Photometry of resolved stars in nearby dwarf spheroidal galaxies

Master Thesis

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Abstract

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Dwarf galaxies make up the bulk of galaxies in the Universe. Studying them can give us a deeper insight in galaxy evolution, formation of the earliest galactic structures and both the local and wider Universe. Nearby dwarfs can be resolved and studied in detail, whilst only the integrated light, dominated by the sparse but most luminous population, can be studied for those farther afield. Comparing the brightest stars in local, resolved dwarf galaxies with detailed star formation histories is not a trivial exercise but can lead to better understanding of distant dwarf galaxies.

In the first part of this work, I reduce optical data of Draco and Ursa Minor dwarf spheroidal galaxies. These data were taken at the 2.5m INT on La Palma and reduced without use of a pipeline. The data corroborates that both dwarf galaxies are dominated by an old population and have a small intermediate age populations. In the remainder, I combine optical and infrared photometry of Fornax and Draco dwarfs to study the properties of the asymptotic giant branch (AGB) population and compare the infrared information with optical star formation histories (SFHs).

Draco has very few AGB stars. Without picking them out individually from previous investigations using spectroscopy, no definite conclusions regarding the AGB branch could be drawn with the used method and data. The RGB branch, also containing the known AGB, is consistent with optical star formation histories.

Comparing the optical and infrared data of Fornax, I have found that the ages of the dominant RGB and dominant AGB populations agree reasonably well with known star formation histories. The bright AGB stars belong mainly to the younger population and are predominantly found in the central area of the galaxy. The dominant population can be found around [Fe/H] = -1 with an age of 4 Gyr. The bright AGB is better characterised using an isochrone for a population with the same [Fe/H] = -1 but a younger age of 1 Gyr.

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| Chapter

Introduction

Dwarf galaxies are the most abundant galaxies in the Universe. Our own galaxy, the Milky Way, is surrounded by dozens of them. Understanding these dwarf galaxies is of great import when trying to understand the Universe and galaxy formation. The bottom-up theory of galaxy formation considers larger galaxies to be built up through many mergers of smaller ones. This suggests that understanding dwarf galaxies is important not just for understanding our current Universe, but also earliest galaxy formation. In the nearby dwarf galaxies it is possible to resolve the stellar population down to the main sequence. When looking at distant dwarfs, only the most luminous stars can be resolved or none at all. In the latter case, the bright stars, though small in number, will dominate the brightness of the dwarf galaxy.

This work explores what we can infer about galaxies looking at luminous asymptotic giant branch (AGB) stars and how this compares to existing detailed star formation histories (SFHs) obtained from the entire colour magnitude diagram (CMD). In this thesis I compare the AGB age and metallicity distribution, through overplotting isochrones, to main sequence turn-off (MSTO) SFH analysis. Checking the consistency of the information from an analysis of the AGB in nearby galaxies can help us better understand populations farther away.

1.1 Dwarf galaxies

Figure 1.1 shows our nearest neighbours, the satellite galaxies around the Milky Way. These dwarf galaxies can be divided into two classes based on their morphology: dwarf spheroidal (dSph) galaxies, which typically have no gas and no current star formation (SF), and dwarf irregular galaxies, which have gas and are currently forming stars with different star formation rates (SFRs). The Magellanic Clouds are an example of the latter and are the easiest to detect as they are clearly visible to the unaided eye in the southern hemisphere. The dSphs, studied here, are more difficult to discern. The Fornax (Fnx) dSph, shown in Figure 1.2, was discovered in 1938 by Shapley on photographic plates. Draco and Ursa Minor (UMi) were discovered in 1954 and 1955 respectively in the Palomar all sky survey (Wilson, 1955).



FIGURE 1.1: The satellite galaxies around our Milky Way from the Gaia satellite data. Credit: A. Moitinho & M. Barros (CENTRA University of Lisbon), on behalf of DPAC.

In a cold dark matter (Λ CDM) universe, galaxies are predicted to form in an hierarchical fashion, so smaller systems, such as dwarfs, are believed to have formed before the larger structures. The proximity of these dwarfs makes them excellent targets for the study of resolved stellar populations. Studying these small systems can teach us about both stellar and galaxy evolution, and help decipher the history of our own galaxy, the Milky Way.



FIGURE 1.2: Fornax from the ESO/Digitized Sky Survey 2 [http://www.eso.org/public/images/eso1007a/].



FIGURE 1.3: Contour maps of the stellar distribution of Fornax, Draco and Ursa Minor on the same spatial scale. Taken from Irwin and Hatzidimitriou (1995).



FIGURE 1.4: Schematic star formation histories from Mateo (1998). The vertical axis shows the relative star formation rate, the horizontal axis shows the age of the population. It can be observed that Draco and Ursa Minor have similar star formation histories while that of Fornax is more extended.

Figure 1.3 shows contour maps of the stellar distribution of the three dwarf galaxies we look at in this work on the same spatial scale.

Even though all dSph galaxies studied in this thesis are satellites of the Milky Way and similar in shape (see Figure 1.3), they each have their own unique characteristics, summarised in Table 1.1. Figure 1.4 shows a schematic view of their star formation histories.

| | RA (J2000) | DEC (J2000) | ellipticity | PA | total mass (M_{\odot}) |
|------------|-------------------------|-------------------------------------|------------------|-------------|--------------------------|
| Fornax | 02 39 59 | - 34 27.0 | 0.30 ± 0.01 | 41 ± 1 | $68 10^6$ |
| Draco | 17 20 19 | +5754.8 | 0.29 ± 0.01 | 82 ± 1 | $23 10^6$ |
| Ursa Minor | 15 09 11 | +67 12.9 | 0.56 ± 0.05 | 53 ± 5 | $22 10^6$ |
| | | | | | |
| | \mathbf{r}_t (arcmin) | $\mathbf{r}_{t,g} \; (\mathrm{pc})$ | (m-M) | D (kpc) | |
| Fornax | 71.1 ± 4.0 | 2078 ± 177 | 20.84 ± 0.04 | 138 ± 5 | |
| Draco | 28.3 ± 2.4 | 498 ± 47 | 19.84 ± 0.14 | 76 ± 6 | |
| Ursa Minor | 50.6 ± 3.6 | 628 ± 74 | 19.41 ± 0.12 | 70 ± 9 | |

TABLE 1.1: Position, total mass (Mateo, 1998), ellipticity, position angle (PA), tidal radius and the geometric mean along the minor axis of the tidal radius (r_t, r_t, g) (de Boer et al., 2012b; Irwin and Hatzidimitriou, 1995), distance modulus (m-M) (Bellazzini et al., 2002; de Boer et al., 2012b) and distance (D) (Tolstoy et al., 2009) of the sample of dwarf spheroidal galaxies.

The average metallicities of the dwarf galaxies are $[Fe/H]_{Fnx} \approx -0.8$, $[Fe/H]_{Draco} = -1.7$ and $[Fe/H]_{UMi} = -1.8$ according to Bellazzini et al. (2002) and de Boer et al. (2012b) respectively, however the range of metallicities and ages differs considerably between the galaxies. Ursa Minor and Draco have predominantly old populations, while Fornax also boasts a significant intermediate age population and has formed stars until about 250 Myr ago (van den Bergh, 1994; de Boer et al., 2012b). A metallicity gradient is observed in Draco (Faria et al., 2007) and Fornax (de Boer et al., 2012b), but is almost entirely lacking in UMi (Carrera et al., 2002). The lack of a metallicity gradient in Ursa Minor might be due to tidal interaction with the Milky Way. Longer episodes of star formation lead to higher chemical enrichment of the stellar population. Fornax is more massive, has seen far more recent star formation and, as a consequence is more metal-rich than Ursa Minor and Draco. In younger populations, the AGB stars are brighter and stand out. We therefore expect to find many more AGB stars in Fornax.

1.2 Colour magnitude diagrams

1.2.1 Stellar evolution

Stars form out of a fragmenting molecular cloud collapsing under gravity. They are objects bound by gravity and, once the temperature in their core has reached a sufficient level, they radiate energy from nuclear fusion. The rate of nuclear fusion will change with time as fuel is a limited resource and will eventually run out. It depends largely on the initial mass of the star how high the internal temperature can become and therefore which elements they can form. For hydrogen fusion, temperatures upwards of $T = 5 \times 10^6$ K are required. For helium fusion, the internal temperature needs to be larger than $T > 10^8$ K and even higher temperatures are required for subsequent phases of stellar evolution. Lower mass stars have denser stellar cores and these cores will become electron degenerate at either the end of the helium or the carbon burning phase preventing the temperature from rising enough to proceed to the next stage of fusion (Carroll and Ostlie, 2007; Salaris and Cassisi, 2005).



FIGURE 1.5: (a) A schematic Hertzsprung-Russell Diagram [https://www.eso.org/public/images/eso0728c/]. (b) Colour magnitude diagram of Fornax (de Boer et al., 2012) who divided the CMD up into the overlaying red boxes, which show the different phases of stellar evolution as studied in the optical filters.

A star spends most of its life burning hydrogen in its core. This is called the main sequence phase. When hydrogen is exhausted in the stellar core, the core will contract. Hydrogen is still burning in a shell around the core and the star moves into the red giant branch (RGB) phase. The burning shell acts as a mirror between the core and the envelope. When the core contracts, the stellar envelope will expand to maintain thermal equilibrium in the shell. The ignition of He burning depends on the mass of the star. The low-mass (below roughly 2 M_{\odot}) stars will ignite He fusion in a degenerate core in a process called the He flash at the end of the RGB phase, while intermediate- (< $8M_{\odot}$) and high-mass stars ignite core He burning in a stable fashion.

In an electron-degenerate core, He ignition happens in a thermal runaway process called the helium flash. A lot of energy is produced in a short amount of time, after which the energy production again decreases and this process may repeat a number of times to lift this degeneracy in these low-mass stars. When this is complete, the star moves on to the horizontal branch (HB). The properties of the HB depend primarily on the metallicity and the mass loss during the RGB phase (Salaris et al., 2013). This phase of core He burning and shell H burning is named for its morphological properties.

Energy can be transported in a star via radiative transfer or through convection. Convection is a process that causes mixing. During the RGB phase, the convective layer dips down so far into the interior of the star that it carries material from the H-exhausted region to the surface. This is called the first dredge-up. This is followed by the second dredge-up in the AGB phase for intermediate-mass stars and the third dredge-up, which occurs during the AGB phase in low-mass stars. The difference between the second and third dredge-up is the composition of the material dredged up to the surface. The second dredge-up increases the abundances of He and N and decreases C and O. The third dredge-up, associated with the thermally pulsing AGB (TP-AGB, see below), brings up C and s-process elements such as Ba, Sr, Y, Zr, La, Pb (Battistini and Bensby, 2015) and believed to be responsible for creating carbon stars. Once this material has mixed with the outer layers of the stellar envelope, one can detect it using spectroscopy. Significant

mass loss starts occurring in the RGB phase. This process continues in the AGB phase, which occurs in low- and intermediate-mass stars.

The AGB phase commences when He is exhausted in the stellar core. The name comes from its morphology where the AGB closely follows the RGB but at a slightly higher effective temperature, creating a parallel sequence that appears to asymptote into the RGB in the CMD. The AGB is a phase of much stronger mass loss than the RGB.

In the early AGB phase (E-AGB), He-shell burning takes place. H-shell burning extinguishes due to the expansion and accompanying drop in temperature associated with the commencement of He shell burning. For low-mass stars, the star goes up and down the same region of the CMD for a number of times, which is observed as the AGB bump (AGBb) as indicated in Figure 1.5 (b). During this period, in intermediate-mass stars, the convective layer of the atmosphere dips down and dredges up material from deeper in the star. Low-mass stars retain effective H-shell burning, preventing this episode. After this phase of He-shell burning, stars ignite C in the core and evolve on to fuse heavier elements, whilst intermediate- and low-mass stars continue on to the TP-AGB phase.

Once the He-shell approaches the existing H/He discontinuity around the core, it extinguishes. The re-ignited H-shell then produces all energy for the star. The newly formed He ends up igniting the He-shell again, which extinguishes the H-shell and so forth. This triggers a series of third dredge-up events. During this phase the star is very bright with a cool exterior due to intense energy production and its increased size (Carroll and Ostlie, 2007; Salaris and Cassisi, 2005). Understanding how a star has evolved up until that point allows us to draw conclusions from observations and helps us to analyse a populations using these very bright stars.

1.2.2 CMD analysis

As stars evolve on timescales much longer than a human life, we are unfortunately not able to observe the whole life of a single star. Instead, we can observe groups of stars that are formed roughly around the same time and study their properties. Dwarf spheroidal galaxies around the Milky Way are particularly suited for this purpose. They are relatively small systems and close enough to us that we can fully resolve their population. The Hertzsprung-Russell Diagram (HRD) and CMD can be seen as maps of stellar evolution. Figure 1.5 shows an example HRD and a CMD of the Fornax dSph.

The HRD maps physical quantities: the effective temperature (T_{eff}) versus the luminosity of a star. These are quantities we cannot directly measure. The conversion between observations versus physical quantities is tricky. To determine the luminosity for example, one needs to know the bolometric magnitude, which is the absolute magnitude integrated over all wavelengths.

We observe magnitudes and colours (the difference between magnitudes in different wavelength bands) rather than temperatures and luminosity. This makes the CMD, which displays observational quantities, a more hands-on way to look at a population when doing photometry. This is the reason CMDs exclusively will feature in the results and the HRD is only used as a visual aid. The difference in distribution of stars in a CMD can tell us about their metallicities and ages by using theoretical models and overlaying them, as will be done in Chapter 3. Figure 1.5 (a) shows the HRD of a number of stars

from the solar neighbourhood. The CMD demonstrates that white dwarfs have a high effective temperature but a low luminosity and that giants and supergiant stars have cooler temperatures but are very luminous. AGB stars fall into the second category. Figure 1.5 (b) shows the CMD of the Fornax dSph galaxy with the stellar evolution phases overplotted, taken from de Boer et al. (2012b). It can be seen that RGB and AGB stars are bright and red and partly overlap. Because of their brightness, they are easy to observe even at greater distances.

1.3 Isochrones

Isochrones are models of a population of stars with a single age and metallacity and a range of masses. They can be used to infer ages and metallicities in observed CMDs. Each isochrone presents a snapshot of single age at a certain metallicity (Z). Isochrones are overlayed to determine whether the ages and metallicities from the optical SFHs are consistent with the infrared properties of the AGB. To do this, it is necessary to use isochrones that model the AGB.

RGB and AGB stars lose significant amounts of mass, which means there is likely to be circumstellar dust affecting the isochrones. Dust absorbs and scatters the light, which affects short wavelengths (blue) much stronger than red. Including dust in the isochrones pushes them redwards.

1.4 Observations

Stellar photometry has been an astronomer's tool for at least three millennia. The first known photometric catalogues of stars date back to the ancient Babylonians in the 12th century BC. A thousand years later, in the second century BC, the Greek philosopher Hipparchus (190-120 BC) compiled a catalogue, at a time when stellar observations were limited to noting the position and how bright the star was. In the second century AD, Ptolemy's Almagest introduced a more systematic way to catalogue the brightness of stars, a system with 6 magnitudes, where the 1st magnitude was used for the brightest stars. Our modern photometric systems still work in a similar way, classifying stars via a logarithmic scale. In early days, these brightnesses were mainly defined for the purpose of identifying the star in the sky. The invention of the telescope lead to the installment of more magnitude classes, as fainter and fainter stars could be detected. William Herschel, motivated by improving on the astrometry and photometry of his predecessors and the study of variable stars, greatly advanced this area of astronomy. He, his sister Caroline and his son John pushed the accuracy of visual estimations to the limit (~ 0.1 mag). In the 19th century, photographic plates, eventually followed by the CCD camera in the 20th, revolutionised the accuracy with which the magnitude of a star can be determined (Miles, 2007). Advances in the fields of computer science and instrumentation have led to deeper and more accurate observations than ever before.

When observing, the flux is measured rather than (absolute) magnitude. The flux, or photon count, from an object on the CCD of the instrument can be converted to an apparent magnitude.

$$m_1 - m_2 = -2.5 \log\left(\frac{F_1}{F_2}\right)$$
 (1.1)

With the use of different filters, one can measure the flux in different wavelength ranges so we can explore different parts of the electromagnetic spectrum. The names of the filters initially stem from the colors (e.g. B for blue). The filters used here are optical bands B and V and infrared J, H and Ks. If the distance to the object is known, the apparent magnitude can be translated to absolute magnitudes using the distance modulus: $m - M = 5\log(d) - 5$ where m is relative magnitude, M absolute and d is distance in parsec. When measuring the flux from many objects belonging to the same population in at least two filters, using for example a wide field camera, a CMD can be constructed.

Enough signal (flux) from the object is required that it is detectable above the background noise. This dictates how faint detectable objects are. While the sky is bright in infrared, optical observations can be much deeper and sample the fainter phases of stellar evolution. An advantage of the infrared is the lower (dust) extinction compared to the optical. Thus there are definite advantages to using different parts of the spectrum. AGB stars are very bright and thus easier to observe at greater distances. Comparing deep optical SFH with AGB properties is a useful test of more distant and even just integrated light studies. In order to make this comparison, it is useful to utilise both optical and infrared data.

1.5 Outline of this thesis

The aim of this thesis is to study three nearby dwarf spheroidals, Fornax, Draco and Ursa Minor.

In Chapter 2, I present and analyse the optical data of Draco and Ursa Minor. First I describe the observations and present information about the raw data, followed by the data reduction process, then the photometry, quality control plots and finally I show the CMD for each galaxy and compare these. In Chapter 3, I introduce the infrared data of dSph Draco and the optical and infrared data of dSph Fornax and the spatial distribution of stars in the available data. I analyse and take a closer look at the RGB and AGB, comparing the bright stars with deep optical star formation histories. Chapter 4 features a summary, conclusion and an outlook on future work.

Chapter 2

Optical Photometry of Draco and Ursa Minor dSph with the INT/WFC

2.1 Introduction

Draco and Ursa Minor are two dSphs visible from the Northern hemisphere. They have similar stellar masses, see 1.1 but a different morphology as demonstrated in Figure 1.3 and Bellazzini et al. (2002) as well as different metallicity distribution. Draco displays a metallicity gradient (Faria et al., 2007), which is almost entirely absent in UMi (Carrera et al., 2002). This mixing of stellar populations and more elongated shape in the direction of observation might be due to tidal interaction with the Milky Way. Ursa Minor has a RGB similar to Draco, but a stronger blue HB. This suggests that Ursa Minor may contain more metal poor, ancient stars than Draco. The width of the RGBs in both Draco and Ursa Minor suggests that they are both predominantly ancient, metal-poor and have a small spread in metallicities. This is supported by Tolstoy et al. (2009), Carrera et al. (2002) and Mateo (1998). Based on its bluer colour, one can assume that its stellar population is more metal-poor than Draco's. Cohen and Huang (2010) and Nykytyuk (2012) confirm this. Bellazzini et al. (2002) state that the average metallicity is <[Fe/H]> = -1.8 for Ursa Minor and -1.7 for Draco, whilst the peak metallicities are -1.9 and -1.6 respectively.

2.1.1 Description of the data

The Kapteyn Institute was granted observation time on the 2.5m Isaac Newton Telescope (INT) on La Palma between April 16 and April 22 2014, to allow students to observe in a professional setting. The observations were conducted with the Wide Field Camera (WFC) on April 21. The central areas of nearby dwarf galaxies Ursa Minor and Draco were observed using Harris B and V filters. The data was taken to make accurate CMDs of the brighter resolved stellar population down to the HB (not studied in this work) and observe any bright AGB if present. Rough star formation histories of these dSphs are presented in Chapter 1. This section describes the data reduction steps to obtain calibrated photometry of individual stars from the raw images. Figure 2.1 shows the

observed fields. Instead of using a pipeline, I have chosen to reduce the data myself in order to better understand the data reduction process and the resulting photometry.



FIGURE 2.1: Combined V-band frames of the observed central fields of Draco (left) and Ursa Minor (right), with inverted colours.

| Field Filter | | Depth | Colour | Total exposure | Total # |
|--------------|---|-------------|----------|----------------|--------------|
| | | (Magnitude) | | (s) | of exposures |
| Draco | В | 21.07 | B-V: 0.5 | 3180 | 11 |
| | V | 20.07 | B-V: 0.5 | 1950 | 9 |
| Ursa Minor | В | 20.8 | B-V: 0.5 | 3190 | 15 |
| | V | 19.8 | B-V: 0.5 | 1980 | 9 |

 TABLE 2.1: Observation summary with used filters, intended observation depth, colour, total exposure time and the total number of observations per filter per galaxy.

2.1.2 Fixing the world coordinate system and data reduction

Whilst the observation headers do contain the central coordinates, they do not contain a world coordinate system (WCS). In order to combine multiple exposures and obtain deeper photometry, this needs to be remedied. This is because one projects a curved space (the sky) onto a flat surface (the CCD). This becomes important when the wide-field images are dithered. Dithering is used in order to get rid of effects of CCD imperfections as well as to minimize the effect of gaps between the CCDs. In the observations a shift in right ascension (RA) and declination (DEC) of between 10 and 20 arcseconds in either direction from the input coordinates is implemented.

In order to introduce the WCS, the file headers of the individual FITS files need to be fixed. Several header keywords were found to contain insufficient or incorrect information. Extraneous parameter keywords were deleted (PV1_1, PV1_2) and others assigned corrected values. These are PV2_1, PV2_2, PV2_3, BIASSEC and TRIMSEC, which respectively govern the projection of coordinates along both axes and trim the image.

The effect of the projection of the sky is most noticeable around the edges of the images. In order to successfully combine the images, several steps need to be taken. The first step is to take the central coordinates and extrapolate from these the coordinates onto the whole image. This has been done using a script from Mike Irwin that modifies the following keywords: CRVAL1, CRVAL2, CRPIX1, CRPIX2, CD1_1, CD1_2, CD2_1, CD2_2, PROPJ1, PROJP3, WAT1_001, WAT2_001 and finally CTYPE1 and CTYPE2. These define reference pixels, transformation matrix, projection coefficients and the coordinate type (RA and DEC). This provides an initial good guess for the world coordinate system.

The multi-extension data are then split into four separate chips (see Figure 2.1) for further processing in IRAF. The individual images are trimmed and a master-bias and -flat are created. The exposures are bias-subtracted and flat-field corrected using IRAF task CCDPROC. Dark correction is omitted as unnecessary due to the dark count being extremely low.

After this reduction step, the coordinate system is refined using the USNO¹ photometric catalogue, which contains stars in the central regions of both galaxies. We select stars between a V-band magnitude of 5 and 15 for Draco, 5 and 18 for Ursa Minor to improve the initial WCS. This is done using the IRAF task MSCTPEAK, which, through manually matching several stars in the observations with the catalogue, followed by fitting, creates a file with parameters for rotation and deformation for a given image. This database needs to be made for each of the four chips in order to establish an accurate WCS. These WCS are applied to all images using MSCSETWCS. For further refinement MSCTPEAK is used multiple times.

Once the fitted WCS has been applied to the files, a more detailed analysis can be carried out with MSCCMATCH, using a deeper catalogue of the same galaxy. This task refines the WCS by fitting the catalogue to the observation automatically. This worked well for Draco. To reach a good fit for Ursa Minor, a deeper catalogue was needed for MSCTPEAK in order to match more stars and refinements were mainly made using this task, rather than MSCCMATCH. Using MSCCMATCH in some cases deteriorated the solution. This process is repeated several times. The final accuracy is checked using contour plots and the full width half maximum (FWHM) of one star over all images. A bad fit will have a range of FWHMs for the same star over several images. Once this is accomplished, all the multiple exposures can be combined using IMCOMBINE to create one short and one long final image per chip. As a last check, it is checked whether the FWHM in the combined images has not broadened significantly with respect to the individual images. If the FWHM becomes much broader, it is a sign that the images are not coadded correctly. If the accurate WCS is not determined the images cannot be accurately coadded, resulting in significantly poorer photometry in the final images.

2.2 Photometry

Details on the individual exposures can be found in Tables 2.2 and 2.3. Not all exposures were suitable for photometry. The 20 second B-band exposures of Ursa Minor have not been used. The integration time proved too short to contribute sufficient flux. One of

¹USNOFS Image and Catalogue Archive operated by the United States Naval Observatory, Flagstaff Station, http://www.nofs.navy.mil/data/fchpix/



FIGURE 2.2: INT data matched with Stetson's calibrated catalogue for Draco (left) and UMi (right). The different symbols denote the INT/WFC detector chips, while the colour denotes the calibrated V-band magnitude for these objects as determined by Stetson.

the 600 second exposures of Ursa Minor in the V-band was removed due to very bad seeing. One of the Draco 600 second V-band exposures was removed due to clouds which led to a loss of tracking. The unused exposures are marked with a * in the tables. The B-band was significantly less affected by the clouds, so all exposures have been used.

Photometry has been done using IRAF's DAOPHOT package (Stetson, 1987). Sources are identified using DAOFIND, after which the coordinate list is fed into PHOT for the photometry. DAOFIND identifies objects, using the user-specified parameters FWHM, standard deviation of the background, a range of good data values, and minimum pixels for detection. The other parameters are determined for each exposure separately. Tables 2.2, 2.3 and A.1 contain details of each individual exposure, they can be compared with Table 2.4 and Table 2.5, which contain FWHM, mean background, the standard deviation of the background and the total exposure time for the combined exposures. FWHM is comparable in the combined exposures to the individual exposures. Appendix A contains data on the observed standard fields for Landolt calibration.

The flux for each object is determined by the IRAF package from the counts on the CCD multiplied by the gain. The header values for gain and readnoise are used. These are the default values and overestimate both as per information on the INT website, but this offset is removed in the calibration phase described in the next section.

Once a catalog of objects has been assembled, photometry is done using the DAOPHOT task PHOT. It is assumed that using a FWHM of 3.5 pixels for all images is sufficient and a saturation limit of 60000 counts has been set as an upper limit for good data. The minimum aperture was set to 4 pixels. RA and DEC are then added to the photometry files using MSCCTRAN, which matches the WCS of the FITS file to the pixel coordinates. An error cut of 0.1 magnitude has been introduced to remove objects with a low signal to noise (S/N).

2.2.1 Photometric calibration using photometry from Stetson

Although we observed standard stars, the conditions were not photometric. Therefore the calibration is done against publicly available photometry in B and V from Stetson $(1979b)^2$. These calibration files include 123 stars for UMi and 1178 for Draco. The majority of those fall in the central area of the galaxy.

The position of the stars that can be matched with Stetson's data are plotted in Figure 2.2. A number of stars could be matched in all chips of Draco, but only chip 1 and 4 can be matched for Ursa Minor. Using least-squares fitting, a straight line is fitted through the photometry to calculate the offset between INT observations and Stetson, as shown in Figures 2.3 and 2.4 for Draco and Figure 2.5. This could be done with some confidence ($m_{err} \sim 0.05$ magnitude) for chip 1 and 4 for all observations except the short exposures of Ursa Minor. The calibration offset values can be found in Table 2.6. The offset between the raw and Stetson data is larger for the short exposures. This is due to exposure time being assumed as 600s for all exposures in previous steps. This calibration removes the artificial offset.

The remaining chips have been calibrated by matching them to chip 4. This chip is calibrated with the smallest uncertainty. Matching has been done by overlaying all the chips in a CMD plot and calibrating them to chip 4 so that the RGB and HB are in the same position on the CMD. The calibration between the long and short exposures has been further tweaked by plotting the photometric offsets between long and short exposures of the same chip. This is demonstrated for chip 4 in Figure 2.6. They are then all compared to the most reliable offset (long exposure, chip 4). The calibration of Ursa Minor is, due to the smaller number of stars in the calibration file, more uncertain. Yet it appears the overall photometric error in Ursa Minor is smaller than in Draco, which is consistent with the conditions at the time of observation, as they were better earlier in the night when UMi was observed.

Figures 2.3, 2.4 and 2.5 show that there is significant scatter at fainter magnitudes. This is partially an effect of the intended depth of the observations and partially caused by the conditions not being ideal on the night of observation. The error in the offset calibration is estimated as 0.05 magnitude for the central chip of the long exposures and closer to 0.1 magnitude for the other exposures.

Figures 2.7 and 2.8 show the calibrated magnitude-error plots of the long exposures of both dwarf galaxies. Similar plots for the short exposures can be found in Appendix B (Figures C.1 and C.2.) By overlaying all chips, the chips that have insufficient overlap with Stetson have been calibrated.

²Photometric data retrieved from http://www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/ community/STETSON/standards/.



FIGURE 2.3: INT data matched with Stetson's calibrated data for the long (left) and short (right) V-band exposures of Draco. A line is fit to the offset between the INT photometry and Stetson's photometry for each chip in order to calibrate the data.



FIGURE 2.4: INT data matched with Stetson's calibrated data for the long (left) and short (right) B-band exposures of Draco. A line is fitted to the offset between the INT photometry and Stetson's photometry for each chip in order to calibrate the data.



FIGURE 2.5: INT data matched with Stetson's calibrated data for the V (left) and B (right) band exposures of Ursa Minor. A line is fitted to the offset between the INT photometry and Stetson's photometry for each chip in order to calibrate the data.



FIGURE 2.6: INT data of chip 4 matched with Stetson's calibrated data for the long and short V-band exposures of Draco and Ursa Minor. A line is fit to the offset between the INT photometry and Stetson's photometry for each chip in order to calibrate the data.



FIGURE 2.7: Final magnitude-error plot for the long exposures of Draco. On the left the B-band is shown, on the right the V-band. The different colours denote the different chips of the INT data.



FIGURE 2.8: Final magnitude-error plot for the long exposures of Ursa Minor. On the left the B-band is shown, on the right the V-band. The different colours denote the different chips of the INT data.



FIGURE 2.9: Colour magnitude diagrams for the long (right) and short (left) exposures of Draco.



FIGURE 2.10: Colour magnitude diagrams for the long (right) and short (left) exposures of Draco, central chip only.

2.3 Colour-magnitude diagrams

Figures 2.9, 2.10, 2.11 and 2.12 show the colour-magnitude diagrams for Draco and Ursa Minor for respectively the full data-set of both long and short exposures and only the central area as captured on the central chip of the detector. In these plots, only sources that have been observed in both B and V with a maximum photometric error of 0.1 magnitude are included. This cut-off disregards additional errors incurred through calibration. Extinction has not been applied in these figures. Values for the extinction, when calculated according to Schlafly and Finkbeiner (2011), are $A_B = 0.117$ and $A_V = 0.088$.

It can be observed that both short and long exposures reach down to the horizontal branch within the completeness limit, which was one of the primary aims in observing the galaxies. Figures 2.9 and 2.11 show the CMDs of the complete data set. These figures also show that the calibration between chips is not perfect and that additionally there is more scatter than there would be in photometric conditions. Figures 2.10 and 2.12 show only the central chip, which coincides with the center of the galaxies. It can



FIGURE 2.11: Colour magnitude diagrams for the long (right) and short (left) exposures of Ursa Minor.



FIGURE 2.12: Colour magnitude diagrams for the long (right) and short (left) exposures of Ursa Minor, central chip only.

be observed that the features of the CMD are more pronounced here as the fraction of foreground contaminants (MW stars) is lower. The RGB and HB are well populated and stand out clearly. For Draco, the center of the blue end of the HB can be found around B - V = 0.5, which is consistent with the colour measured by Faria et al. (2007), Grillmair et al. (1998) and Stetson (1979a). For Ursa Minor, a colour of B - V = 0.7 is determined, which is consistent with Faria et al. (2007).

The CMDs presented in section 2.3 clearly show the RGB, AGB and HB in both galaxies.

When comparing Ursa Minor and Draco, it can be seen that the Ursa Minor data go quite a bit deeper and that the photometry is more accurate. This can be seen from the error plots (see Figures 2.7 and 2.8) and the decreased scatter around the RGB in the CMD. The deeper photometry at equal exposure time for Ursa Minor can be explained mainly by two causes. The Ursa Minor dSph lies somewhat closer to us and observing conditions were better when doing the Ursa Minor observations. However a comparison can still be made between the two galaxies.

In conclusion, the most accurate and well calibrated photometry is only available for the central chip (4). This is demonstrated by the overlap between the two datasets in Figure 2.2 and the following calibration plots. In the following analysis only the data from chip 4 will be used to determine properties of the stellar population of Draco and Ursa Minor.

2.4 Interpretation and isochrone fitting

In order to get a better handle on the quality of the data and comparison between the two galaxies, intermediate and old isochrones from Marigo et al. (2008) with a range of metallicities are overlayed on the optical CMDs of Draco and Ursa Minor. The isochrones were selected based on the schematic SFHs shown in Figure 1.4 in combination with the metallicity information given in the previous paragraph. This analysis is limited by a minimum metallicity of [Fe/H] = -2.2 and a maximum age of 11 Gyr, thus the oldest and most metal poor stars may not be accurately modelled.

Figure 2.13 shows the data from chip 4 for both galaxies overlaid with metal-rich intermediate age stars and average metallicity up to metal-poor old age isochrones. For Draco these are values of [Fe/H] = -1.7, age 10 Gyr, [Fe/H] = -2.2, age 11 Gyr and [Fe/H] = -1.4, age 5 Gyr, for Ursa Minor [Fe/H] = -1.8, age 10 Gyr, [Fe/H] = -2.2, age 11 Gyr and [Fe/H] = -1.4, age 4 Gyr. We expect that an isochrone of the dominant age with average metallicity will fit the RGB branch very well and this is indeed what is observed. We also note that the Ursa Minor data is deeper than the Draco data. UMi lies closer to us, so exposures of the same length should produce photometry reaching farther down the CMD. We see that the blue end of the horizontal branch has not been modelled well with the used isochrones, as the blue HB of Ursa Minor extends slightly more bluewards than the HB of the isochrones. Less scatter is observed in Ursa Minor, which is consistent with the worsening weather conditions during the observations of Draco. Isochrones represent range of ages and metallicities. The isochrones with the literature values for the average metallicities of both galaxies fit the RGB branch well. The blue horizontal branch is not well modelled using these isochrones. This is likely due to the limited age and metallicity range of the isochrones ([Fe/H] = -2.2 and ages up to 11 Gyr). The RGB is in both galaxies flanked by the isochrones with outlying ages



FIGURE 2.13: Isochrones overlaid on the photometric data of (a) Draco and (b) Ursa Minor. Only data from the central CCD chip has been used with an photometric error cut implemented of 0.1 magnitude. The centre of the dSph is focussed on. Less scatter is observed in Ursa Minor. The isochrones with average metallicity fit the RGB branch well.

and metallicities and overlayed by the average, as expected. There is a relatively high scatter near the AGB branch, making it difficult to select true AGB stars in this optical sample. The data corroborates that both dSph are generally old and metal-poor.

| Object | RA | Dec | UT | Airm | Texp | Filter | Background | FWHM |
|--------|-------------|-------------|-------|-------|-------|--------|------------|----------|
| | (J2000) | (J2000) | | | (sec) | | | (direct) |
| UMi* | 15:09:00.44 | 67:13:38.71 | 00:47 | 1.322 | 20 | В | 10 | 4.27 |
| UMi* | 15:09:02.53 | 67:13:23.72 | 00:50 | 1.319 | 20 | В | 9 | 3.6 |
| UMi* | 15:08:58.69 | 67:13:54.72 | 00:51 | 1.318 | 20 | В | 10 | 4.12 |
| UMi | 15:09:02.48 | 67:13:56.72 | 00:52 | 1.316 | 40 | В | 38 | 4.15 |
| UMi | 15:08:57.19 | 67:13:27.43 | 00:54 | 1.315 | 40 | В | 37 | 4.33 |
| UMi | 15:09:02.88 | 67:13:19.54 | 00:56 | 1.313 | 40 | В | 37 | 4.04 |
| UMi | 15:09:02.88 | 67:13:19.74 | 00:58 | 1.311 | 20 | V | 60 | 3.56 |
| UMi | 15:08:57.49 | 67:13:53.65 | 01:00 | 1.310 | 20 | V | 60 | 3.58 |
| UMi | 15:09:02.18 | 67:13:26.70 | 01:01 | 1.308 | 20 | V | 60 | 3.63 |
| UMi | 15:09:03.69 | 67:13:49.78 | 01:04 | 1.307 | 10 | V | 20 | 3.39 |
| UMi | 15:09:02.83 | 67:13:51.94 | 01:05 | 1.306 | 10 | V | 19 | 3.42 |
| UMi | 15:08:58.34 | 67:13:58.70 | 01:06 | 1.305 | 10 | V | 17 | 3.48 |
| UMi | 15:08:58.34 | 67:13:58.50 | 01:08 | 1.299 | 600 | В | 800 | 4.38 |
| UMi* | 15:09:02.71 | 67:13:18.73 | 01:21 | 1.293 | 20 | В | 7 | 3.93 |
| UMi* | 15:09:02.71 | 67:13:18.83 | 01:23 | 1.290 | 600 | V | 2170 | 3.52 |
| UMi | 15:09:02.71 | 67:13:18.83 | 01:35 | 1.284 | 600 | В | 890 | 3.81 |
| UMi | 15:08:57.01 | 67:13:28.52 | 01:48 | 1.279 | 600 | V | 2550 | 3.27 |
| UMi | 15:08:57.01 | 67:13:28.52 | 02:01 | 1.276 | 600 | В | 1550 | 3.32 |
| UMi | 15:09:03.00 | 67:13:50.75 | 02:14 | 1.275 | 600 | V | 3750 | 2.95 |
| UMi | 15:09:03.00 | 67:13:50.85 | 02:26 | 1.276 | 600 | В | 2070 | 3.21 |
| UMi | 15:08:57.82 | 67:13:56.47 | 02:39 | 1.279 | 600 | В | 2270 | 3.20 |
| UMi | 15:08:57.82 | 67:13:56.57 | 02:51 | 1.281 | 30 | V | 175 | 2.64 |
| UMi | 15:08:58.53 | 67:13:52.31 | 02:52 | 1.281 | 30 | V | 175 | 2.75 |
| UMi | 15:09:03.40 | 67:13:19.77 | 02:54 | 1.282 | 30 | V | 175 | 2.81 |

2.5 Tabulated data of Draco and Ursa Minor

TABLE 2.2: Details for the individual exposures of Ursa Minor, Draco and the standard fields. Due to saturation, different stars have been chosen between bands and exposure length where necessary to determine a comparable FWHM. Stars denote data that has been removed from the final photometry.

| Object | RA | Dec | UT | Airm | Texp | Filter | Background | FWHM |
|---------|-------------|-------------|-------|-------|-------|--------|------------|----------|
| | (J2000) | (J2000) | | | (sec) | | | (direct) |
| DRACO | 17:20:18.66 | 57:55:05.55 | 03:02 | 1.192 | 20 | V | 225 | 3.49 |
| DRACO | 17:20:18.66 | 57:55:05.55 | 03:03 | 1.190 | 20 | В | 105 | 3.66 |
| DRACO | 17:20:20.14 | 57:55:19.66 | 03:05 | 1.188 | 20 | V | 200 | 3.40 |
| DRACO | 17:20:20.15 | 57:55:19.66 | 03:07 | 1.187 | 20 | В | 115 | 3.98 |
| DRACO | 17:20:16.26 | 57:55:16.28 | 03:08 | 1.185 | 20 | V | 265 | 3.63 |
| DRACO | 17:20:16.26 | 57:55:16.28 | 03:10 | 1.183 | 20 | В | 130 | 3.65 |
| DRACO | 17:20:20.27 | 57:55:22.57 | 03:12 | 1.181 | 40 | В | 240 | 3.62 |
| DRACO | 17:20:20.27 | 57:55:22.57 | 03:14 | 1.180 | 30 | V | 340 | 3.40 |
| DRACO | 17:20:20.56 | 57:54:47.69 | 03:16 | 1.178 | 40 | В | 205 | 3.89 |
| DRACO | 17:20:20.56 | 57:54:47.69 | 03:18 | 1.176 | 30 | V | 255 | 3.38 |
| DRACO | 17:20:20.31 | 57:54:48.67 | 03:19 | 1.175 | 40 | В | 175 | 3.42 |
| DRACO | 17:20:20.31 | 57:54:48.57 | 03:21 | 1.173 | 30 | V | 210 | 3.37 |
| DRACO | 17:20:20.56 | 57:54:47.69 | 03:27 | 1.165 | 600 | В | 2780 | 3.73 |
| DRACO | 17:20:20.56 | 57:54:47.69 | 03:38 | 1.158 | 600 | V | 5290 | 3.28 |
| DRACO | 17:20:20.18 | 57:54:49.66 | 03:50 | 1.152 | 600 | В | 3380 | 3.40 |
| DRACO | 17:20:20.19 | 57:54:49.56 | 04:01 | 1.148 | 600 | V | 10800 | 2.99 |
| DRACO | 17:20:20.30 | 57:54:54.57 | 04:15 | 1.145 | 600 | В | 4450 | 3.24 |
| DRACO * | 17:20:20.30 | 57:54:54.67 | 04:26 | 1.145 | 600 | V | 12600 | 4.06 |
| DRACO | 17:20:16.26 | 57:55:20.48 | 04:40 | 1.146 | 600 | В | 5600 | 3.15 |
| DRACO | 17:20:20.40 | 57:55:21.68 | 04:53 | 1.149 | 600 | В | 5400 | 3.20 |

TABLE 2.3: Continuation of table 2.2. Details for the individual exposures of Ursa Minor, Draco and the standard fields. Due to saturation, different stars have been chosen between bands and exposure length where necessary to determine a comparable

FWHM. Stars denote data that has been removed from the final photometry.

| Exposure | FWHM | Background (mean) | Stddev Backgr. | Total exp. time |
|--------------|------|-------------------|----------------|-----------------|
| DracoBlong1 | 3.3 | 3650 | 30 | 3000 |
| DracoBlong2 | 4.5 | 2730 | 25 | 3000 |
| DracoBlong3 | 4 | 3330 | 30 | 3000 |
| DracoBlong4 | 3.4 | 2760 | 25 | 3000 |
| | | | | |
| DracoVlong1 | 3.3 | 6400 | 60 | 1200 |
| DracoVlong2 | 3.5 | 4740 | 50 | 1200 |
| DracoVlong3 | 4.5 | 6100 | 70 | 1200 |
| DracoVlong4 | 3.2 | 5300 | 60 | 1200 |
| | | | | |
| DracoBshort1 | 3.7 | 150 | 6 | 180 |
| DracoBshort2 | 4.2 | 100 | 4 | 180 |
| DracoBshort3 | 4.8 | 140 | 6 | 180 |
| DracoBshort4 | 3.7 | 105 | 5 | 180 |
| | | | | |
| DracoVshort1 | 3.5 | 280 | 7 | 150 |
| DracoVshort2 | 4 | 190 | 5 | 150 |
| DracoVshort3 | 4 | 270 | 7 | 150 |
| DracoVshort4 | 3.5 | 225 | 5 | 150 |
| | | | | |

TABLE 2.4: Parameters of all combined exposures of Draco and Ursa Minor, determined using imexam and imstat.

| Exposure | FWHM | Background (mean) | Stddev Backgr. | Total exp. time |
|-------------|------|-------------------|----------------|-----------------|
| UrsaBlong1 | 3.5 | 1075 | 20 | 3000 |
| UrsaBlong2 | 5 | 790 | 15 | 3000 |
| UrsaBlong3 | 4.6 | 980 | 20 | 3000 |
| UrsaBlong4 | 3.5 | 800 | 15 | 3000 |
| | | | | |
| UrsaVlong1 | 3.4 | 3100 | 40 | 1200 |
| UrsaVlong2 | 4 | 2300 | 30 | 1200 |
| UrsaVlong3 | 4.6 | 3000 | 40 | 1200 |
| UrsaVlong4 | 3.3 | 2600 | 30 | 1200 |
| | | | | |
| UrsaBshort1 | 4.4 | 60 | 7 | 120 |
| UrsaBshort2 | 4.7 | 30 | 5 | 120 |
| UrsaBshort3 | 5 | 60 | 5 | 120 |
| UrsaBshort4 | 4.8 | 40 | 4 | 120 |
| | | | | |
| UrsaVshort1 | 3.2 | 80 | 4 | 180 |
| UrsaVshort2 | 4.5 | 40 | 3 | 180 |
| UrsaVshort3 | 3.5 | 80 | 4 | 180 |
| UrsaVshort4 | 3.4 | 60 | 3 | 180 |
| | | | | |

TABLE 2.5: Parameters of all combined exposures of Draco and Ursa Minor, determined using imexam and imstat.

| Exposure | В | V | B - V |
|--------------|-------|-------|-------|
| Draco Long1 | -0.08 | -0.03 | -0.05 |
| Draco Long2 | -0.35 | -0.35 | 0 |
| Draco Long3 | -0.15 | -0.08 | -0.07 |
| Draco Long4 | -0.35 | -0.23 | -0.12 |
| | | | |
| Draco Short1 | -3.30 | -3.39 | -0.09 |
| Draco Short2 | -3.58 | -3.71 | -0.13 |
| Draco Short3 | -3.39 | -3.44 | -0.05 |
| Draco Short4 | -3.58 | -3.49 | -0.09 |
| | | | |
| Ursa Long1 | 0.31 | 0.33 | -0.02 |
| Ursa Long2 | -0.02 | 0.04 | -0.06 |
| Ursa Long3 | 0.21 | 0.28 | -0.07 |
| Ursa Long4 | 0.04 | 0.14 | -0.1 |
| | | | |
| Ursa Short1 | -3.5 | -3.39 | 0.11 |
| Ursa Short2 | -3.81 | -3.66 | 0.13 |
| Ursa Short3 | -3.59 | -3.47 | 0.12 |
| Ursa Short4 | -3.52 | -3.57 | 0.05 |
| | | | |

TABLE 2.6: Calibration values of the INT data with respect to Stetson. The error in these values are estimated as 0.05 magnitude for chip 4 of the Draco and Ursa Minor exposures and 0.05 to 0.09 magnitude for all other exposures.

| Exposure | Object count | Exposure | Object count |
|--------------|--------------|-------------|--------------|
| Draco Long1 | 1238 | Ursa Long1 | 3094 |
| Draco Long2 | 786 | Ursa Long2 | 2446 |
| Draco Long3 | 1209 | Ursa Long3 | 2877 |
| Draco Long4 | 3059 | Ursa Long4 | 6467 |
| | | | |
| Draco Short1 | 1652 | Ursa Short1 | 638 |
| Draco Short2 | 1861 | Ursa Short2 | 479 |
| Draco Short3 | 1036 | Ursa Short3 | 855 |
| Draco Short4 | 2363 | Ursa Short4 | 1764 |

TABLE 2.7: Object counts for all exposures. No distinction has been made between false or dubious detections, galaxies and stars.

Chapter

Studying the AGB populations of Fornax and Draco dSph galaxies

3.1 Introduction

Asymptotic giant branch stars are bright, interesting and still relatively poorly understood compared to other phases in stellar evolution. Their brightness, however, makes them excellent targets for study both at short and intermediate distances. In this chapter I focus on the infrared photometry of Fornax and Draco. The infrared is used because the luminous AGB is very red and therefore easier to see in a redder part of the spectrum. Reddening due to interstellar and circumstellar dust is also less of an issue for the used wavelengths in the near infrared. We combine optical and infrared photometry of both Fornax and Draco to compare them using isochrones, which decresses the influence of age-metallicity degeneracy. Figure 3.1 shows features of the Fornax galaxy using different colour combinations. It can be observed that the features are most spread out using both optical and infrared data. J-Ks has the advantage of having a clearer distinction between RGB-tip and luminous AGB. The data are described in more detail in the relevant section later on.

Previous near-infrared studies have found distances and average metallicities for both galaxies. For Fornax, Gullieuszik et al. (2007) have found a distance modulus of $(m-M)_0 = 20.73 \pm 0.11$, which agrees with the value of $(m - M)_V = 20.84 \pm 0.04$ used in de Boer et al. (2012b). Both these studies find a metallicity gradient, with the younger, metal-rich stars concentrated towards the centre. Using a combination of J-K and V-K data, Gullieuszik et al. (2007) find an average RGB metallicity of [M/H] = -0.9, which is in agreement with de Boer et al. (2012b) who finds [Fe/H] = -1 for this population. Gullieuszik et al. (2007) favour an older population than the 4 Gyr found by de Boer et al. (2012b).

Cioni and Habing (2005) find a metallicity gradient in Draco and show that previously identified carbon (AGB) stars need spectroscopic rather than photometric identification. These stars fall over the RGB branch and are not outstandingly bright. It $(m - M)_0 = 19.49 \pm 0.06$ (stat) ± 0.15 (sys), which brings Draco slightly closer than the distance

found by Bellazzini et al. (2002) of $(m - M)_0 = 19.84 \pm 0.14$. Cioni and Habing (2005) photometrically find two quite different values for the average metallicity of 1.95 or 1.34 respectively, whilst Bellazzini et al. (2002) favour the lower metallicity estimate, finding an average metallicity of [Fe/H] = -1.7 and a peak metallicity of [Fe/H] = -1.6. The latter values are used in this work.



FIGURE 3.1: Optical and infrared photometry of Fornax dSph, showing different colour combinations (B-V, J-Ks and B-Ks respectively). Note the very different scales on the x-axis. The features: RGB, RC, AGBb and AGB are taken from de Boer et al. (2012b) as shown in Figure 1.5. It can be observed that the features are more spread out when using both infrared and optical data, in particular the AGB stars above the tip of the RGB. However the clearest distinction between the RGB-tip and the luminous AGB appears to be in the combination J-Ks.

3.2 Isochrones

Isochrones are overlaid to determine whether the ages and metallicities from the optical SFHs are consistent with the infrared properties of the AGB. To do this, it is necessary to use isochrones that model the AGB. In this thesis, I have used the Marigo et al. (2008) isochrones with the Girardi et al. (2010) case A corrections for low-mass, low-metallicity AGB tracks¹.

¹http://stev.oapd.inaf.it/cgi-bin/cmd



FIGURE 3.2: Fornax infrared photometry with Marigo (M08) isochrones overplotted. [Fe/H] = -1, Age = 4 Gyr, $[\alpha/Fe] = 0$. This demonstrates that dust composition makes a small difference in the slope. In black the composite dust, in light blue the pure amorphous carbon for C stars and pure Silicate for M stars, in black the composite dust. Isochrones are shifted to both coincide with the RGB tip. This introduces a shift of x = +0.06 and y = -0.28 for the composite dust and x = +0.03, y = -0.35 for the non-mixed dust.

For the bolometric corrections applied to non-carbon stars, I have chosen the corrections as described in Girardi et al. (2008). For carbon stars, I have opted for the Loidl et al. (2001) bolometric corrections, as both are associated with the Marigo isochrones. I have assumed the lognormal, bottom-light IMF from Chabrier (2001) and Chabrier (2003), which is the default option.

RGB and AGB stars lose significant amounts of mass, which means there is likely to be circumstellar dust affecting the isochrones. The choice has been made to use a 60% Silicate and 40% Aluminium oxide dust for M stars and 85% amorphous carbon and 15% Silicon Carbide for C stars following Groenewegen (2006). Including dust pushes the isochrones towards redder colours in the later evolutionary phases. The dust composition has a small influence on the slope of the isochrone in the RGB and AGB phase. This is demonstrated in Figure 3.2. This demonstrates that dust composition makes a small difference in the slope. In this figure, the isochrones are shifted to both coincide with the RGB tip. This introduces a shift of x = +0.06 and y = -0.28 for the composite dust and x = +0.03, y = -0.35 for the non-mixed dust. The chosen dust appears to fit the data marginally better but dust composition appears to make little difference in this case.

The photometry has been corrected for extinction (see section 3.3.3) when overlaying isochrones, while the distance modulus has been applied to the isochrones. This is done to stay as close as possible to the data, while still using the accurate, star by star extinction correction in Fornax. For consistency, the same approach is used in Draco, despite using averaged extinction values.

Figure 3.3 shows the difference between the Dartmouth isochrone (Dotter et al., 2008) for the dominant RGB population as used in de Boer et al. (2012b) and the Marigo isochrone with the same input parameters. The Marigo isochrone lies farther bluewards on the RGB than the Dartmouth isochrone. The Dartmouth isochrone does not model the TP-AGB, which is why we choose to use the Marigo isochrones for this work.



FIGURE 3.3: Fornax infrared photometry with Marigo (M08) and Dartmouth (Dart) isochrone overplotted. [Fe/H] = -1, Age = 4 Gyr, $[\alpha/Fe] = 0$.

3.2.1 Note on metallicity conversions

Values of metallicities from the literature are usually given in [Fe/H]. For the set of isochrones used (Marigo et al., 2008), metallicity is given in terms of Z, for which the following relation can be used:

$$[M/H] = \log \frac{Z}{Z_{\odot}} \tag{3.1}$$

Solar metallicity for this relation is given as $Z_{\odot} = 0.019$ (Marigo et al., 2008). M is total metallicity. Salaris et al. (1993) gives us the following equation to translate between [M/H] and [Fe/H]:

$$[M/H] \cong [Fe/H] + \log(0.638f_a + 0.362)$$
 (3.2)

The total metallicity [M/H] is [Fe/H] plus a correction factor where $f_a = 10^{[\alpha/\text{Fe}]}$ is the enhanced factor of the alpha elements. Alpha elements are elements with nuclei that are multiples of He (O, Mg, Ca, Si, Ti). Supernovae type II (SNII) contribute many alpha elements to the interstellar medium, causing the next generation of stars to be alpha enhanced. This effect starts to become smaller once supernovae type Ia (SN Ia) kick in. Whilst producing some alpha elements, they contribute more iron-peak elements, like Ti, Cr, Co, Ni (Mendel et al., 2007). The following relation from de Boer et al. (2012a) is used to determine the $[\alpha/\text{Fe}]$ abundance for Fornax.

$$\left[\alpha/\mathrm{Fe}\right] = \frac{\left[\mathrm{Mg/Fe}\right] + \left[\mathrm{Ca/Fe}\right] + \left[\mathrm{Ti/Fe}\right]}{3} \tag{3.3}$$

The younger populations of neither Fornax nor Draco are significantly alpha-enhanced. The Mg abundances of Fornax are found in de Boer et al. (2012b). Letarte et al. (2010) present spectroscopic observations of a limited sample of stars in the central region of Fornax. No significant alpha element enhancement has been found in these stars in Letarte's study. To best compare with the results from deep MSTO SFH as determined by de Boer et al. (2012b), I have assumed a similar linear relation between $[\alpha/\text{Fe}]$ and [Fe/H]. Using the information given about the MSTO region in their work, where isochrones are used of respectively [Fe/H] = -2.45, with $[\alpha/\text{Fe}] = 0.40$ dex, [Fe/H] = -1.00, $[\alpha/\text{Fe}] = 0$ and [Fe/H] = -0.3, with $[\alpha/\text{Fe}] = -0.2$ dex, I recover the relation $[\alpha/\text{Fe}] \approx -0.2786*[\text{Fe/H}] - 0.2816.$

For Draco, Shetrone et al. (2001) find $[\alpha/\text{Fe}] = 0.09 \pm 0.02$. Using the equation from Salaris et al 1993 (3.2), taking the α enhancement into account modifies the [Fe/H] value by 0.066. This has a negligible effect on Z, so I assume [M/H] = [Fe/H]. The same assumption has been made for Ursa Minor in the previous chapter using the Shetrone results on alpha enhancement ($[\alpha/\text{Fe}] = 0.13 \pm 0.04$).

3.3 Description of the photometry used and assumed SFH



3.3.1 Fornax

FIGURE 3.4: In green the area of the infrared VISTA photometry of Fornax, overlaid on the optical CTIO/MOSAIC photometry in blue. The central part of Fornax (which has a tidal radius $r_t = 71.1'$) is well covered. The blue points are much more dense, as the optical survey reaches over 4 magnitudes deeper than the infrared. On the right is the B-Ks CMD from the combined optical and infrared photometry. It can be observed that the horizontal branch has not been detected in the infrared.

Fornax is one of the larger Milky Way dwarfs with a tidal radius of $71' \pm 4'$ or 2.85 ± 0.16 kpc. The optical data of Fornax from the 4m CTIO/MOSAIC telescope is from de Boer et al. (2012b) and contains 270 000 stars out to an elliptical radius of 0.8 degrees, see Figure 3.4. This is a deep survey down to the MSTO, from which a detailed SFH has been determined. The Fornax infrared data is from the VISTA VIKING survey which covers the central area of the galaxy, as can be seen in the left panel of Figure 3.4 and contains about 175000 objects of which 22000 are classified as stars in all three bands. The data have been reduced by CASU and cover the J, H and Ks bands to a depth of $K_s \sim 19.7$, see Figures 3.5 and 3.6. The sky is much brighter in infrared and this survey is about four magnitudes less deep than the CTIO/MOSAIC data. The horizontal branch was not detected in the IR.

Fornax is dominated by an intermediate age population with ages between 1 and 10 Gyr, but it also boasts an ancient population of between 10 and 14 Gyr and a young



FIGURE 3.5: The error distribution of the Fornax infrared (J,H, Ks) photometry using an error cut of 0.1 magnitude. The double tail to the error distribution is due to combining two different infrared datasets of different depths, one with a central pointing and one pointing north and east of the center. The north pointing has fewer stars in the used subset, which is why one tail is less populated.



FIGURE 3.6: The error distribution of the Fornax optical (B,V) photometry using an error cut of 0.1 magnitude. The feature at $B \sim 22$ and $V \sim 21$ may be explained due to the objects being mainly in a crowded region in the central area.

component with ages below 1 Gyr. It has an age and metallicity gradient, with the young, metal-rich stars in the center. Going out from the centre an increase in age and a decrease in metallicity is observed. Figure 3.7 shows the overall SFH determined by de Boer et al. 2012. Within the observed radius of around $r_{\rm ell} \approx 0.8$ degrees, it has formed around 4.3×10^7 M_{\odot} in stellar mass up until 250 Myr ago. The average metallicity <[Fe/H]> rose rapidly from below -2.5 dex to -1.5 dex between 8 and 12 Gyr ago and then rose in a more gradual fashion up to -0.8 dex around 3 Gyr ago. A rapid decrease in [Mg/Fe] for stars with [Fe/H] \geq -1.5 dex is observed with a trend in decreasing age.

The SFH analysis from de Boer et al. (2012b) finds a dominant 4 Gyr old RGB population with a metallicity of [Fe/H] = -1. Looking at the peak age and metallicity for the individual annuli, the peak in each annulus out to 0.4 degrees lies around [Fe/H] = -1. For the annuli and CMDs of the stars contained therein, see Figures 3.8 and 3.9. Going outwards the mean age rises from 4 Gyr to ≈ 7.5 Gyr. In Figure 3.8 we note that the bright AGB are most abundant in the inner regions of the galaxy. Farther out, the foreground becomes increasingly significant, as expected.

Figure 3.10 shows the bright AGB stars. These are defined as stars up and redwards of the RGB tip. It is likely that some of these stars are foreground stars but this is minimised by choosing stars redwards of the RGB. This demonstrates that the bright AGB population is concentrated towards the centre of the galaxy. By this selection



FIGURE 3.7: The overall star formation history (a) and chemical evolution history (b) of the Fornax dSph, out to an elliptical radius of 0.8 degrees. Figure is from de Boer et al. (2012b).



FIGURE 3.8: The CMDs from the infrared Fornax photometry at different annuli from the center, using similar elliptical radii (r_ell) as in de Boer et al. (2012b). The foreground becomes more and more dominant as you move away from the center of the galaxy.



FIGURE 3.9: An overview of the Fornax combined dataset of optical and infrared data with elliptical radius overlaid, for which CMDs are plotted in Figure 3.8.



FIGURE 3.10: The red datapoints are stellar Fornax data within an elliptical radius of 0.2 degrees. In dark blue the bright AGB stars over the whole Fornax dataset. The bright AGB stars are defined as anything up and right of the RGB tip. Overplotted in light blue are the bright AGB in the central area. It can be seen that more than half the young AGB stars lie within the central area, which is consistent with the observed age gradient.

criterion, I find 82 stars in the central area (light blue), compared with 156 over the entirety of Fornax (all blue). These 156 stars are treated as bright AGB.

3.3.2 Draco



FIGURE 3.11: In red the infrared WFCAM observations of Draco ($r_t = 28.3'$, the cross denotes the center of the galaxy), overlaid on the optical data from the INT (grey). It is clear that only the central chip overlaps well with the infrared dataset. On the right, B-Ks CMD from the matched data of the central chip of the optical data with the infrared.



FIGURE 3.12: The error distribution of the Draco infrared photometry ((a) J, (b) H and (c) Ks) of the central area of the dSph using an error cut of 0.1 magnitude.

The optical data of Draco has been described in the previous chapter. The infrared photometry of Draco is from UKIRT WFCAM data and contains just under 37000



FIGURE 3.13: Draco infrared dataset with elliptical radii of 0.1, 0.2 and 0.4 degrees overlaid.

objects of which 3561 have a stellar classification in all infrared bands, see Figure 3.11. The left panel of this Figure shows the optical and infrared cover of the galaxy, the right panel a B-Ks CMD containing the stars that can be matched between the optical and infrared bands. The data have been reduced by Mike Irwin and cover the J, H and Ks bands down to a magnitude of Ks = 19.5; see Figure 3.12 for the observation depth. The sky is much brighter in infrared than in the optical, hence these observations are not very deep. When matching the optical and infrared catalogues, only 900 objects remain. To retain the largest possible sample, I therefore overlay the isochrones separately in the optical and infrared. Figures 3.13 and 3.14 show the distribution of stars within different annuli drawn around the center of the galaxy. The population of Draco is best defined when looking at the stars within an annulus of 0.2 degrees, which covers most of the central chip. This area has proportionally the least contamination from foreground stars.

Figure 3.15 shows the metallicity distribution of Draco, as found by Nykytyuk (2012). The peak metallicity lies around [Fe/H] = -1.8, with a small excess at higher metallicity: [Fe/H] = -1.2. The vast majority of the stars in Draco lie in the range -2.1 < [Fe/H] < -1.5. I combine this with the very rough star formation history from Mateo 1998 (see Figure 1.4) to overlay isochrones with ages between 5 and 11 Gyr and metallicities in the range -2.2 < [Fe/H] < -1.2 in section 3.5.2. The low metallicity and upper age limit are dictated by the limitations of the used isochrones.

3.3.3 Extinction correction

Extinction due to dust must be taken into account. Extinction values in the optical vary significantly over the surface of Fornax, as shown in Figure 3.16, which shows the extinction in the V-band. Therefore it is not trivial to calculate extinction in all bands for each source individually. This has been done using the dust, extinction and reddening tool as described in Schlegel et al. (1998)². Using COBE/DIRBE and IRAS/ISSA maps with the zodiacal foreground where confirmed point sources are removed. The reddening in Fornax is on average $E(B - V) = A_b - A_v = 0.03$ mag.

²http://irsa.ipac.caltech.edu/applications/DUST/



FIGURE 3.14: Infrared Draco photometry. CMD using the elliptical radii as Figure 3.13. The foreground becomes more and more dominant as you move away from the center of the galaxy.



FIGURE 3.15: The metallicity distribution function of Draco, from Nykytyuk (2012)



FIGURE 3.16: Schlegel V-band extinction map overplotted on infrared Fornax data. Extinction calculated as described in Schlegel et al. (1998).



FIGURE 3.17: Variation in extinction and reddening over the area of Draco covering the matched area of the infrared and optical data. This area displays low variation in these values.

The variation in the optical extinction is much smaller in Draco. This is shown in Figure 3.17. For this reason the average NED³ values are used instead of the extinction. These values are $A_B = 0.098$, $A_V = 0.074$, $A_J = 0.019$, $A_H = 0.012$, $A_K = 0.008$.

The photometry overplotted with isochrones have been corrected for extinction. Everywhere else, the uncorrected photometry is plotted.

³http://ned.ipac.caltech.edu/

3.4 CMD and Colour-colour plots



FIGURE 3.18: Fornax photometry. (a) and (b) show infrared CMDs, J-Ks and H-Ks respectively, with the stars within 0.2 degrees of the centre overplotted in blue on the full dataset. (c) Shows a colour-colour plot, B-V vs J-Ks, using the full wavelength range of the observations with the stars within 0.2 degrees overplotted in blue. (d) Shows the same as (c), but now with the red clump and AGBbump overlaid as shown in Figure 1.5 b.

Figures 3.18 and 3.19 show a range of CMD and colour-colour plots of Fornax and Draco respectively, further demonstrating the stellar content and morphological differences between the two dSphs. Looking at Figure 3.18, it can be observed that, as expected, the filters with the larger wavelength gap between them (a) give a steeper slope on the giant branch compared with (b). This makes it easier to identify the stars lying redwards of the RGB and filter out Milky Way stars in the foreground. The central population holds a very significant part of the very red population and has much less scatter than the population farther outwards. This is consistent with the previously established age gradient found in Fornax. The younger population, where more AGB stars are found, is concentrated more centrally. The colour-colour plots (c) and (d) show that the AGB branch and red clump lie in a different orientation in colourspace from the (rest of the) RGB but are difficult to disentangle in this parameterisation, hence the colour magnitude diagram provides more direct means of quantifying the population.



FIGURE 3.19: Draco CMD of the infrared colours (a) and colour-colour plot of the full range of wavelengths (b). In (a), stars within a radius of 0.2 degrees are overplotted on the full dataset.

Figure 3.19 gives an overview of Draco. The population of this dSph looks significantly less complex, which is expected when looking at their respective SFHs, which show that Draco has a smaller range of ages and metallicities. The large discrepancy may also be partially explained by the difference in size of sample of both galaxies. Fornax clearly shows a redwards branch while Draco has very few bright stars redder than J-Ks = 1. Draco is much more metal-poor. Salaris and Cassisi (2005) predict an AGB branch with a much shallower slope redwards, and as such, morphologically more an extension of the RGB. Keeping the initial He content fixed, a higher metallicity leads to longer lasting phases of evolution at a lower luminosity and effective temperature, hence the AGB branch should be more difficult to distinguish from the RGB. The absence of luminous AGB is entirely in line with predictions.



FIGURE 3.20: Infrared Fornax photometry. The red isochrone is the dominant RGB age (4 Gyr) and metallicity ([Fe/H] = -1) as found by de Boer et al. (2012b). In blue also an isochrone with the same metallicity, but a younger age. The latter isochrone extends farther red and fits more of the AGB.

3.5 Metallicity and age

Studying the star formation history of Fornax and Draco (de Boer et al., 2012b; Mateo, 1998), it can be seen that Draco is dominated by an old population while Fornax sports a larger range of ages and has seen star formation up until recent times.

3.5.1 Fornax

Figure 3.7 shows the overall SFH and chemical evolution history (CEH) of Fornax as determined by de Boer et al. (2012b).

For the RGB of Fornax, de Boer et al. (2012b) have found a strong RGB population with an average age of 4 Gyr and an average metallicity of [Fe/H] = -1 dex. Using the dusty isochrone as described above, its slope also neatly falls over the lower AGB branch of Forna, see Figure 3.20. This Figure also shows a younger population with the same metallicity, which appears to be a closer fit to the AGB but a poor fit to the RGB. One caveat is that the isochrones have been calibrated by matching the isochrone



FIGURE 3.21: Infrared Fornax photometry. The dark blue isochrone is the dominant RGB age (4 Gyr) and metallicity ([Fe/H] = -1, $[\alpha/Fe] = 0$) as found by de Boer et al. (2012b). In light blue a metal-poor, old isochrone [Fe/H] = -2.45, $[\alpha/Fe] = 0.4$, 12 Gyr and in grey a young, metalrich isochrone: [Fe/H] = -0.3, $[\alpha/Fe] = -0.2$, 250 Myr. The very young and old isochrones fall on the blue side of the RGB while the median falls right on top and follows the RGB onto the luminous AGB. The very old isochrone traces a population which should have no stars on the AGB and indeed tapers off long before, while the very young isochrone goes to high luminosities which the AGB branch does not reach.



FIGURE 3.22: Infrared Fornax photometry with isochrones overlaid with [Fe/H] = -1, $[\alpha/\text{Fe}] = 0.0$. The legend shows the log of the age. $8.7 \approx 500$ Myr, 9 = 1 Gyr, $9.2 \approx 1.5$ Gyr, $9.4 \approx 2.5$ Gyr, $9.6 \approx 4$ Gyr. The AGB falls neatly between these isochrones. The isochrones have been shifted so that the dominant RGB population found by de Boer et al. 2012 fits the RGB tip. This introduced a shift of -0.28 on the y axis, and one of 0.06 on the x axis.

with [Fe/H] = -1 dex at 4 Gyr to the RGB tip. The shift applied to make this fit has been applied to all isochrones. This uses the assumption that the determined age of the dominant RGB population is correct.

At [Fe/H] = -1, younger ages trace the AGB much better in this central area of the galaxy. The youngest populations are expected to be here, producing the brightest AGB stars. The galaxy is still dominated by intermediate and old stars, which could explain the sparse RGB branch in this age. When looking at older ages, the AGB branch is expected at fainter magnitudes for this metallicity as well as a stronger RGB branch.

Figure 3.21 shows the isochrones for the old, young and intermediate population as chosen in de Boer et al. (2012b), overlayed on the full Fornax dataset. Both the extreme isochrones lie bluewards of the RGB, while the intermediate population appears to be dominant in the RGB. For this reason, I have looked closer at the regime [Fe/H] = -1. No AGB is expected in the very old population, and further we expect only a very few AGB stars in the extremely young population. Figure 3.22 shows a further age range with this metallicity overplotted as an extension of Figure 3.20. Isochrones with ages ranging from 500 Myr up to 4 Gyr, with a metallicity of [Fe/H] = -1 are overlayed on the full dataset of Fornax. It can be observed that the older isochrones have a good fit with the RGB and that this range of ages entirely envelops the AGB. Few very young stars are expected, which is consistent with these results. Ages of 1 and 2 Gyrs provide especially good fits of the AGB. This suggests that the AGB is overall younger than the average population. It is likely that whilst the average age of the population agrees with what is observed in the AGB, the entire optical age and metallicity range may be more difficult to pick out in the IR AGB observations due to a strong degeneracy in age and metallicity.

In Figure 3.23 the same age range is overplotted onto the Fornax data, using elliptical radii. This confirms the imperfect fit between the optical observations and the IR AGB observations over the different areas in the galaxy. It can be observed that most of the bright AGB stars can be found towards the centre of Fornax, confirming our previous expectations and results.

There is a certain amount of degeneracy involved in isochrone fitting. Different agemetallicity combinations can yield isochrones covering the same position in the CMD. Figure 3.24 overplots different ages on the central area of Fornax using different metallicities. Figure 3.24 (a) shows us the same age range as Figure 3.23 but using a metallicity of [Fe/H] = -1.5. It can be observed that there is a large mismatch between the RGB and the isochrones. The only isochrone with a reasonable fit on the AGB is the intermediate age of 1 Gyr. Figure 3.24 (b) a higher metallicity of [Fe/H] = -0.8. This higher metallicity sample has a much better match to the RGB and AGB, except for the very youngest ages. This is a viable alternative to fitting the AGB using a metallicity of [Fe/H] = -1. However the lower metallicity appears to yield marginally better results, fitting the youngest ages better.



FIGURE 3.23: Infrared Fornax photometry with isochrones overlaid with [Fe/H] = -1, $[\alpha/{\rm Fe}] = 0.0$ at different elliptical radii. The legend shows the log of the age. 8.7 \approx 500 Myr, 9 = 1 Gyr, 9.2 \approx 1.5 Gyr, 9.4 \approx 2.5 Gyr , 9.6 \approx 4 Gyr. The AGB falls neatly between these isochrones. The isochrones have been shifted so that the dominant RGB population found by de Boer et al 2012 fits the RGB tip. This introduced a shift of -0.28 on the y axis, and one of 0.06 on the x axis.



FIGURE 3.24: Fornax data within $r_{ell}=0.2$ overplotted isochrones of (a) [Fe/H] = -1.5 and (b) [Fe/H] = -0.8 in a range of ages. The same shift in x and y axis introduced as in previous plots.

3.5.2 Draco



FIGURE 3.25: Draco data. Overplotted in grey, an isochrone respresenting the younger population in Draco of 5 Gyr, with [Fe/H] = -1.2. In light blue, the older population with an age of 11 Gyr and [Fe/H] = -2.2. This is the limit of the used isochrones, used to approximate the estimated oldest population of 14 Gyr and [Fe/H] = -2.5. In dark blue, the average/dominant population with an age of 10 Gyr and [Fe/H] = -1.7. Figure (a) shows the whole sample while figure (b) shows only the inner 0.2 degrees of Draco.



FIGURE 3.26: Draco data. The same isochrones as in Figure 3.25 overplotted on the optical data and a colour-colour plot, where a cut has been made for the colour-colour plot to only include the stars within an elliptical radius of 0.2 degrees of the core. It can be seen that the isochrones follow the data.

Figures 3.25 and 3.26 show the Draco data overlayed with isochrones representing the oldest, average and youngest ages and appropriate metallicities from Nykytyuk (2012) and SFH from Mateo (1998). It can be observed that the population close to the centre of the galaxy falls within the overplotted isochrones. Comparing with the CMDs of Fornax, comparable foreground populations are assumed, as they are both significantly out of the galactic plane. Draco does have a somewhat stronger foreground since it is slightly closer to the Milky Way midplane. This implies a foreground that is column-like in the J-Ks vs Ks CMD, lies mostly between J-Ks = 0.3 and 0.9, tending stronger towards the red side. This can explain why the strong redder population lies off the

isochrones. It is likely composed of foreground stars and can be ignored for the purpose of this work.

Figure 3.25 shows that the overlayed isochrones appear biased towards the redder side of the RGB and therefore do not encompass the entire population. However, any AGB stars found are likely to lie over the RGB and would be almost impossible to identify without using spectroscopic information.

Because the population farther from the centre is redder and doesn't fall within this isochrone range, using integrated light of an entire galaxy might give very different results. It shifts the average brightness in a filter redwards, so without filtering out the foreground it might be difficult to apply this method at greater distances.

Chapter 4

Conclusion and discussion

4.1 Conclusion and discussion

In Chapter 2 raw observations have been reduced to produce optical photometry for Draco and Ursa Minor dSph. The sub-optimal observing conditions are reflected in the quality of the data. The importance of having a good WCS in order to combine exposures and produce photometry has been demonstrated. The most reliable data has been found to be the central chip (4) of the observations, which covers the centre of each galaxy.

Draco and Ursa Minor dSph, although close to each other in the sky and both very old and relatively metal-poor, are very distinct and unique galaxies. One way this is observed is their morphologically very different HBs and different slopes in the infrared RGBs. Ursa Minor has a strong blue HB, which confirms it is more metal-poor than Draco. These old dSphs are predicted to have few AGB stars and these are likely to be less bright and lie in the same area of the CMD as the RGB, making them impossible to pick out without using spectroscopy.

In Chapter 3 Draco and Fornax have been analysed. Optical and infrared data have been used to pick out the AGB stars and overlay isochrones. AGB stars are very bright, so when we look for nearby AGB stars, only short exposure times are needed. This decreases the required telecope time. At larger distances, AGB stars are possible to detect in contrast to fainter parts of the population and can dominate the integrated light of a galaxy.

When overlaying isochrones on the data, I have assumed that the dominant population as identified in the SFHs is correct and, when needed, shifted the isochrone of this dominant age to match the data. This calibration accounts for the difference between isochrone sets and may influence the accuracy of the results. The difference between the Dartmouth isochrones, as used by de Boer et al., and the Marigo isochrones, which include the TP-AGB, is significant. In March 2016, new PARSEC isochrones including the TP-AGB came out (Rosenfield et al., 2016). For the dominant Fornax RGB population, these are not significantly different, hence I have continued with the Marigo isochrones.

Draco has several carbon (AGB) stars (Faria et al., 2007), but these lie in the same area of the CMD as the RGB and are not outstandingly bright. Photometrically, these are very difficult to pick out. This makes Fornax a far better subject, with a younger, brighter AGB population that is much more numerous than that of Draco. Looking at the RGB, the isochrones suggested from the rough star formation history presented by Mateo (1998) agree with the data.

Fornax has a far larger AGB population, concentrated towards the centre of the galaxy. It boasts a wide range of ages. de Boer et al. (2012b) found a dominant RGB population of [Fe/H] = -1 and an age of 4 Gyr using photometric and spectroscopic data. The strongest component of this population is found in the central area. An age gradient is found with older populations dominating towards the edge, as demonstrated in Figures 3.8 and 3.23. Focussing on the central area, the lower AGB branch is well fit with an isochrone of [Fe/H] = -1 and age 4 Gyr, whilst the bright AGB are better characterised using an isochrone with an age of 1 Gyr for that metallicity. This means most of the bright AGB stars will fall in the age bracket of 1 to 4 Gyr and have a relatively high metallicity.

I have found that Fornax has a bright AGB population of approximately 150 stars, with an average age of 1 Gyr and [Fe/H] = -1. This agrees reasonably well with deep optical star formation histories (SFHs). In the infrared the same populations are traced as in the optical.

The bright AGB appear to predominantly belong to a younger generation. Tracing only those could lead to an underestimation of the age of the system.

In conclusion, the isochrone ages I find for the AGB and RGB populations in these nearby dwarfs are consistent with the SFHs from deep optical MSTO photometry. The optical and infrared data are in agreement.

4.2 Outlook

Spectroscopic investigations of luminous AGB are suggested for future work. In order to better investigate Draco, a more accurate SFH should be determined. Further analysis of the difference between isochrone sets and how they model the AGB phase could also improve results.

More research could also be done in investigating the exact numbers of AGB stars in each galaxy. This could help better constrain star formation histories and allow targeted spectroscopic study of individual stars. The new PARSEC isochrones appear more accurate than Marigo 2008 in predicting AGB numbers as demonstrated in Figure 7 of Rosenfield et al. (2016). This is an area largely unexplored in this work but may prove worthwhile.

Understanding AGB stars is far from trivial. As active stars, pulsating, losing mass, experiencing dredge-ups that change the chemical composition of the outer layers we measure, they are very challenging. Their advantage is that they are not only bright, which decreases telescope time, but the redder AGB stars are clearly separated from other parts of the CMD in the near infrared, whilst other phases are almost superimposed on each other. A better understanding of the processes in the AGB phase and the

corresponding photometric and spectrographic properties can provide a very useful tool to study galaxies at varying distances.

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The future is bright as an AGB star.



Tables

Appendix A provides an overview of the data tables.

| Object | RA | Dec | UT | Airm | Texp | Filter | Background | FWHM |
|---------|-------------|-------------|-------|-------|-------|--------|------------|----------|
| | (J2000) | (J2000) | | | (sec) | | | (direct) |
| 101-324 | 9:55:57.40 | -00:23:27.9 | 20:47 | 1.151 | 30 | V | 150 | 4.23 |
| 101-324 | 9:55:57.40 | -00:23:27.9 | 20:49 | 1.149 | 30 | В | 65 | 4.5 |
| 104-334 | 12:42:20.49 | -00:40:29.0 | 21:03 | 1.567 | 30 | V | 140 | 4.82 |
| 104-334 | 12:42:20.50 | -00:40:28.9 | 21:06 | 1.550 | 30 | В | 37 | 4.86 |
| 104-334 | 12:42:20.50 | -00:40:28.9 | 00:27 | 1.161 | 30 | В | 40 | 3.30 |
| 104-334 | 12:42:20.49 | -00:40:28.9 | 00:30 | 1.163 | 30 | V | 155 | 3.18 |
| 110-365 | 18:42:58.33 | +00:07:39.8 | 05:11 | 1.159 | 30 | В | 370 | 3.25 |
| 110-365 | 18:42:58.39 | +00:07:34.1 | 05:18 | 1.153 | 30 | V | 530 | 2.76 |

TABLE A.1: Details for the individual exposures of the standard fields. Due to saturation, different stars have been chosen between bands and exposure length where necessary to determine a comparable FWHM.

| r | | - | | | | - | | | | | 1 | | | r | , | | | | | | · · · · · | _ |
|-----------------------|-------|-------------|---------------|-------------|-------------|---------------|---------------|--------------|-------------|-------------|---------------|-----------|------|---------------|-------------|-------------|--------------|---------------|----------------|----------------|----------------|---|
| V_error | mag | 0.001 | -9.99 | -9.99 | 0.001 | -9.99 | 0.001 | -9.99 | 0.001 | -9.99 | 0.003 | 0.002 | | -9.99 | -9.99 | 0.001 | 0.001 | 0.153 | -9.99 | 0.002 | 0.001 | |
| Λ | mag | 17.755 | -9.99 | -9.99 | 16.923 | -9.99 | 18.017 | -9.99 | 16.794 | -9.99 | 19.637 | 18.89 | | -9.99 | -9.99 | 17.161 | 17.24 | 24.054 | -9.99 | 18.657 | 16.284 | |
| B_error | mag | 0.002 | 0.001 | 0.001 | 0.001 | -9.99 | 0.002 | 0.001 | 0.001 | 0.001 | 0.004 | 0.003 | | -9.99 | -9.99 | 0.001 | 0.002 | 0.001 | -9.99 | 0.002 | 0.001 | |
| в | mag | 18.978 | 17.206 | 16.529 | 18.082 | -9.99 | 18.846 | 17.774 | 17.487 | 17.618 | 20.444 | 19.596 | | -9.99 | -9.99 | 17.95 | 18.718 | 17.13 | -9.99 | 19.358 | 17.064 | |
| e_B-V | mag | 0.0438 | 0.0014 | 0.0047 | 0.0103 | 0.0009 | 0.0094 | 0.0057 | 0.0038 | 0.0078 | 0.034 | 0 | | 0.0018 | 0.0024 | 0.016 | 0.0199 | 0.0014 | 0.001 | 0.0389 | 0.0099 | |
| e_V | mag | 0.024 | 0.0085 | 0.0023 | 0.0048 | 0.0015 | 0.0078 | 0.0032 | 0.0038 | 0.004 | 0.031 | 0 | | 0.0037 | 0.0027 | 0.0045 | 0.0078 | 0 | 0.0095 | 0.0248 | 0.0014 | |
| B-V | mag | 1.200 | 0.546 | 0.983 | 1.052 | 1.161 | 0.729 | 1.155 | 0.577 | 0.996 | 0.757 | 0.602 | | 1.153 | 0.493 | 0.784 | 1.531 | 0.554 | 0.622 | 0.630 | 0.512 | |
| Λ | mag | 14.79 | 13.65 | 12.58 | 13.82 | 9.74 | 14.92 | 13.44 | 13.72 | 13.46 | 16.50 | 15.77 | | 11.25 | 11.55 | 14.30 | 14.38 | 13.71 | 11.67 | 15.60 | 13.48 | |
| DEC2000 | d:m:s | -00 12 28 | $-00\ 13\ 50$ | -00 11 44 | -00 22 19 | $-00\ 23\ 02$ | $-00\ 26\ 56$ | -00 25 37 | -00 27 07 | -00 18 09 | $-00\ 21\ 25$ | -00 18 36 | | $-00\ 27\ 16$ | -00 18 20 | -00 29 36 | -00 31 43 | $-00\ 35\ 31$ | -00 33 12 | -00 31 18 | -00 32 32 | |
| RA2000 | h:m:s | 095609 | $09\ 56\ 10$ | 095615 | 09 55 34 | 095558 | 095609 | $09\ 56\ 10$ | 095622 | 09 55 42 | $09\ 55\ 30$ | 095536 | | 095451 | 095453 | 095608 | $09\ 56\ 19$ | 095627 | $12 \ 42 \ 21$ | $12 \ 41 \ 36$ | $12 \ 42 \ 20$ | |
| Star | | $101 \ 408$ | $101 \ 410$ | $101 \ 413$ | $101 \ 320$ | $101 \ 324$ | $101 \ 326$ | $101 \ 327$ | $101 \ 330$ | $101 \ 404$ | 101 L1 | 101 L2 | | $101 \ 315$ | $101 \ 316$ | $101 \ 262$ | $101 \ 268$ | $101 \ 270$ | $104\ 335$ | $104\ 423$ | $104 \ 444$ | |



| 8 0.002 67 0.002 61 0.001 8 0.001 8 0.002 8 0.002 80 0.002 | 7 0.002 61 0.001 8 0.001 66 0.002 89 0.002 | 1 0.001 8 0.001 66 0.002 89 0.002 | 8 0.001 66 0.002 89 0.002 | 6 0.002 89 0.002 | <u>89</u> 0.002 | | 9 0.002 | 27 0.002 | 0.001 | 0 | 96-99 | 0.002 | 4 0.106 | 600.002 | 900.002 | 0.001 | 32 0.001 | 0.003 | 0.002 | 35 0.003 | 0.002 | 0.001 |
|--|--|---|---------------------------------|---------------------|-----------------|----------------|----------------|------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|--------------|----------------|----------------|
| 18.83 | | 18.48 | 16.66 | 17.56 | 19.25 | 18.63 | 19.1 | 18.32 | 16.90 | 0 | -9.96 | 19.10 | 23.71 | 19.28 | 18.93 | 17.10 | 18.03 | 19.70 | 19.05 | 19.63 | 18.32 | 16.90 |
| | 0.003 | 0.002 | 0.001 | 0.001 | 0.003 | 0.003 | 0.003 | 0.003 | 0.001 | 0 | 0.0 | 0.003 | 0.001 | 0.003 | 0.002 | 0.001 | 0.002 | 0.003 | 0.003 | 0.003 | 0.003 | 0.001 |
| SWITT | 19.656 | 19.274 | 17.341 | 18.544 | 19.976 | 19.606 | 19.908 | 19.413 | 18.308 | 0 | 16.064 | 19.54 | 17.252 | 19.85 | 19.47 | 17.533 | 18.739 | 20.169 | 19.807 | 20.088 | 19.413 | 18.308 |
| mag | 0.0431 | 0.0276 | 0.0031 | 0.0072 | 0.0219 | 0 | 0.0265 | 0 | 0.0087 | 0.003 | 0.001 | 0.0389 | 0.0099 | 0.0431 | 0.0276 | 0.0031 | 0.0072 | 0.0219 | 0 | 0.0265 | 0 | 0.0087 |
| mag | 0.0163 | 0.0103 | 0.0047 | 0.0067 | 0.0078 | 0 | 0.019 | 0 | 0.0061 | 0.0067 | 0.0095 | 0.0248 | 0.0014 | 0.0163 | 0.0103 | 0.0047 | 0.0067 | 0.0078 | 0 | 0.019 | 0 | 0.0061 |
| mag | 0.694 | 0.594 | 0.518 | 0.830 | 0.591 | 0.832 | 0.650 | 1.088 | 1.356 | 1.592 | 0.622 | 0.630 | 0.512 | 0.694 | 0.594 | 0.518 | 0.830 | 0.591 | 0.832 | 0.650 | 1.088 | 1.356 |
| mag | 15.58 | 15.30 | 13.48 | 14.40 | 16.06 | 15.46 | 16.05 | 15.40 | 13.94 | 9.37 | 11.67 | 15.60 | 13.48 | 15.58 | 15.30 | 13.48 | 14.40 | 16.06 | 15.46 | 16.05 | 15.40 | 13.94 |
| | -00 41 39 | -00 40 43 | -00 40 31 | $-00\ 40\ 02$ | -00 38 36 | -00 41 43 | $-00\ 35\ 16$ | -00 51 21 | $-00\ 46\ 36$ | -00 37 15 | -00 33 12 | -00 31 18 | -00 32 32 | -00 41 39 | -00 40 43 | -00 40 31 | $-00\ 40\ 02$ | -00 38 36 | -00 41 43 | -00 35 16 | -00 51 21 | $-00\ 46\ 36$ |
| h:m:s | 12 42 03 | 12 42 12 | $12 \ 42 \ 21$ | $12 \ 42 \ 25$ | $12 \ 42 \ 31$ | $12 \ 42 \ 34$ | $12 \ 42 \ 19$ | 12 42 17 | $12 \ 42 \ 23$ | $12 \ 41 \ 04$ | $12 \ 42 \ 21$ | $12 \ 41 \ 36$ | $12 \ 42 \ 20$ | $12 \ 42 \ 03$ | $12 \ 42 \ 12$ | $12 \ 42 \ 21$ | $12 \ 42 \ 25$ | $12 \ 42 \ 31$ | $12 \ 42 \ 34$ | $12\ 42\ 19$ | $12 \ 42 \ 17$ | $12 \ 42 \ 23$ |
| | $104 \ 325$ | $104 \ 330$ | $104 \ 334$ | $104\ 336$ | $104\ 338$ | $104\ 339$ | 104 L2 | $104\ 237$ | $104\ 239$ | $104 \ 306$ | $104\ 335$ | $104\ 423$ | $104 \ 444$ | $104 \ 325$ | $104\;330$ | $104 \ 334$ | $104\ 336$ | $104\ 338$ | $104\ 339$ | 104 L2 | $104\ 237$ | $104\ 239$ |

TABLE A.3: Continuation of table A.2. The first 7 columns are taken from Landolt Landolt (1992), the last 5 columns are INT data.

| | | | 1 | 1 | | | | | | | | | 1 | | | 1 | | |
|-----------------------|-------|---------------|-----------------|---|--------------|-----------------|------------|--------------|---------------|---------------|---------------|---------------|---------------|---------------|------------|---------------|------------|-----------------|
| V_error | mag | 0.002 | 0.179 | | -9.99 | 0.001 | -9.99 | 0.001 | -9.99 | 0.002 | 0.065 | -9.99 | 0.003 | -9.99 | -9.99 | -9.99 | 0.001 | 0.002 |
| Λ | mag | 18.56 | 23.638 | | -9.99 | 18.067 | -9.99 | 17.728 | -9.99 | 18.697 | 22.698 | -9.99 | 19.181 | -9.99 | -9.99 | -9.99 | 17.859 | 19.146 |
| B_error | mag | 0.001 | 0.078 | | -9.99 | 0.003 | -9.99 | 0.002 | -9.99 | 0.006 | 0.001 | 0.002 | 0.01 | -9.99 | -9.99 | -9.99 | -9.99 | 0.001 |
| В | mag | 17.348 | 22.61 | | -9.99 | 19.381 | -9.99 | 19.13 | -9.99 | 20.295 | 18.032 | 18.922 | 20.937 | -9.99 | -9.99 | -9.99 | -9.99 | 17.963 |
| e_B-V | mag | 0 | 0.0015 | | 0.0028 | 0 | 0.003 | 0.0192 | 0.0022 | 0 | 0.0067 | 0.0091 | 0 | 0.0144 | 0.0006 | 0 | 0 | 0 |
| e_V | mag | 0 | 0.0015 | | 0.0014 | 0 | 0.0028 | 0.0094 | 0.0022 | 0 | 0.0021 | 0.0027 | 0 | 0.0034 | 0.0029 | 0 | 0 | 0 |
| B-V | mag | 1.039 | 0.555 | | 0.889 | 1.088 | 1.023 | 1.197 | 0.632 | 1.333 | 1.133 | 2.261 | 1.752 | 2.151 | 0.708 | 0.586 | 0.988 | 0.999 |
| Λ | mag | 14.43 | 11.12 | | 12.02 | 15.10 | 11.94 | 14.62 | 12.43 | 15.69 | 13.62 | 13.47 | 16.25 | 13.00 | 11.90 | 12.71 | 13.61 | 14.76 |
| DEC2000 | d:m:s | $+00\ 14\ 39$ | $+00 \ 19 \ 18$ | | +00 04 44 | $+00 \ 09 \ 52$ | +00 08 02 | +00 08 48 | $+00\ 07\ 42$ | $+00\ 06\ 04$ | $+00\ 07\ 32$ | $+00\ 06\ 58$ | $+00\ 06\ 48$ | $-00\ 04\ 02$ | -00 01 37 | $+00\ 04\ 58$ | +00 08 04 | $+00 \ 09 \ 37$ |
| RA2000 | h:m:s | $18\ 42\ 36$ | 18 43 34 | | $18\ 42\ 50$ | 18 42 13 | 18 42 19 | $18\ 42\ 40$ | 18 42 45 | 18 42 48 | $18\ 42\ 52$ | 18 42 57 | $18\ 42\ 50$ | 18 43 07 | 18 43 22 | 18 41 51 | 18 41 27 | 18 41 55 |
| Star | | $110 \ 358$ | 110 441 | | $110\ 266$ | 110 349 | $110\ 355$ | $110\ 360$ | $110 \ 361$ | 110 362 | 110 364 | 110 365 | 110 L1 | $110\ 280$ | $110\ 290$ | $110\ 246$ | $110\ 339$ | $110 \ 346$ |

TABLE A.4: Continuation of table A.2. The first 7 columns are taken from Landolt Landolt (1992), the last 5 columns are INT data.

| Landolt field | Airmass |
|---------------|---------|
| | |
| $101 \ 324$ | 1.151 |
| $101 \ 324$ | 1.149 |
| $104 \ 334$ | 1.567 |
| $104 \ 334$ | 1.550 |
| $104 \ 334$ | 1.161 |
| 104 334 | 1.163 |
| $110 \ 365$ | 1.159 |
| $110 \ 365$ | 1.153 |
| | |

TABLE A.5: Observed landolt field and the airmasses during the observations.

Appendix B

Photometric calibration using Landolt standard fields

The calibration of the photometry could done using Landolt standard star fields Landolt (1992). Details of the observations can be found in Appendix A.

Landolt uses 7" apertures (radius) for his photometry, which corresponds to 21 pixels on our detectors. The used apertures for photometry, 10 pixels, are significantly smaller due to the crowded fields of the galaxies. The standard fields corrections are thus at the same time aperture corrections. This method is chosen to ensure uniform photometry. Table A.2, A.3 and A.4 contain the details for all standard fields, separated by chip and in order of observation. The corresponding airmasses are found in table A.5. Field 104 has been observed twice, the airmasses are, again, in order of observation.

A correction from machine magnitudes to relative magnitudes can be done with standard stars as observed by Landolt, via the following fit:

$$V_i = v_{ik} + a_1(B - V)_i + a_2X_k + a_0$$
(B.1)

$$B_i = b_{ij} + c_1(B - V)_i + c_2X_j + c_0 \tag{B.2}$$

Here, capital letters B and V denote the magnitudes found by Landolt, while small b and v are the observed values. X_j and X_k are the airmasses of the observations. A fit is done for the constants a_x and c_x respectively. This is done via the matrix equations of the shape $V_i - v_{ik} = a_1(B - V)_i + a_2X_k + a_0$, translating to [V] = [a][X]. For the V-band the found constants are $a_0 = -4.57$, $a_1 = -0.28$ and $a_2 = 1.01$.

In figure B.1 we see the best fit for the observed stars, compared to the photometry done by Landolt. It can be observed here that the conditions on the night were not photometric. For this reason, calibration of the data has been done using Stetson only.



FIGURE B.1: Calibration for the V-band using Landolt standard fields Landolt (1992).

| | | |
|---------------|---|------|
| l Appendix | Ŀ | |

Magniture Error Plots Draco and Ursa Minor



FIGURE C.1: Final calibrated magnitude-error plot for the short INT exposures of Draco. B-band can be seen on the left, V-band on the right.



FIGURE C.2: Final calibrated magnitude-error plot for the short INT exposures of Ursa Minor. B-band can be seen on the left, V-band on the right.

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