carina
(Majewski et al., 2000, 2005), although these features are not so prominent in more recent work (McMonigal et al., 2014). Sculptor is another dwarf spheroidal which may (Westfall et al., 2006), or may not (Coleman et al., 2005) show an extra tidal break radius. The large tidal radius observed in Sextans also suggests that the extended stellar halo-structure is bound by the galaxy’s gravitational field. Although part of this structure is in proximity to the tidal radius, the majority of structure is well contained. This is consistent with the results of Peñarrubia et al. (2009), where it is noted that there is no evidence to suggest extra tidal features in the radial profile, however they caution that the profile of Sextans was only probed to four times the core radius (approximately 51′ based on their Table 2).

According to Walker et al. (2008), Sextans is receding from its perigalactic distance of $66^{+17}_{-61}$ kpc towards an apogalactic distance of $129^{+113}_{-33}$ kpc. The large uncertainties make it difficult to discern how eccentric the orbit of Sextans is, and Walker et al. (2008) state that any orbital eccentricity in the range $0.25 - 0.89$ is within the 95% confidence interval. A more circular orbit would help explain the appearance of the substructure we see surrounding Sextans, as a more eccentric orbit would pass closer (within 5kpc, Walker et al., 2008) to the Galactic centre and cause more severe tidal disruption. It has also been shown that a tidally disrupting dwarf may return to a more spherical shape after a few Gyr, depending on the tidal forces involved (Lokas et al., 2012). Furthermore, simulations have demonstrated that a galaxy travelling between perigalacticon and apogalacticon will have its tidal tails dissolve, and new ones develop on a relatively short time scale (Klimentowski et al., 2009). These scenarios suggest it is possible Sextans is experiencing tidal disruption, but is presently in a period of morphological transition. The alignment along and perpendicular to the major axis of Sextans over-densities may be an indication the dwarf is in the process of dissolving its tidal tails and developing new ones.

Given the extended substructure features we have found in this galaxy, as well as variations in the distribution of BHB and BSS populations, it appears that Sextans may have a varied star formation history but is not necessarily undergoing strong tidal disruption. Although it is possible Sextans is in the midst of a morphological transition due to tidal stirring, it is also possible this galaxy has a circular orbit, exposing it to relatively little influence from the MW. The stars we have identified as belonging to over-densities associated with the Sextans dwarf spheroidal galaxy provide good candidates for spectroscopic follow up. Velocity measurements for these stars will provide a better picture of the kinematics in the outskirts of this galaxy, and provide us with a better understanding of the nature of its extended substructure.
CHAPTER 4

Extended stellar substructure surrounding the Boötes I dwarf spheroidal galaxy

This chapter has previously been published as “Extended stellar substructure surrounding the Boötes I dwarf spheroidal galaxy”, Roderick, T.A. et al., 2016 MNRAS, 461 (4) pp. 3702-3713

4.1 Abstract

We present deep stellar photometry of the Boötes I dwarf spheroidal galaxy in $g$ and $i$ band filters, taken with the Dark Energy Camera at Cerro Tololo in Chile. Our analysis reveals a large, extended region of stellar substructure surrounding the dwarf, as well as a distinct over-density encroaching on its tidal radius. A radial profile of the Boötes I stellar distribution shows a break radius indicating the presence of extra-tidal stars. These observations strongly suggest that Boötes I is experiencing tidal disruption, although not as extreme as that exhibited by the Hercules dwarf spheroidal. Combined with revised velocity dispersion measurements from the literature, we see evidence suggesting the need to review previous theoretical models of the Boötes I dwarf spheroidal galaxy.

4.2 Introduction

The study of the origin and nature of the Milky Way (MW) dwarf galaxy population has received increased attention since the advent of digital all-sky surveys. As a result, a new class of ultra-faint stellar systems has been discovered (e.g. Belokurov et al., 2007a; Walsh et al., 2007; Koposov et al., 2007; Bechtol et al., 2015; Koposov et al., 2015a; Kim & Jerjen, 2015a; Kim et al., 2015a; Laevens et al., 2015; Drlica-Wagner et al., 2015). According to the concordance cosmological model, ΛCDM, the dwarf galaxy population is one of the visible remnants of the galaxy formation process. In this context, galaxies have formed through
Chapter 4 Extended stellar substructure surrounding the Boötes I dwarf spheroidal galaxy

the accretion and merger of baryonic matter embedded in dark matter halos (see: Moore et al., 1999; Diemand et al., 2007; Diemand & Moore, 2011). This scenario is supported by the high dark matter content inferred in the dwarf galaxies (e.g. Simon & Geha, 2007; Martin et al., 2007; Simon et al., 2011; Kirby et al., 2015; Koposov et al., 2015b). However, observations show that most of the currently known MW satellite galaxies are aligned in a vast polar structure (Pawlowski et al., 2015), said to be inconsistent with a primordial origin. A similar structure seen amongst the Andromeda satellites (Ibata et al., 2013) has lent support to an alternative explanation where the MW satellite population is largely made up of tidal remnants from the interaction of the MW with another galaxy (see: Kroupa et al., 2005; Pawlowski et al., 2013; Yang et al., 2014; Pawlowski & McGaugh, 2014).

In order to resolve the conflict between these fundamentally different scenarios and gain a better understanding of the MW neighbourhood, further investigation is required. In depth studies of the MW dwarf galaxy population have demonstrated that a number of these dwarfs show signs of tidal disruption (e.g. Ibata et al., 1994; Palma et al., 2003; Battaglia et al., 2012; Newby et al., 2013; McMonigal et al., 2014; Roderick et al., 2015). A result of this is that velocity dispersion measurements of such galaxies can be inflated by unbound stars (Klimentowski et al., 2007). Moreover, mass-to-light ratios determined from kinematic samples assume a system is in dynamic equilibrium. Where this is not the case, the mass-to-light ratio can be over-estimated. Furthermore, several cases exist in which improved membership determination has led to considerably lower velocity dispersion estimates, and consequently mass-to-light ratios (Lokas, 2009; Koposov et al., 2011).

Our recent work (Roderick et al., 2015, 2016) has demonstrated the effectiveness of deep, wide-field, photometric observations in revealing extended stellar substructure associated with MW dwarf galaxies, leading to improved understanding of their current dynamic state. Following on from this, we present here a wide-field, photometric study of the Boötes I dwarf spheroidal galaxy.

The Boötes I dwarf (see Table 4.1), discovered in the Sloan Digital Sky Survey (SDSS, Belokurov et al., 2006), is relatively unstudied compared to many of its other MW satellite companions. Boötes I is a low luminosity ($M_V = -5.92 \pm 0.2$, Okamoto et al., 2012), metal poor ($\text{Fe/H} = -2.55 \pm 0.11$, Norris et al., 2010b) system, and is one of the most gas poor dwarfs known (Bailin & Ford, 2007). It shows an elongated stellar distribution (Belokurov et al., 2006; Okamoto et al., 2012), and has a high mass-to-light ratio ($> 100$, Muñoz et al., 2006; Martin et al., 2007; Koposov et al., 2011). Results from N-body simulations, using a number of models of Boötes I, have led to the conclusion that its progenitor must have been dark matter dominated, since a purely baryonic star cluster could not reproduce the observed velocity dispersion (Fellhauer et al., 2008). However, more recent work by Koposov et al. (2011) has demonstrated that Boötes I not only has a much lower velocity
dispersion than previously thought, it also exhibits a secondary hot component alongside its dominant, colder component. This calls into question our previous understanding of the dark matter content of Boötes I, and presents a potentially interesting dynamic history.

Study of the stellar population of Boötes I has shown it to be old (> 13Gyr, Okamoto et al., 2012), and consistent with a single epoch, short period burst of star formation (Belokurov et al., 2006; Okamoto et al., 2012). Boötes I has a population of variable stars (Siegel, 2006; Dall’Ora et al., 2006), and blue straggler stars (BSS) (Santana et al., 2013), and shows chemical properties consistent with essentially primordial initial abundances (Gilmore et al., 2013). Despite its projected proximity to the Sagittarius stream, any association has been ruled out (Law & Majewski, 2010).

Although its elongation and irregular shape were noted upon its discovery, as well as more recently (Belokurov et al., 2006; Okamoto et al., 2012), little has been done to characterise the spatial extent of Boötes I quantitatively. This may in part be due to the difficulty in observing such a faint object, particularly on any broad spatial scale. However, the emergence of wide-field CCD cameras such as the Dark Energy Camera (DECam, Flaugher et al., 2015), on the 4m Blanco telescope at Cerro Tololo in Chile, makes such observations possible. Here we present deep, wide-field observations of the Boötes I dwarf spheroidal galaxy with the intention of conducting a quantitative analysis of stellar substructure associated with the system. In Section 4.3 we present our observations and data reduction. This is followed by foreground discrimination and spatial mapping in Sections 4.4 and 4.5. We perform a brief analysis of the structural parameters of Boötes I in Section 4.6. In Section 4.7 we present our substructure analysis and methodology. Finally, Sections 4.8 and 4.9 present our discussion and summary.

4.3 Observations and Data Reduction

Observations were carried out as part of observing proposal 2013A-0617 (PI: D. Mackey), on 2013 February 15, using DECam on the 4m Blanco telescope at Cerro Tololo in Chile. DECam is comprised of a hexagonal mosaic of 62 2K×4K CCDs, each with a pixel scale of 0\'′27/pix, creating a total field-of-view of 3 square degrees.

The data set consists of a single pointing taken in the direction of Boötes I (see Figure 4.1), in g and i band filters. A total of 3 × 300s exposures were taken in each filter, providing a total integration time of 900s each, with an average seeing of 1\′′30 and 1\′′14 in g and i respectively.

The raw images were processed with the DECam community pipeline\(^1\) (Valdes et al., 2014). This processing included the subtraction of sky-background, WCS solution fitting,

\(^1\)http://www.ctio.noao.edu/noao/content/Dark-Energy-Camera-DECam
Table 4.1: Fundamental Parameters of Boötes I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Ref.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
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<td>1</td>
</tr>
<tr>
<td>DEC (J2000)</td>
<td>+14:30:00</td>
<td>1</td>
</tr>
<tr>
<td>$l$</td>
<td>358.1°</td>
<td>1</td>
</tr>
<tr>
<td>$b$</td>
<td>69.6°</td>
<td>1</td>
</tr>
<tr>
<td>$D_\odot$</td>
<td>65 ± 3 kpc</td>
<td>2</td>
</tr>
<tr>
<td>$(m - M)_0$</td>
<td>19.07 ± 0.11</td>
<td>2</td>
</tr>
<tr>
<td>$r_h$</td>
<td>12.5′ ± 0.3′</td>
<td>2</td>
</tr>
<tr>
<td>$M_V$</td>
<td>$-5.92 ± 0.2$ mag</td>
<td>2</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>2.4$^{+0.5}_{-0.2}$ km s$^{-1}$</td>
<td>3</td>
</tr>
<tr>
<td>$v_\odot$</td>
<td>101.8 ± 0.7 km s$^{-1}$</td>
<td>3</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>$-2.55 ± 0.11$ dex</td>
<td>4</td>
</tr>
<tr>
<td>$\theta$</td>
<td>13.8° ± 3.9°</td>
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</tr>
<tr>
<td>$\epsilon$</td>
<td>0.26 ± 0.01</td>
<td>5</td>
</tr>
<tr>
<td>$r_t$</td>
<td>31.6′ ± 4.0′</td>
<td>5</td>
</tr>
</tbody>
</table>

*References: (1) Belokurov et al. (2006), (2) Okamoto et al. (2012), (3) Koposov et al. (2011), (4) Norris et al. (2010b), (5) This work

and the co-addition of images into a single, deep, multi-extension FITS image for each filter. Each of these images is presented as nine image slices, or tiles, contained in nine separate extensions of the FITS file.

4.3.1 Photometry and Star/Galaxy Separation

The photometry was carried out using the pipeline described by Roderick et al. (2015). This involved several key steps outlined in the following.

First, WeightWatcher\(^2\) (Marmo & Bertin, 2008) was used in combination with the weight maps from the DECam community pipeline, in order to mask out non-science pixels in the images prior to the performance of aperture photometry. The photometry was then conducted with Source Extractor\(^3\) (Bertin & Arnouts, 1996) in two passes on each image. The first pass was shallow, providing an estimate of the average FWHM ($\overline{F}$) across the field. A second, deeper pass was then performed, using this information as input for aperture sizes. Flux was measured inside $1 \times \overline{F}$ and $2 \times \overline{F}$, separately on each of the nine image tiles for each filter. This allowed the aperture size to vary across the large field-of-view, allowing for fluctuations in the point-spread-function.

\(^2\)http://www.astromatic.net/software/weightwatcher

\(^3\)http://www.astromatic.net/software/sextractor
Once the photometry was complete, star/galaxy separation was performed. The technique used is described in detail in Roderick et al. (2015), and involves taking the magnitude difference between apertures for each source in the catalogue, revealing a clear stellar locus in the data. Figure 4.2 demonstrates this process for the central image tile of Boötes I, and clearly shows the stellar locus. The locus is isolated by fitting an exponential to the distribution to the right of the mean, and reflecting it to create a selection region. This is combined with the Source Extractor classification flag (flag $\xi < 0.35$) and achieves star/galaxy separation to a depth over a magnitude greater than that achieved by Source Extractor alone. As seen in Roderick et al. (2016), the Source Extractor classification flag can be inconsistent when used across multiple fields with large variations in seeing. However, for individual fields (such as Boötes I), when used conservatively it can assist in star/galaxy separation for faint objects (Roderick et al., 2015). The star/galaxy separation was performed on the $i$-band catalogue prior to cross-matching with the $g$-band catalogue. The product of this process was a single catalogue of stellar sources, containing the photometry for both filters.

After completion of the catalogue, it was calibrated to the SDSS photometric system. For that purpose, the catalogue was cross-matched with stars from SDSS data release 10 (SDSS DR10: Ahn et al., 2014). The SDSS magnitudes were compared to the catalogue magnitude inside the $2 \times \overline{F}$ aperture, and a zero point ($ZP$) and colour term ($c$) determined for each filter, where colour is defined as $(g - i)_{\text{inst}}$. These values, determined by a least squares fit, are summarised in Table 4.2. Once calibrated, a correction for Galactic extinction was applied. This has a greater effect on the $g$-band than the $i$-band, with $0.048 < A_g < 0.107$ (approximately 3% differential variation in magnitude across the field).

Figure 4.1: All point sources in our DECam field-of-view. North is up, and East is to the left. The black ellipse denotes the half-light radius of Boötes I. Note that two CCDs were faulty at the time of observing, and have been masked out. There are two bright stars in close proximity to one another on the western side of the field, leading to a lack of detections in that area. This is discussed later in the paper.
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Figure 4.2: Magnitude difference between apertures for each source extracted in the central $i$-band image tile. Stellar objects are shown as a clear locus, with a selection region shown by black lines. The selection region was determined by fitting an exponential to the distribution of stars and reflecting it about the locus.

Table 4.2: Properties of the observations taken for Boötes I.

<table>
<thead>
<tr>
<th>Property</th>
<th>$g$</th>
<th>$i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average seeing</td>
<td>1''30</td>
<td>1''14</td>
</tr>
<tr>
<td>$ZP$</td>
<td>31.124</td>
<td>31.314</td>
</tr>
<tr>
<td>$c$</td>
<td>0.069</td>
<td>0.078</td>
</tr>
<tr>
<td>50% Completeness</td>
<td>24.69</td>
<td>23.94</td>
</tr>
</tbody>
</table>

Rather than applying a single correction based on the average extinction, the correction factor was allowed to vary across the field. This was achieved in a simple manner by making use of the calibration to SDSS DR10. Each star in the catalogue was matched to its nearest SDSS neighbour, and the corresponding correction value used. According to Stoughton et al. (2002), the extinction correction values in SDSS DR10 are given by $A_g = 3.793E(B - V)$ and $A_i = 2.086E(B - V)$, and are based on the extinction maps of Schlegel et al. (1998).
4.3.2 Completeness

A completeness test was performed in order to assess the limiting magnitudes and photometric uncertainties in each filter. This was achieved by adding artificial stars to each image with the IRAF addstar task. Artificial stars were added to each image in magnitudes ranging between 18.0 and 26.75 mag, with randomly assigned coordinates. Each image was then processed through the photometry pipeline to recover the artificial stars. This process was repeated 30 times, with a total of 145,800 artificial stars added to each image. The resulting completeness curve for each filter is shown in Figure 4.3. The relation from Fleming et al. (1995) was fit to each completeness curve in order to determine the 50% completeness limit. These relations are shown in Figure 4.3, and the limiting magnitudes listed in Table 4.2. The catalogue was cut at the 50% limiting magnitude in each filter and is limited by the $i$-band observations, with the 50% limiting magnitude 0.75 mag brighter than the $g$-band. However, the stellar catalogue still reaches down to $i=23.9$ mag, or approximately 1.5 mag below the main sequence turn off.

The photometric uncertainties in each band were determined by comparing the recovered magnitude of each artificial star to its input magnitude. The resulting distributions were each fit with an exponential function, which was then used as a reference to calculate the photometric uncertainty of each individual star in each filter.

4.4 Foreground Discrimination

In order to investigate stellar over-densities associated with Boötes I, it is essential to first remove as much contamination from MW halo stars as possible. This is difficult to do, however reasonable discrimination can be achieved with the assistance of a colour-magnitude diagram (CMD) (see Roderick et al., 2015, 2016). We use the same method as Roderick et al. (2015) to weight stars according to their position on the CMD and proximity to the Boötes I fiducial. The Boötes I fiducial is closely approximated using a model isochrone. This isochrone is then used to create a weight mask by assigning a Gaussian profile in the colour-space, along discrete magnitude intervals. The Gaussian profile is determined for each magnitude interval using the colour of the isochrone at that magnitude as the peak of the Gaussian, and the photometric uncertainty in colour as the width. Each Gaussian has a peak value of 1, such that stars closest to the isochrone are given the highest weight.

For the Boötes I mask, we selected a model isochrone from the Dartmouth Stellar Evolution Database (Dotter et al., 2008), with an age, metallicity and alpha abundance of 15 Gyr, $-2.49$ dex and $0.2$ dex, respectively. These values are consistent with the literature, and the isochrone provides an excellent approximation of the Boötes I fiducial. Once the mask was created, each star in the catalogue was assigned a weight $w$ between 0 and 1 based on the
Figure 4.3: Top and bottom panels show the results of the completeness test in $g$ and $i$ respectively. The fitting relation described by Fleming et al. (1995) is shown by the dashed lines. The 50% completeness limits determined by the fitting relation are given in Table 4.2.

mask, providing a flexible means of selecting stars consistent with membership of Boötes I. Choosing a larger or smaller weight decreases or increases the size of the selection box around the Boötes I stellar population, whilst simultaneously considering the photometric uncertainties in the data.

Figure 4.4 illustrates both the Boötes I stellar population, and the mask. The left panel shows the CMD of stars inside the half-light radius ($r_h = 12.5' \pm 0.3'$ Okamoto et al., 2012) of Boötes I, demonstrating a clear fiducial sequence belonging to the galaxy. Red and blue boxes also outline candidate blue horizontal branch (BHB) stars and BSS, respectively. They are not included in the mask, but will be used later as a consistency check. The central panel in the figure shows a Hess diagram of the entire DECam field (with bin sizes of 0.07 and 0.06 in $g$ and $g - i$ respectively). Although Boötes I is still apparent, the amount of contamination from the MW foreground is considerable and demonstrates the need for discrimination. The right hand panel in the figure presents the weight mask, where the values range from 0 to 1. The increasing photometric uncertainties broaden the mask at faint magnitudes.
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4.5 Spatial Mapping

With each star in the catalogue assigned a weight, we created a map of the spatial distribution of Boötes I. This facilitates both the analysis of structural parameters of the dwarf as well as the search for stellar substructure associated with it. The process used follows closely the method used by Roderick et al. (2015, 2016).

First, the catalogue was separated into two groups, one containing stars consistent with Boötes I membership, and the other containing everything else. This was done in order to create a kind of ‘foreground’ map which could be used to remove the foreground contamination. A weight of \( w \geq 0.5 \) was chosen as the cutoff weight to create these two groups, since it encompasses as much of the Boötes I population as possible without introducing much contamination from the MW (see right panel of Figure 4.4).

Once the two groups were defined, they were binned in R.A. and Dec to create normalised (to bin area and sample size) 2D histograms (or pixelated maps). After experimenting with several different bin sizes, a bin size of \( 20'' \times 20'' \) was chosen since it provided the most detail without too much noise. The two associated histograms were then smoothed with a Gaussian kernel to create density maps. Different kernel sizes were trialled, however a smoothing factor of 7 pixels was chosen (equivalent to smoothing over \( 140'' \)). We note that the same major structural features were apparent in the maps independently of the chosen kernel size, however this size again provided the most detail with the least amount of noise. Once the two density maps were established, the ‘foreground’ map was first used to divide through the Boötes I map like a flat field, before being subtracted from the Boötes I map to reveal an elongated halo surrounding the Boötes I dwarf. The foreground map was scaled during this process to ensure an appropriate subtraction was performed.

**Figure 4.4:** Left: Colour magnitude diagram of all stars within the central half-light radius of the Boötes I dwarf galaxy. The red and blue boxes denote the regions of candidate blue horizontal branch and blue straggler stars respectively, which are excluded from the mask. Centre: 2D histogram of the complete Boötes I catalogue, showing considerable contamination from MW halo stars. Right: Weight mask generated from the Dartmouth model isochrone that best resembles the Boötes I stellar population. The width of the mask increases with increasing photometric uncertainty at faint magnitudes.
Figure 4.5: The process of creating a smoothed density map for detection of stellar over-densities associated with Boötes I. Left: Smoothed density map of stars consistent with Boötes I membership ($w \geq 0.5$). Centre: Smoothed density map of stars inconsistent with Boötes I membership ($w < 0.5$). Right: The smoothed, ‘foreground’ subtracted density map revealing the distribution of stars that are most likely Boötes I members. Note that the inter-chip gaps between CCDs in the left and central panels disappeared, highlighting the success of the foreground subtraction. The position of the two bright foreground stars in the field are visible as a white gap in the map. The density scale increases from blue to red in each panel, however while the left and centre panels share the same scale, the right panel has a different scale for visual clarity.

It was noted that scaling did not change the main features in the final map, however it did change the contrast. The scaling was performed so as to provide the best contrast in the final map. Each of the smoothed, normalised histograms are illustrated in Figure 4.5, as well as the final density map. Note that the inter-chip gaps between CCDs are not visible in the final smoothed, subtracted density map. The position of the two bright stars in the field are also visible as a white gap in the map (this part of the map is assigned a “NaN” value and treated as such in the analysis).

In order to identify structure in the map, a measure of the average background pixel value was determined by averaging over all pixels outside three times the half-light radius. Using the standard deviation of the background, $\sigma_t$, contours are defined in units of $\sigma_t$ above the mean. These contours are used as the basis for detection thresholds later in the substructure analysis, with the subscript $t$ serving as a reminder that this standard deviation defines the thresholds. Figure 4.6 displays contours from the density map at $3\sigma_t$, $4\sigma_t$, $5\sigma_t$, $6\sigma_t$, $7\sigma_t$, $10\sigma_t$, $15\sigma_t$, and $20\sigma_t$. As a means of confirming the robustness of our initial star/galaxy separation, we compared the contours with the distribution of background galaxies downloaded from SDSS, and found no correlation.

### 4.6 Structural Parameters

Prior to the substructure analysis, we determined the orientation angle, $\theta$, ellipticity, $\epsilon$ and centroid for Boötes I, and made a radial profile (shown in Figure 4.7). In a similar process to McConnachie & Irwin (2006), we used the contours from our density map in the
determination of $\theta$, $\epsilon$ and the centroid. For each contour, at intervals of $1\sigma_t$ in the range between $3\sigma_t$ and $20\sigma_t$, a maximum likelihood bivariate normal fit was performed using the astroML$^4$ (VanderPlas et al., 2012) machine learning package. The results were averaged across all contours, giving $\theta = 13.4^\circ \pm 6^\circ$, $\epsilon = 0.33 \pm 0.06$ and a centroid offset in degrees from the central R.A. and Dec of $0.010 \pm 0.006$, $0.018 \pm 0.008$. These values are comparable to those found in the literature ($0.22 < \epsilon < 0.39$, $\theta = 14^\circ \pm 6^\circ$, Belokurov et al., 2006; Martin et al., 2008; Okamoto et al., 2012). The irregular shape of Boötes I contributes to the large uncertainty in the orientation angle, however basing the measurement on the contours provides a robust estimate of the uncertainty intrinsic to this dwarf. Note that the centroid is varies from the centre of the $15\sigma_t$ contour by 0.002 and 0.01 degrees in R.A. and Dec respectively.

$^4$http://www.astroml.org/
Using the values determined for $\theta$, $\epsilon$ and the centroid, we created elliptical annuli about the centre of Boötes I, with widths of 1.5 – 5 arcminutes increasing radially outward until the limiting edge of the field (45 arcmin along the major axis from the centre of Boötes I). The star density of each annulus was recorded, and the background density subtracted (found by averaging over random samples of the field). Although there are inter-chip gaps present between the CCDs, these are regular and systematic across the field. Thus it was deemed that they would not affect the overall outcome of the profile. The resulting profile is shown in Figure 4.7. Both a King profile (King, 1962) and exponential profile were fit to the data. The King profile provides a better fit to the central region (< 20 arcmin) than the exponential profile. However, there appears to be a break radius at this point, where the exponential profile provides a better fit. According to the King profile, the tidal radius is $r_t = 32.5 \pm 3.4$, with a core radius of $r_c = 15.1 \pm 1.6$, placing the break radius inside the tidal radius. This may indicate that Boötes I has underlying substructure. We will discuss the break radius further in Section 4.8.

4.7 Structural Analysis

This section contains the identification and quantification of substructure associated with Boötes I, and provides the focus of this paper. The analysis process is comprised of several parts; the explicit identification of substructure is based on the density map developed in Section 4.5, and followed by quantification of each individual over-density. We also
include a brief analysis of the distribution of candidate BSS and BHB stars. Each part of the analysis is described in the following.

### 4.7.1 Identification of Substructure

Since this paper is most concerned with the outskirts of Boötes I, and the central region provides sufficient signal to dominate the statistical analysis, we exclude the region inside the $15 \sigma_t$ contour and concentrate on the structure outside this region. The density map was then ‘segmented’ using the Python package `scipy.ndimage`, and individual structures given a segment identification number (see Roderick et al., 2015, 2016). The segmentation process was performed at six different detection thresholds, where the thresholds are given by the $3 \sigma_t$, $4 \sigma_t$, $5 \sigma_t$, $6 \sigma_t$, $7 \sigma_t$, $10 \sigma_t$ contours. In each case, everything above the detection threshold was considered a potentially significant over-density. Additionally, we performed the segmentation process at a threshold of $2 \sigma_t$. Despite the fact that this threshold revealed a lot of ‘noisy’ detections, the contour surrounding the main body of Boötes I was determined to be statistically significant during the course of analysis. While this detection threshold is not discussed further, the significant contour is presented in our summary.

There was a total of eight detections at the $3 \sigma_t$ level, some of which were also detected at higher detection thresholds. Where there are repeat detections, the naming scheme of the $3 \sigma_t$ level is adopted. The detections and labelling scheme are illustrated in Figure 4.6. Once formally identified, the stars associated with each individual over-density were extracted from the catalogue to test the level of significance. All stars in the over-density were extracted, regardless of their weight, to ensure unbiased testing. A control sample of stars was also necessary to calibrate against. This provided a comparison for our detections to assess their significance. We do not have a separate field for comparison, however the DECam field-of-view provides a large region of sky unoccupied by Boötes I. Since the stellar over-densities were identified as anything above the detection threshold, we define a suitable control region as any part of the sky below the detection threshold. This ensures a reasonable representation of the sky, making use of as much of the DECam field as possible without including any regions which may be associated to Boötes I.

### 4.7.2 Quantification of Substructure

We use the same method as Roderick et al. (2015) to quantify the significance of our over-density detections. For the purpose of testing we consider a star to be in close proximity to the Boötes I isochrone if it is weighted $w \geq 0.8$.  

5http://docs.scipy.org/doc/scipy/reference/ndimage.html
Using the previously defined control region, a sample of stars are drawn equal in number to the over-density being tested (for the purpose of testing each detection threshold independently of the others, we count only stars ‘between’ thresholds, such that stars detected at higher thresholds are not counted in the lower thresholds). In both the sample and the over-density, stars in close proximity to the isochrone \((w \geq 0.8)\) are counted and noted. This is repeated for the control region 10,000 times, with the sample drawn randomly each time. A frequency distribution is created from this, and a Gaussian function fit to provide a mean and standard deviation \((\sigma)\). The significance \((\zeta)\) is then determined by comparing the number of stars in the over-density with \(w \geq 0.8\) \((N_{w\geq0.8}(OD))\) with the average value determined for the control sample \((N_{w\geq0.8}(CS))\). The significance is defined as the separation between the two values in units of \(\sigma\):

\[
\zeta = \frac{N_{w\geq0.8}(OD) - \langle N_{w\geq0.8}(CS) \rangle}{\sigma}
\]

In order to assess the level of significance, we also performed a test of the null hypothesis. We defined 550 random over-densities across the field, varying in size between 4 and 400 square arcminutes, but avoiding regions previously defined as candidate over-densities belonging to Boötes I. We then performed the same significance testing using the control sample, with the expectation that the frequency distribution of \(\zeta\) values should be centred on approximately zero (the frequency distribution is shown in Figure 4.8). We fit a Gaussian function to the distribution, and found a mean of \(-0.33\) and standard deviation of 1.04. Based on this, we consider any detection with a significance value of three standard deviations or more above the mean to be statistically significant, providing a quantitative assessment value of \(\zeta \geq 2.79\). The results of the significance testing are shown in Figure 4.9. As can be seen from the figure, there are two main over-densities considered significant, with the main structure surrounding Boötes I detected at multiple levels. The results of testing for each significant detection are listed in Table 4.3.
Figure 4.9: Graphical representation of the significance of each detection (listed in Tables 4.3). Circles, diamonds, squares, stars, triangles and hexagons represent thresholds $3\sigma_t$ to $10\sigma_t$ respectively. The grey dashed line represents $\zeta = 2.79$.

Table 4.3: Significance values for the statistically significant detections, where segment labelling corresponds to Figure 4.6. Each detection threshold is separated by a horizontal line, with the top rows corresponding to $3\sigma_t$, progressing down the table to $10\sigma_t$.

<table>
<thead>
<tr>
<th>Segment</th>
<th>$N_*$</th>
<th>$N_{w \geq 0.8(OD)}$</th>
<th>$\langle N_{w \geq 0.8(CS)} \rangle$</th>
<th>$\zeta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD 1</td>
<td>187</td>
<td>49</td>
<td>31</td>
<td>3.59</td>
</tr>
<tr>
<td>OD 2</td>
<td>457</td>
<td>109</td>
<td>75</td>
<td>4.32</td>
</tr>
<tr>
<td>OD 6</td>
<td>6</td>
<td>4</td>
<td>0</td>
<td>2.90</td>
</tr>
<tr>
<td>OD 2</td>
<td>308</td>
<td>76</td>
<td>50</td>
<td>3.87</td>
</tr>
<tr>
<td>OD 2</td>
<td>292</td>
<td>89</td>
<td>48</td>
<td>6.21</td>
</tr>
<tr>
<td>OD 2</td>
<td>203</td>
<td>63</td>
<td>33</td>
<td>5.69</td>
</tr>
<tr>
<td>OD 2</td>
<td>444</td>
<td>149</td>
<td>73</td>
<td>9.98</td>
</tr>
<tr>
<td>OD 2</td>
<td>777</td>
<td>290</td>
<td>128</td>
<td>16.05</td>
</tr>
</tbody>
</table>

To take this one step further, we made a visual inspection of the CMDs for each of the over-densities detected at each threshold (Figure 4.10). The Boötes I fiducial is clearly present in OD 2 at each detection threshold, keeping in mind that these diagrams do not contain stars from the very centre of the dwarf ($> 15\sigma_t$). The marginally significant OD 6 contains only 6 stars, making its significance unclear. However, the almost significant OD 8 forms part of the $2\sigma_t$ structure which is statistically significant. This suggests it is plausible that the Boötes I substructure does extend as far north as OD 8.

As a final check for our over-densities, we made a comparison between their spatial distribution and the distribution of background galaxies in the field (using the galaxy catalogue from Tempel et al., 2012). No correlation was found, supporting the stellar nature of the over-densities.
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4.7.3 BSS and BHB Populations

As one last step to the analysis, we also made a brief investigation into the radial distribution of candidate BSS and BHB stars. It was noted that there appeared to be an absence of these populations from the very core of Boötes I. Whilst the absence of these stars appears to coincide with the central stellar density of Boötes I (see Figure 4.5), crowding or inter-chip gaps between CCDs does not appear to be a factor (see Figure 4.11). The
distance of each star from the centre of Boötes I was calculated in terms of the major axis distance, and a cumulative distribution function plot for each population (see Figure 4.12). A Kolmogorov-Smirnoff (K-S) test was performed to test the likelihood of the two populations being drawn from the same distribution. With a calculated \( p \)-value of 1.0, this test shows that to be highly likely. During the course of the analysis, it was also noticed that there appeared to be a difference in the radial distribution of bluer BHB stars. The difference was most notable at \( g - i = -0.22 \), and can be observed in Figure 4.11; inside the \( 12' \times 12' \) frame of the image, there is only one bluer star compared to seven redder stars.

To investigate this further, the BHB star population was split in two at this point and a cumulative distribution function and K-S test performed (see dashed and dotted lines in Figure 4.12). This test also yielded a \( p \)-value of 1.0, demonstrating a high likelihood that the two samples do belong to the same population. However, with so few stars, it is difficult to analyse the absence of various stellar populations in the core of Boötes I further.

### 4.8 Discussion

The elongation and irregular shape of Boötes I (Belokurov et al., 2006; Fellhauer et al., 2008; Okamoto et al., 2012) suggests the possibility that this dwarf galaxy is in the process of being tidally disrupted. The over-densities we have detected show remarkable correlation with the contours shown in Figure 1 of Fellhauer et al. (2008), and the overall shape appears similar to that of Okamoto et al. (2012). Figure 4.13 shows a summary of our analysis.
Those over-densities determined to be statistically significant ($\zeta \geq 2.79$) during the course of our analysis are shown at each detection threshold, colour coded according to their $\zeta$ value at a given threshold. Stars inside the central region (> $15\sigma_t$) were omitted from the analysis in order to reduce the effect of the dominant central region and reveal the underlying substructure. The dashed contour represents a significant detection ($\zeta = 6.19$) at the $2\sigma_t$ threshold. This contour connects the main body of Boötes I with OD 1, and extends far enough north to encompass OD 8, an ‘almost’ significant detection.

The detected substructure appears more extended towards the north of Boötes I, relative to the central coordinates. The shape of the substructure surrounding Boötes I suggests the possibility of the beginning of “S-shaped” tidal tails, also suggested by Fellhauer et al. (2008). However, the elongation and structure seen are not as extreme as that seen in Hercules (Roderick et al., 2015). Also unlike Hercules, the BHB population (and additionally BSS) does not appear aligned in any particular direction. These populations appear more uniformly dispersed like those seen in Sextans (Roderick et al., 2016). There is a separate over-density (OD 1) toward the south-west of the centre, which is also in approximately the same direction as one of the model orbital paths suggested by Fellhauer et al. (2008). Brief investigation of the spatial distribution of BHB and BSS populations suggests a high likelihood that they are drawn from the same underlying population, consistent with the idea that Boötes I had a single period of star formation (Belokurov et al., 2006; Okamoto et al., 2012).

Figure 4.13 also shows two stars (Boo-980, Boo-1137) identified as member stars by Norris et al. (2008) using radial velocity measurements. Both stars are extremely metal poor and
lie at large distances of 2.0 and 3.9 half-light radii from the centre of Boötes I. Boo-1137 has been the subject of detailed spectroscopic follow up (Norris et al., 2010a). Both stars have been noted to show radial velocities in remarkable agreement with the mean velocity of the Boötes I system (Koposov et al., 2011). While these stars do not directly coincide with our detections, they do align with the direction of extension of our substructure.

Based on a King model fit to our radial profile, we determined a tidal radius for Boötes I of \( r_t = 32\,\text{pc} \pm 3\,\text{pc} \) (shown as a grey ellipse in Figure 4.13). The most extended over-densities reach beyond the tidal radius, lending weight to the scenario in which Boötes I is being tidally disrupted. The radial profile also shows a break radius (at a major axis distance of approximately 20'), indicating the presence of extra-tidal stars. The appearance of such a break radius is somewhat controversial in the MW dwarf spheroidals; despite the lack of an appearance in Draco and Sextans (Odenkirchen et al., 2001a; Ségall et al., 2007; Roderick et al., 2016), the existence of a break radius in Carina and Sculptor is somewhat ambiguous (Majewski et al., 2000, 2005; Coleman et al., 2005; Westfall et al., 2006; McMonigal et al., 2014). Similar profiles have also been generated by Okamoto et al. (2012) for Canes Venatici I, Boötes I, Canes Venatici II, and Leo IV. Although they mention an excess in stellar density in the outskirts of Canes Venatici II, and Leo IV, they do not see such an occurrence in Boötes I. This may in part be due to the fact that their radial profile does not extend beyond 30', where the excess in stellar density becomes more prominent.

A number of orbital scenarios have been put forward for Boötes I in an attempt to identify its most likely progenitor (Fellhauer et al., 2008). The two main scenarios they suggest pose that either the progenitor was a purely baryonic star cluster being tidally disrupted, or that it was a dark matter dominated, cosmologically motivated system. The possibility was also considered that the extended stellar substructure surrounding Boötes I was the result of sparse stellar photometry, and therefore an observational artefact. The result of the analysis by Fellhauer et al. (2008) ruled out the scenario of the baryonic star cluster because it could not reproduce the velocity dispersion observed. However, this model reproduced the observed radial surface density profile quite well, as opposed to the dark matter dominated models, which did reproduce the velocity dispersion but not the radial surface density profile. Given the revised observed velocity dispersion of \( \sigma = 2.4_{-0.5}^{+0.9} \text{ km s}^{-1} \) (Koposov et al., 2011) (note this is corresponds to the dominant kinematic component, which is much closer to that provided by the baryonic model of Fellhauer et al. (2008), the best estimate for a single component dispersion is 4.6 km s\(^{-1}\)), and our own analysis demonstrating the statistical significance of the extended substructure surrounding Boötes I, this suggests that the possible orbital scenarios for Boötes I should be reconsidered. Our analysis clearly demonstrates that the substructure seen around Boötes I is not an observational artefact, and therefore cannot be ignored in the modelling of orbital scenarios.
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Figure 4.13: Summary figure of the results of our substructure detection and significance testing across all detection thresholds. Contours show an increasing line-width with an increase in detection threshold between $3\sigma_t$ and $10\sigma_t$. A dashed contour with $\zeta = 6.19$ for the $2\sigma_t$ threshold is shown without a fill colour. All other detection thresholds are overlaid on top of each other, and colour coded according to the $\zeta$ value. Open, green circles represent the Blue Horizontal Branch stars (outlined in red in Figure 4.4), while the blue, filled circles represent Blue Straggler stars (outlined in blue in Figure 4.4). Note that the Blue Horizontal Branch stars are split into two groups by colour, where large points represent $g-i < -0.22$ and small points represent $g-i \geq -0.22$. The tidal radius is represented by a grey ellipse. The box outlined by a dashed line at the centre of the figure corresponds to the region displayed in Figure 4.11. The black arrow represents the model orbital path favoured by Fellhauer et al. (2008). The two purple-filled stars represent Boo-980 and Boo-1137, identified as member stars by Norris et al. (2008) using radial velocity measurements.

The orbital direction favoured by Fellhauer et al. (2008) is shown in Figure 4.13 as a black arrow. This orbit would place Boötes I relatively close to an apo-galacticon of 76 kpc, with a peri-galacticon of 37 kpc. Given the lack of abundant free-floating debris compared to Hercules (Roderick et al., 2015), Boötes I is unlikely to follow as extreme an orbit as the model proposed for Hercules, particularly given it has an estimated infall time of $7-10$ Gyr compared to the $2-8$ Gyr estimated for Hercules (Rocha et al., 2012).
4.9 Summary

We have demonstrated quantitatively that the Boötes I dwarf spheroidal galaxy shows significant, extended stellar substructure. An analysis of the radial profile has also revealed the presence of extra-tidal stars, providing strong evidence to suggest that Boötes I is experiencing tidal disruption. In conjunction with the revised velocity dispersion measurements from Koposov et al. (2011), this suggests that Boötes I may not possess the high mass-to-light ratio previously thought, and suggests a review of previous orbital models and possible progenitors may be necessary.
CHAPTER 5

Concluding Remarks

This thesis has provided in depth observations and discussion on each of three of the MW satellites: Hercules, Sextans and Bootes I. The focus of these observations has been the search for stellar substructure associated with each dwarf, and has resulted in a broader picture for each case. However the wide-field, homogeneous, nature of these observations also provides an opportunity to discuss the results of each analysis in relation to each other, and place the combined results in the broader context of galactic archaeology and near-field cosmology. In the following discussion, the results will be briefly summarised in context with each other, and then discussed in broader terms of galaxy formation.

5.1 Contextual Summary

The three dwarf galaxies presented in this thesis represent a variety of the different MW dwarfs. While Sextans is a classical dwarf, Hercules and Boötes I are more representative of the ultra-faint regime; the properties of each are summarised in Table 5.1. Morphologically, all three galaxies are classified as dwarf spheroidals, and in the context of ΛCDM, are all dark matter dominated. With regard to star formation histories found in the literature, all three dwarfs show old, metal poor stellar populations. While Hercules and Boötes I show comparable metallicities (-2.41 and -2.55 respectively), Sextans appears slightly less metal poor, with [Fe/H]=-1.93. Interestingly, Sextans also appears to show the remnants of a disrupted metal-poor star cluster at its core (Karlsson et al., 2012), suggesting that it has undergone different processes to Hercules and Bootes I. All three galaxies conform to the luminosity-metallicity relation (e.g. Simon & Geha, 2007), where metallicity decreases with lower luminosities.

Each of the dwarfs is at a different heliocentric distance, with Hercules at 132 ± 12 kpc (Coleman et al., 2007), Sextans at 86 ± 4 kpc (Lee et al., 2009), and Boötes I at 65 ± 3 kpc (Okamoto et al., 2012). Interestingly, this does not correlate with the level of disruption
Table 5.1: Fundamental Parameters of Hercules, Sextans and Boötes I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hercules</th>
<th>Sextans</th>
<th>Boötes I</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
<td>16:31:02</td>
<td>10:13:03</td>
<td>14:00:06</td>
</tr>
<tr>
<td>DEC (J2000)</td>
<td>+12:47:30</td>
<td>-1:36:53</td>
<td>+14:30:00</td>
</tr>
<tr>
<td>l</td>
<td>28.7°</td>
<td>243.5°</td>
<td>358.1°</td>
</tr>
<tr>
<td>b</td>
<td>36.9°</td>
<td>42.3°</td>
<td>69.6°</td>
</tr>
<tr>
<td>$D_\odot$</td>
<td>132 ± 12 kpc</td>
<td>86 ± 4 kpc</td>
<td>65 ± 3 kpc</td>
</tr>
<tr>
<td>$M_V$</td>
<td>$-6.6 \pm 0.4$</td>
<td>$-9.3 \pm 0.5$ mag</td>
<td>$-5.92 \pm 0.2$ mag</td>
</tr>
<tr>
<td>$(m-M)_0$</td>
<td>20.6 ± 0.2</td>
<td>19.67 ± 0.1</td>
<td>19.07 ± 0.11</td>
</tr>
<tr>
<td>$v_\odot$</td>
<td>45.2 ± 1.1 km s$^{-1}$</td>
<td>224.3 ± 0.1 km s$^{-1}$</td>
<td>101.8 ± 0.7 km s$^{-1}$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>3.7 ± 0.9 km s$^{-1}$</td>
<td>7.9 ± 1.3 km s$^{-1}$</td>
<td>2.41 ± 0.5 km s$^{-1}$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.63 ± 0.02</td>
<td>0.29 ± 0.03</td>
<td>0.33 ± 0.06</td>
</tr>
<tr>
<td>$\theta$</td>
<td>113.8 ± 0.6°</td>
<td>56.7° ± 2.8°</td>
<td>13.4° ± 8.6°</td>
</tr>
<tr>
<td>$r_h$</td>
<td>330 pc</td>
<td>695 pc</td>
<td>236 pc</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>$-2.41 \pm 0.04$</td>
<td>$-1.93 \pm 0.01$ dex</td>
<td>$-2.55 \pm 0.11$ dex</td>
</tr>
<tr>
<td>Mass-to-Light ratio</td>
<td>$10^{3.83 \pm 0.48}$</td>
<td>97 ± 51</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>$r_{\text{tidal (theoretical)}}$</td>
<td>0.49 kpc</td>
<td>2.08 kpc</td>
<td>0.58 kpc</td>
</tr>
</tbody>
</table>

References: (a) Belokurov et al. (2007a), (b) Coleman et al. (2007), (c) Martin et al. (2008), (d) Adén et al. (2009a), (e) Jerjen (2012), (f) Sand et al. (2009), (g) Adén et al. (2009b), (h) Irwin et al. (1990), (i) Lee et al. (2009), (j) Walker et al. (2009), (k) Irwin & Hatzidimitriou (1995), (l) Kirby et al. (2011), (m) Belokurov et al. (2006), (n) Okamoto et al. (2012), (o) Koppov et al. (2011), (p) Norris et al. (2010b), (q) Lokas (2009), (r) Muñoz et al. (2006), (s) Martin et al. (2007)

observed in each dwarf. As shown in Chapters 2 to 4, Hercules appears to be undergoing considerable tidal disruption, while Sextans appears extended but not necessarily significantly disrupted. The level of substructure in Boötes I indicates its level of disruption is somewhere in between Hercules and Sextans. This will be discussed further in the following sections.

5.2 Stellar Substructure

The highest level of disruption was observed in Hercules. With an ellipticity of 0.63 ± 0.02, Hercules is the most elongated of the three dwarfs. Nine associated substructures were identified in preferential alignment along its major axis, containing approximately the same amount of flux as the main body. The analysis undertaken in Chapter 2 suggested Hercules has made more than one peri-galactic pass and is accompanied by free-floating debris. It was also put forward that the slight misalignment of Hercules’ substructure with its major axis suggests a similar orbital scenario to the globular cluster Palomar 5, and
may indicate that the tidal tails are transitioning to an orientation toward the MW as Hercules approaches apo-galacticon.

In stark contrast to this is Sextans, with a relatively circular structure ($\epsilon = 0.29 \pm 0.03$) and little extra-tidal debris; the dwarf is surrounded by a significant, extended, halo-like structure, which appears to be well contained inside the tidal radius. However, Sextans does show signs of a varied star formation history at its core, with a population of blue straggler stars more centrally concentrated than blue horizontal branch stars. When considered with literature suggesting there may be a remnant star cluster inside the dwarf, it appears that Sextans has a colourful formation history, despite its lack of extra-tidal substructure.

Boötes I shows an elongated structure more like Hercules, although not as extreme ($\epsilon = 0.33 \pm 0.06$). The substructure is encroaching on the tidal radius of the galaxy, and is elongated in the direction of a model orbital path favoured by Fellhauer et al. (2008). The direction of extension of the substructure is also in alignment with the position of two stars identified kinematically as members of Boötes I by Norris et al. (2008). These two stars lie at distances of 2.0 and 3.9 times the half-light radius from the centre of the galaxy.

The tidal radius (based on the best fit King profile, so not necessarily a measure of each system’s true tidal radius) of each dwarf galaxy correlates with the differences seen in substructure. Hercules, showing the most extreme features, has the smallest tidal radius ($r_t = 0.49$ kpc), followed by Boötes I ($r_t = 0.58$ kpc), and Sextans with by far the largest tidal radius ($r_t = 2.08$ kpc). This is interesting since Hercules is the furthest of the three from the MW, and Boötes I is the closest. However it is sensible, since it is expected that smaller objects would be more highly influenced by the potential of the MW. This will be discussed further in terms of orbital characteristics in the next section.

### 5.3 Orbital Characteristics

Simulations and present day kinematics have been used to determine infall times for the MW dwarfs (Rocha et al., 2012), and demonstrate that Boötes I and Sextans were likely to have been accreted by the MW early on (7-10 Gyr), whereas Hercules has a more intermediate infall time (2-8 Gyr). When considered with the work in this thesis, this provides insightful discussion on the possible orbits for these dwarfs.

As discussed in Section 5.2, Hercules appears to be undergoing considerable tidal disruption, while Boötes I shows less extreme substructure, and Sextans appears extended but not necessarily disrupted. This is interesting in the context of their respective infall times. Despite being the most significantly disturbed, Hercules likely has the most recent infall time (suggesting fewer peri-galactic passes). It has been suggested, that Hercules has a very eccentric orbit (Coleman et al., 2007), with an extremely close peri-galactic passage.
Chapter 5 Concluding Remarks

(Adén et al., 2009b). The more recent infall time in conjunction with its high level of disruption would support this idea. In contrast, it has been postulated that Sextans has a more circular orbit (Walker et al., 2008), and given its halo-like substructure combined with its potentially early infall, this is a plausible scenario. Boötes I on the other hand has a comparable infall time to Sextans but appears more elongated and shows a higher level of disruption. This makes sense given that Boötes I is closer to the ultra-faint regime and therefore more susceptible to the tidal field of the MW. Also worth noting is that Boötes I is likely to be close to its apo-galacticon, whereas Sextans is likely to be receding from its peri-galacticon (Fellhauer et al., 2008; Walker et al., 2008). Given their current heliocentric distances (65 kpc and 86 kpc respectively), this suggests Boötes I spends more time in close proximity to the MW than Sextans does, which also correlates with their differing levels of substructure.

Caution should be taken when considering infall times, as they are not well constrained. However, if this relationship holds true across the MW dwarf galaxy population, then it provides evidence that smaller halos in close proximity to the MW may already have dissipated into the halo, however those at larger distances may still exist. With larger sample sizes, it may be possible to develop well constrained boundary conditions on the size and proximity requirements for a satellite to survive to be observable in the present day. This may prove useful in future models of galaxy formation, particularly in regard to solving problems such as the ‘Missing Satellites’ problem.

The results of this analysis can also be used to suggest potential candidates that may possess extra-tidal stellar features. By comparing these results to Table 1 of Rocha et al. (2012), candidates can be identified by looking for similarities (such as luminosity, heliocentric distance and infall time) to Sextans and Boötes I. Since Hercules has a highly elliptical orbit, it is more difficult to use as a basis for comparison. Instead, it is better to assume candidates have a low orbital eccentricity similar to Sextans, as this is conservative assumption in this context. Dwarfs that are fainter, closer and/or have earlier infall times than Sextans and Boötes I, must surely have the potential for extra-tidal stellar features. Based on this, the following candidates can be identified: Ursa Minor, Draco, Ursa Major II, Segue 1, Coma Berenices, and Willman 1. Other less likely candidates include: Carina, Ursa Major I, and Leo IV. Table 5.2 details the luminosity, heliocentric distance and infall time according to Rocha et al. (2012) for each candidate, as well as for Sextans and Boötes I for ease of comparison.

5.4 Disc of Satellites

With regard to the disc of satellites, recent work has shown that the majority of MW satellites do indeed share a similar orbital plane to the Magellanic Clouds (Pawlowski et al., 2015). The three satellites considered in this thesis provide a surprisingly diverse
Table 5.2: Potential candidates for extra-tidal stellar features based on Table 1 of Rocha et al. (2012).

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Heliocentric Distance (kpc)</th>
<th>Luminosity ( (L_{\odot}, v) )</th>
<th>Infall Time (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sextans</td>
<td>96 ± 3</td>
<td>( 5.9^{+1.7}_{-1.4} \times 10^5 )</td>
<td>7-9</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>77 ± 4</td>
<td>( 3.9^{+1.7}_{-1.43} \times 10^5 )</td>
<td>8-11</td>
</tr>
<tr>
<td>Draco</td>
<td>76 ± 5</td>
<td>( 2.2^{+0.7}_{-0.6} \times 10^5 )</td>
<td>8-10</td>
</tr>
<tr>
<td>Carina</td>
<td>105 ± 2</td>
<td>( 4.3^{+1.1}_{-0.9} \times 10^5 )</td>
<td>7-9</td>
</tr>
<tr>
<td>Boötes I</td>
<td>66 ± 3</td>
<td>( 2.8^{+0.6}_{-0.4} \times 10^4 )</td>
<td>7-10</td>
</tr>
<tr>
<td>Ursa Major II</td>
<td>32 ± 4</td>
<td>( 4.0^{+1.0}_{-0.9} \times 10^3 )</td>
<td>8-11</td>
</tr>
<tr>
<td>Segue 1</td>
<td>23 ± 2</td>
<td>( 3.4^{+1.0}_{-0.7} \times 10^2 )</td>
<td>7-10</td>
</tr>
<tr>
<td>Coma Berenices</td>
<td>44 ± 4</td>
<td>( 3.7^{+1.0}_{-0.7} \times 10^3 )</td>
<td>8-11</td>
</tr>
<tr>
<td>Willman I</td>
<td>38 ± 7</td>
<td>( 1.0^{+0.6}_{-0.5} \times 10^3 )</td>
<td>6-11</td>
</tr>
<tr>
<td>Ursa Major I</td>
<td>97 ± 4</td>
<td>( 1.4^{+0.4}_{-0.3} \times 10^4 )</td>
<td>6-10</td>
</tr>
<tr>
<td>Leo IV</td>
<td>160 ± 15</td>
<td>( 8.7^{+0.4}_{-0.6} \times 10^3 )</td>
<td>5-9</td>
</tr>
</tbody>
</table>

sample in relation to this. While Sextans lies on this plane, Boötes I lies in relatively close proximity to the plane, and Hercules is one of the few outliers from the plane. Placed in context with the previous discussion, it is interesting to note that Sextans and Boötes I have early infall times, while Hercules has a more recent infall time (perhaps after the Magellanic Clouds; Rocha et al., 2012). It is also worth noting that Sextans is the closest to the plane (in this sample), and may contain the remnants of a metal poor star cluster. If this inner structure is not primordial in nature, but the remnant of something that was disrupted by Sextans (e.g. Kleyna et al., 2003), then it could be viewed as an example of the hierarchical galaxy formation scenario. However its location in the disc of satellites also makes it a plausible remnant from a tidal dwarf galaxy (see Yang et al., 2014). There appears to be a correlation between the level of elongation and substructure, and distance from the plane. That is, Hercules is furthest from the plane and shows the most extreme substructure, followed by Bootes I, with Sextans being the least extreme example and also lying on the plane. If this trend holds for other MW dwarfs, it provides an excellent constraint for modelling the Galaxy’s formation process. While one might expect a homogeneous distribution under the ΛCDM paradigm, the observed distribution of Hercules, Sextans and Boötes I might make more sense in a tidal infall scenario; similarly to a dwarf that has made more than one peri-galactic pass and is accompanied by free floating debris. With such a small sample however, such a correlation may be spurious and should be followed up with larger sample sizes.
5.5 Dark Matter Content

It has been demonstrated in the literature that all three galaxies have high mass-to-light ratios. This is true even after these measurements have been reviewed; improved membership discrimination for Hercules led to a lower estimate than previously thought \( (M/L \approx 103, \text{ Adén et al., 2009b}) \), and despite a high velocity dispersion measurement for Sextans \( (\sigma \approx 7.9 \text{ km s}^{-1}, \text{ Walker et al., 2009}) \), strict dynamic-interloper removal techniques have shown that it has a mass-to-light ratio of approximately 97 (Lokas, 2009). Of the three dwarfs, Boötes I appears to have the highest mass-to-light ratio \( (M/L > 100, \text{ Muñoz et al., 2006; Martin et al., 2007; Koposov et al., 2011}) \), even considering the most recent, and considerably lower, velocity dispersion measurement \( (\sigma \approx 2.4 \text{ km s}^{-1}, \text{ Okamoto et al., 2012}) \).

With regard to stellar substructure, there is no apparent correlation. Given that the determination of the mass-to-light ratio assumes dynamic equilibrium (a virialised system), then it is not necessarily a fair measurement of the dark-matter content for these systems. As discussed at the end of Chapter 4, Boötes I potentially fits the model of a baryonic system rather than a dark matter dominated system. If one equates mass-to-light ratio with dark matter content and primordial origins, then it becomes apparent that there are different formation mechanisms and scenarios for each MW dwarf, and the population as a whole may not be representative of the dark matter halo formation scenario under ΛCDM.

The level of substructure present in all three dwarfs suggests a need for extreme caution when identifying member stars for velocity dispersion measurements and mass-to-light estimates; dark matter content may easily be over-estimated.

5.6 Hierarchical Galaxy Formation

In the context of hierarchical galaxy formation, the three dwarfs analysed in this thesis provide ambiguous results. Hercules and Boötes I both appear to be showing the effects of tidal disruption due to the tidal forces of the MW. Although Hercules is twice the heliocentric distance of Boötes I, both of these galaxies are in elliptical orbits and have close peri-galactic passages. This could be seen as an active example of the hierarchical galaxy formation process, and supports a primordial origin for these dwarfs under ΛCDM. Given that Sextans has a much larger tidal radius, and a potentially circular orbit, it does not contradict a primordial origin. It also shows signs that it may have merged with a star cluster during its formation, providing a further example of hierarchical formation processes. However, the alignment of Sextans and Boötes I with the disc of satellites would appear contrary to a primordial origin, and instead is more supportive of a tidal formation process. Given that there appears to be a correlation between the distance from the disc
of satellites and the level of stellar substructure present in the dwarfs, it is arguable that more dwarf galaxies should be studied in depth before any conclusions can be drawn.

5.7 Galactic Archaeology

The differences seen in the three galaxies discussed in this thesis suggest that they have a diverse formation history, and may have evolved through differing formation mechanisms. The brightest of the three shows possible evidence of a remnant star cluster at its core, has an early infall time, and lies on the disc of satellites. This is also the galaxy with the least extreme substructure in the sample, the largest tidal radius, and potentially has the most circular orbital path. The two less-luminous galaxies show smaller tidal radii, and more extreme substructure, with one having an early infall time, and the other a more intermediate infall time. The most elongated and extended of the two, with the intermediate infall time, has the greatest likelihood of having the most eccentric orbit, but also the closest peri-galactic passage. This demonstrates that the level of tidal influence on the dwarfs from the MW may largely be the result of orbital eccentricity, peri-galactic distance and dwarf size rather than the number of completed orbits.

The analysis of each of the three galaxies in this thesis has yielded new information on their structure and potential orbital scenarios. As a result, there are new constraints to compare formation models to, as well as new stellar candidates for spectroscopic follow up. This provides a unique opportunity for developing a better understanding of galactic archaeology and cosmology in relation to these dwarfs. The characterisation of their tidal structures provides a starting point for improved orbital models, and spectroscopic follow up of the tidal debris may yield an improved understanding of the kinematic and chemical distribution of stars interacting with the MW halo.

5.8 Future Work

The results presented in this thesis provide enormous opportunity for continued research. Each individual analysis provides a list of stars which are candidates for membership in the associated substructures of each dwarf galaxy. They are weighted according to their position in the colour-magnitude diagram and therefore present an excellent prioritised list for spectroscopic follow up. In the era of multi-fibre spectrographs, this provides an unprecedented opportunity to obtain both kinematic and chemical information in the most extended regions of the dwarf galaxies. Such combined photometric and spectroscopic detail will provide the most detailed observations yet, leading to superior theoretical models of orbits, star formation and the galaxy formation process.
Further to the follow-up potential of each individual analysis, the combined results of this thesis demonstrate the potential of wide-field, homogeneous, observations in developing our understanding of galaxy formation in terms of galactic archaeology and near-field cosmology. By extending the sample of dwarf galaxies, it may be possible to properly quantify the influence of tides from the MW in terms of luminosity, distance and orbital parameters. Including such galaxies as Leo T, Phoenix and NGC 6822 may also place a morphological context on the formation scenarios for the dwarf galaxy population. Such large-scale detail of the dwarf galaxies will provide unrivalled potential for theoretical models and cosmological simulations, leading to an understanding of their role in the formation of the MW, and cosmology on a broader scale.
APPENDIX A

Supplementary Tables

The following tables provide coordinates, magnitudes and the colour-magnitude-space weights for the statistically significant substructures identified in Chapters 2 to 4. Note that ‘nan’ values are assigned to stars considered to be Blue Horizontal Branch or Blue Straggler stars; since these stars were used for comparative analyses in the relevant chapters they were not assigned a weight. These tables are excerpts from full digital versions available as an electronic supplement.

Table A.1: Stars belonging to the Hercules stellar substructure.

<table>
<thead>
<tr>
<th>R.A.</th>
<th>Dec</th>
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</thead>
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<td>20.9399</td>
<td>20.2973</td>
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</tr>
</tbody>
</table>
Table A.2: Stars belonging to the Sextans stellar substructure.

<table>
<thead>
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<th>$i_0$</th>
<th>weight</th>
</tr>
</thead>
<tbody>
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<td>10:15:10.32000</td>
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Table A.3: Stars belonging to the Bootes I stellar substructure.

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