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Shining Light on the Invisible: The Faint Structures Around Galaxies in the Local Volume

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Stellar halos are faint spherical envelopes of galaxies which contain about 1−10% of the total stellar mass in the galaxy. While they are difficult to observe due to their sparse nature, they contain important clues of the galaxy’s past. As small galaxies get pulled inwards by their larger counterparts, they are shredded by the gravitational forces and deposit their stars in the forms of features such as streams or shells, depending on their trajectory of entry. Over billions of years, a galaxy undergoes numerous collisions with other small galaxies, thus building up its mass and leaving visible evidence in its outskirts.

Every stellar halo is unique – while one galaxy may have a small, uniform or even barely existent stellar halo, another may have a vast amount of starlight deposited in its stellar halo, sometimes even distinct features visible with each representing collisions with different galaxies.

The remnant stars deposited in the stellar halo from minor galaxy mergers and accretions are usually about 10 billion years old, which is why the study of stellar halos is often referred to as galactic archaeology. Currently, the best method to study stellar halos of nearby galaxies is through resolved stellar populations. This means that each star is observed as a single point. To observe the stellar halos in this way, one must either use wide-field ground-based telescopes to capture the full view of stellar halos around the nearest galaxies, or use small-field space telescopes to avoid distortions from observing through the atmosphere. Both methods have their pros and cons, and therefore both should be used in tandem to analyse the stellar halos.

As the mechanism behind galaxy formation is still not fully known, stellar halos hold the key to understanding the galaxy assembly. In this thesis, I present my analysis of stellar halos and galaxy outskirts to provide further insight into galaxy formation.
In Chapter 2 I study the stellar halo of the M81 Galaxy which is currently undergoing a strong gravitational interaction with two other nearby galaxies – M82 and NGC 3077. I analyse the resolved stars in the outskirts of M81 and quantify how its stellar halo varies in both star density and heavy element abundance in stars across the sky. My new analysis suggests a bigger and less chemically–enriched halo than previous work. In Chapter 3 I present a discovery of a tidal tail of stars emanating from a small galaxy F8D1 which lies ~20 thousand lightyears away from M81. F8D1 is likely being disrupted by M81 and has already lost at least 36% of its original mass. In Chapter 4 I present a search for tightly–packed clusters of stars (globular clusters) in the stellar halo of the NGC 1052 galaxy. I found 643 candidates and analysed their properties such as their distribution on the sky, brightness and colour. In Chapter 5 I summarise my conclusions of the aforementioned projects and briefly present ideas for potential follow–up work based on the results of this thesis and more general prospects for stellar halo work which are planned in the next decade.
Abstract

The low surface brightness component that envelops every galaxy – the stellar halo – is a crucial tool for galactic archaeology, as it holds the fossil record of past galactic mergers. Thus far, detailed studies of stellar halos have only been done on the nearest galaxies – Milky Way and M31. To broaden our understanding of galaxy assembly, it is necessary to extend this type of resolved star analysis to galaxies beyond the Local Group. However, this poses many challenges, as it requires deep wide-field observations with large telescopes to map individual stars and star clusters over large areas.

In this thesis, I present an analysis of the stellar halos of two high mass ($\sim 10^{11} M_\odot$) galaxies, M81 ($D = 3.63$ Mpc) and NGC 1052 ($D = 19.2$ Mpc), and a smaller ultra-diffuse galaxy F8D1 ($D = 3.67$ Mpc), using state-of-the-art wide-field data from Hyper Suprime-Cam on the 8.2m Subaru telescope and MegaCam on the Canada-France-Hawaii 3.6m telescope (CFHT). I study the stellar halos of these systems out to radii of >60 kpc using red giant branch (RGB) stars and globular clusters (GCs).

The Milky Way analogue, M81, sits at the centre of a small group of galaxies and has two close companions, M82 and NGC 3077 with which it is tidally interacting. In the first chapter, I examine the properties of the M81 stellar halo using RGB star count data from the Subaru telescope. I quantify the shape of the halo and extract star count profiles along several directions. Merging these with a diffuse light profile extracted from deep CFHT $g$-band observations, I construct a composite surface brightness profile that can be traced over 70 kpc. I use a multi-component model to derive the luminosity and mass of the stellar halo and quantify its radial behaviour. I find that the M81 stellar halo profile shows a shallow slope of $-1.6 \pm 0.1$, similar to that of M31 but in contrast to smaller area studies which suggested a steeper fall-off. I also quantify the metal content $[M/H]$ of the halo using the colours of the RGB stars and find evidence for some
asymmetries along different axes, suggesting that the halo may not be well-mixed at the present epoch.

In the second chapter, I present the discovery of a significant ongoing accretion event in the halo of M81. Discovered more than 20 years ago, F8D1 is an ultra-diffuse galaxy that lies 115 kpc in projection to the Southwest of M81. My analysis of the distribution of RGB stars in the surrounding region uncovers a previously unknown giant tidal tail stretching for ≥60 kpc in the direction of NGC2976 and M81. I quantify the structure of the tail across and along its length, and measure its photometric metallicity. I also use deep CFHT data to extract improved measurements for the main body of F8D1. The distance to NGC2976 and the main body of F8D1 is estimated via the tip of the Red Giant Branch method to deduce the 3D distribution of the system. Although closer in projection, NGC2976 was found not to be associated with the stream and was merely projected in the foreground. I found that the tail contains approximately 36% of F8D1’s luminosity, demonstrating that F8D1 is being severely disrupted, likely by M81.

In contrast to the M81 analyses which focus on RGB stars, the stellar halo of NGC1052 has been studied via its population of GCs in the third chapter of this thesis. Using $ugi$-band data taken under excellent seeing conditions, I search for new candidate GCs using their photometric and morphological properties. The search criteria are devised by using the properties of a sample of spectroscopically-confirmed GCs in the halo of NGC1052 and its neighbouring dwarf galaxies. I identify 643 GC candidates using their location in colour-colour space and characterise their spatial distribution, luminosity function and colour distribution. I show that GC candidates in the NGC1052 stellar halo follow a smooth and shallow radial power law $\gamma = -2.24\pm0.21$ out to $\sim120$ kpc. In the inner stellar halo, the GCs show a striking correlation with faint tidal debris features associated with the ongoing merger between NGC1052 and NGC1047. No significant red/blue bimodality was found in the NGC1052 stellar halo. The GC populations of dark matter deficient ultra-diffuse galaxies NGC1052–DF2 and –DF4 have distinct properties compared to those of the NGC1052 halo and hence are unlikely to be associated.
Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Parts of this work have been published in [Zemaitis et al.] (2023).

(Rokas Žemaitis, May 2023)
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This thesis is dedicated to my future grandchildren. I wrote this thesis with the title page of my late grandfather Feliksas’s thesis on Thermoengineering hanging on the wall right above my screen. I hope you will hang my PhD thesis title page on your wall whilst pursuing the title of Doctor and research something even more elaborate than Thermoengineering or Extragalactic Archaeology.
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Chapter 1

Introduction

1.1 Background

Stellar halos are faint envelopes of galaxies that contain around 1−10% of galaxy’s stellar mass. They consist of a smooth component, tidal streams, globular clusters (hereafter GCs), dwarf galaxies and other substructures. It is well established that the stellar halo grows a significant part of its mass via accretion and minor mergers (e.g., Johnston et al. 1996, Bullock et al. 2001). The satellites such as dwarf galaxies or GCs get stripped of their content over time due to tidal forces, which produce tidal streams. The sparse streams get dispersed when they get close to other substructures or the pericenter of their orbit around the host until they become a part of the smooth halo component (e.g., Newberg 2016, Helmi 2020).

While it is generally accepted that galaxies are embedded in significantly larger Dark Matter (DM) halos (e.g., Navarro et al. 1996), it is not possible to observe them directly. This requires an indirect method to trace the DM. For example, the stellar streams of both GCs or infalling galaxies place direct constraints on the shape of the DM halo (e.g., Johnston 1998, Helmi & White 1999) which can then be used in simulations to recreate the formation of the galaxy (e.g., Prada et al. 2019). By measuring the shape, spatial distribution and kinematic properties of stellar streams, constraints can be made on the stellar halo circular velocity and DM halo shape (e.g. flattening) as well as mass (e.g. Bovy et al. 2016, Malhan & Ibata 2019). Moreover, DM subhalos could also be tracked with
dwarf satellites that are in the process of accretion by analysing their phase–space properties (e.g., Price-Whelan & Bonaca 2018).

Due to their faint and diffuse nature, stellar halos are difficult to observe at large distances. The most precise way to study stellar halos is using resolved stellar populations, which allows us to probe the spatial distribution of stars and investigate their properties. However, such studies are currently limited to the nearest galaxies only. On the other hand, larger samples of stellar halos can be studied using diffuse light, but these studies cannot reach the same surface brightness depths and suffer degeneracies in ages and metallicities of the populations.

One of the first galaxy formation models explaining the history of the Milky Way, and in particular the properties of its stellar halo, was proposed by Eggen et al. (1962). The authors claimed that the stellar halo was formed at the early period of the galaxy formation from a rapid monolithic collapse of gas that gave birth to the protogalaxy. Meanwhile, the rest of the galaxy dissipated to a disc shape, cooled down and started forming stellar disc populations. The outer part of the halo should therefore have metal–poor stellar populations, while the inner regions should contain stars richer in metals due to gas being reprocessed during the collapse onto a disc. The theory that the whole galaxy was formed in–situ seemed plausible at the time, and it meant that the stellar halo could simply be modeled as a power–law – an extension to the galactic disc.

After a decade, a different theory of stellar halo formation emerged. New results from observations indicated that while there was no radial gradient in chemical abundance in both GCs and horizontal branch stars, there was a radial colour gradient along the Galactocentric radius (Searle & Zinn 1978). The evident radial change in colour was therefore interpreted to have emerged due to differences in age. It was suggested that the gas fell into the galaxy continuously, even after the central part has collapsed into a disc. The pristine infalling gas dissipated its kinetic energy in the halo and formed high density regions which in turn formed the star clusters and dwarf galaxies. Through cosmic time, the gas was deposited to the inner regions of galaxies due to chemical evolution, while the substructures and GCs from protogalactic fragments remained in the regions of outer stellar halos and underwent stochastic dispersion. This proposed theory changed the picture of the smooth stellar halo and it was the start of the hierarchical merger theory of galaxy formation, which was later evolved beyond the baryon-only understanding of the Universe.
Modern theories of stellar halo formation are presented within the current cosmological framework, which is the Lambda (Λ) cold dark matter model, or ΛCDM (Navarro et al., 1996). ΛCDM is a cosmological model that is the currently accepted model of the Universe (e.g., Planck Collaboration et al., 2020). The Λ stands for the cosmological constant that describes the accelerating expansion of the Universe, with vacuum (dark) energy being the driver of the acceleration. Its density stays constant through the expansion. The cold description of the dark matter means that it moves at non-relativistic speeds.

As dark matter is only observed by proxy and has never been detected as an actual particle, there are many proposed candidates for dark matter. The best current contenders for CDM are WIMPs (weakly interactive massive particles) (e.g., Tao, 2020). They have masses of the order of GeV (e.g., Marrodán Undagoitia & Rauch, 2016). On the other hand, there are other DM models proposed. Warm DM (WDM) particles, i.e. particles that moved at relativistic speeds at an early epoch but are now non–relativistic were also proposed. The best known example of a WDM particle is a sterile neutrino (e.g., Peebles, 1982). A sterile neutrino decouples from the primordial plasma at early universe times and slows down to non-relativistic speeds through cosmic time. At large scales, the CDM and WDM models behave the same, thus requiring to test smaller scales such as the Local Group (e.g., Lovell et al., 2014). WDM is predicted to have far lower particle masses than CDM, at a factor of ∼keV (e.g., Viel et al., 2013; Lovell et al., 2014; Kennedy et al., 2014).

The existence of dark matter is evident at a wide range of cosmic scales. Photometric observations of the light in galaxies combined with either measurements of rotation or velocity dispersion do not agree in estimated mass if only baryonic matter is assumed. The discrepancy between the two methods yields the “mass–to–light ratio”. The observed values of this ratio are well-explained by the existence of dark matter halos encompassing the galaxies, as photometric measurements only measure the mass coming from baryonic sources – stars and gas. The ratio tends to be higher for low surface brightness galaxies and dwarfs – their mass is more dominated by the dark matter (e.g., Mateo, 1998).

While a spherical dark matter halo shape is well described by the velocities in the outer regions of the galaxy for both high and low–surface brightness galaxies (e.g., Salucci & Borriello, 2003), the shape of the DM density profile closer to the galaxy centre is still unclear. ΛCDM simulations suggest a cuspy dark matter profile (e.g., Navarro et al., 1996; Reed et al., 2005) that is steeper than the one found in
observations – a flat, cored profile (e.g., Gentile et al., 2004). This is regarded as the “core–cusp problem”. One solution to this discrepancy comes from considering the baryonic processes such as supernova feedback, which would flatten the cuspy DM profile in the inner regions (e.g., Macciò et al., 2012). This still poses an expectation that low-mass galaxies with a quiet star formation history should retain a centrally–concentrated cuspy profile given the lack of supernovae. For example, it was found that Draco, a dwarf spheroidal galaxy near the Milky Way, has a cuspy DM profile. This was deduced by measuring the velocities of stars that belong to the system (e.g. Read et al., 2018; Massari et al., 2020). By finding more examples of cuspy DM halos in the low-mass regime, the inconsistency between the simulations and observations will be further diminished.

Additional evidence for existence of dark matter comes from gravitational lensing. Light coming from background objects travelling by massive galaxies experiences gravitational lensing, thus distorting the image of the background object, at times producing multiple distorted arc–shaped images of it in the case of strong lensing. The estimated magnitude of distortion can be used to measure the mass profile of the galaxy. Observations show that a baryon+ΛCDM mass model fits the observational results well in both strong and weak lensing regimes (e.g., Koopmans & Treu, 2003; Hoekstra et al., 2004; Abbott et al., 2022). Such tests on the nature of dark matter can be expanded to larger scales, such as galaxy clusters (e.g., Jauzac et al., 2018) and smaller scales, i.e. looking at the dark matter halo substructure (e.g., Moustakas & Metcalf, 2003).

According to the ΛCDM model for structure formation, galaxies form hierarchically, i.e. smaller proto-galaxy systems collide, thus creating larger entities which continue on merging though cosmic time, building up mass. In the context of the stellar halo, dwarf galaxies merge with a massive host galaxy, and during the course of this they are tidally disrupted and deposit their stellar constituents in its outer regions. Small galaxies are the building blocks of the host’s stellar halo and can leave substructure in the form of tidal streams. On the other hand, the smooth halo component is still expected to hold a significant fraction of stellar mass (e.g., Zolotov et al., 2009; Font et al., 2011).

The dynamical timescales required to disperse the substructures are long – the features stay coherent for billions of years. Thus, they preserve the fossil record on what they were in the past. Moreover, by studying many tidal remnants around the galaxy, the history of its assembly can be revealed. Simulations predict that most of the tidal stripping events are significantly below the surface brightness
level of 25 mag arcsec\(^{-2}\) (Johnston et al., 2008). Nevertheless, surveys have managed to observe and capture the underlying characteristics of stellar halos around the Milky Way and beyond for the past two decades.

When a dwarf galaxy enters the vicinity of the larger galaxy with high eccentricity, the resultant tidal stream ends up being largely dispersed after the galaxy crosses the pericentre. Tidal streams may also become increasingly dispersed over time until it is impossible to spatially distinguish the structure from the background. This effect is known as phase mixing. However, it is still possible to recover the hidden structures in the seemingly smooth halo. By looking at the velocity space rather than the position space, one can detect them as distinct kinematic overdensities, owing to the fact that it takes significantly longer for velocity coherence to dissipate.

1.2 Observational Techniques

In this section, I will review the observational methods that are used in the analysis of the stellar halos of the Milky Way and other galaxies outside the Milky Way domain.

1.2.1 Resolved Star Analyses

Currently, the most potential method for observing stellar halos is the resolved stellar population technique. By observing a galaxy through at least two bands of different colours, each individual resolved star is assigned a brightness value in each band and a colour which is the brightness difference between the bands. This forms the colour–magnitude diagram (CMD), which is the photometric equivalent of a Hertzsprung–Russell diagram. The CMD is a powerful tool as it allows one to separate out stars at different stages of evolution, ages and metallicities. This is especially useful if different types of stars trace different parts of a galaxy. A synthetic CMD containing stars in various stages of evolution is shown in Figure 1.1. The different ages and metallicities affect the locations of the stars in the CMD.

The close distance to the Milky Way stellar halo makes it more accessible for observations compared to its distant counterparts. However, because we are
Figure 1.1: Synthetic colour–magnitude diagram (CMD) of a 13 Gyr old system with constant star formation rate and linear metallicity (Z) increase from 0.0001 to 0.02. Distinctive evolutionary stages are marked. Figure taken from (Aparicio & Gallart, 2004).

observing from the inside of the galaxy, the disc obscures a significant portion of the sky, meaning that the full view of the halo is unfeasible. Additionally, galactic cirrus covers a significant amount of the sky as well, causing extinction and obscured regions of the halo. Galactic cirrus surrounds the Milky Way and is composed of dust, thus partially or completely blocking the view beyond the galaxy in some directions.

The stellar halos outside the Milky Way are at a further distance, leaving some techniques used for Milky Way analysis unavailable with our current observational capabilities. For example, radial velocity determination of individual stars is unachievable in most cases due to faintness of the stars. The 3D positions of stars are also often not available, requiring to work with 2D projection maps instead (e.g., Carlin et al., 2016). The main disadvantage of external galaxies is the fact that observations of halo Main Sequence Turnoff (MSTO) stars are not feasible due to distance, thus requiring to use sparser tracers, e.g. Red Giant
Branch (RGB) stars, Asymptotic Giant Branch (AGB) stars, GCs and planetary nebulae.

On the other hand, studying external galaxies’ stellar halos gives a significant advantage – they may be observed radially outwards to a much higher extent, with full azimuthal freedom. The stars lie at essentially the same distance, making it easier to trace the stellar halo. Essentially, one gets a “bird’s eye view” of the galaxy. In contrast, a considerable fraction of the Milky Way’s halo is concealed by the disc. As for external galaxies, the disc may be inclined relative to us, uncovering a larger area of the halo. This allows measurements of radial profiles with azimuthal cuts, such as elliptical “wedges” along the major and minor axes. That way, it is possible to infer what the shape of the smooth halo component is – does it mimic the shape of the disc, or is it spherically symmetric?

Studies of extragalactic stellar halos typically are either wide and shallow, or deep pencil–beam. The wide surveys provide a full panoramic view of the stellar halo at a cost of lower spatial resolution and photometric depth. As a result, star–galaxy separation becomes a challenging task, limiting the ground-based to distances of $\leq 7$ Mpc. On the contrary, the deep space telescope surveys have significantly higher sensitivity, detecting stars at far fainter magnitudes, easily separated from contaminant background galaxies when observed at distances of up to $\leq 10$ Mpc. However, the space telescopes have pencil–beam fields at Local Volume distances ($D < 5 Mpc$) which are considerably smaller, making it difficult to deduce whether the observed stellar densities come from an incident substructure or a smooth halo component. Therefore, both types of resolved stellar population observations have to be done to provide us the full detailed knowledge of the stellar halo.

Even if there is no spectroscopic data available, it is still possible to photometrically estimate the metallicities of resolved stars if appropriate isochrone parameters are used. Some isochrone databases include: PARSEC (Marigo et al., 2017), BaSTI (Percival et al., 2009), MIST (Choi et al., 2016) and Dartmouth (Dotter et al., 2008). When surveys are not sensitive enough to detect old halo populations in the main sequence, brighter RGB stars are observed instead. The assumed age for fitted isochrones usually ranges from 9 to 13 Gyr. While colours of RGB stars depend on both on ages and metallicities, the colours old stellar halo populations are significantly more sensitive to metallicity rather than age (e.g., Ferguson & Mackey, 2016). Therefore, each star in the RGB can be assigned a metallicity by using the best-fitting isochrone. By utilising the Metallicity Distribution Functions (MDF), the peak metallicity of a sample of
stars can be estimated (e.g., An et al., 2013). After performing such analysis over several radial intervals, a metallicity gradient can be estimated. Alternatively, the existence of the metallicity gradient may be determined using the colour gradients. This method does not require the use of an isochrone model, but it is not a physical measurement, thus requiring a follow–up metallicity analysis. Some studies improved the method further by defining a new colour that would be aligned perpendicularly to the RGB colour spread, leading to increased sensitivity of gradient detection (e.g., Monachesi et al., 2016).

Every stellar population of intermediate or old age has distinct features of stellar evolution in the CMD which are universal for all stellar populations, such as the MSTO, the Red Clump (RC), the RGB, etc. By identifying these features, one can use them to determine the distance to stellar populations.

When faint substructures are observed, the matched filter technique can be used to enhance the signal over noise. An observed noisy signal in space or colour-magnitude domain is convolved with a synthetic template that one would expect to see in an ideal case. This technique was originally used for detections of tidal streams, and the first observed stream was coming from the GC Palomar 5 (Rockosi et al., 2002; Odenkirchen et al., 2003). The pioneering matched filter technique version used a minimum variance estimate to derive the number of cluster stars visible. Using a model for estimating the distribution of field stars, the stars in regions of fewer background stars were assigned larger weights than the ones in regions of expected higher contamination. That way, without perfect knowledge of every background object one can still minimise the effect of contaminants. The authors used both spatial and colour-magnitude domains for a 4–dimensional fit, thus increasing statistical credibility.

Over time, the matched filter technique was modified to tailor for specific surveys. For example, Grillmair (2009) version enabled the use of matching filters without knowing the relative distance from the progenitor to the expected stream in advance. Another study modified it to incorporate Poissonian noise and maximum likelihood estimations (Bate et al., 2015). The matched filter technique may be used for other purposes besides stellar stream searches – it may also be used in detections of dwarf galaxies as described by Martin et al. (2013). Besides that, the authors matched multiple filters to create a multicolour image of the stellar halo weighted by metallicities of the resolved stars.
1.2.2 Diffuse Light Analyses

If stars are too crowded or too faint, they cannot be resolved. In these conditions, it is better to analyse the diffuse light instead. It lets us measure the overall surface brightness instead of looking at individual stars, which is feasible at smaller radii from the centre of a galaxy than the resolved star technique. At larger radii, the background dominates, which limits the extent of diffuse light usage. When modelling the radial halo profile, resolved stellar populations are complemented with integrated light at radii near the disk of the galaxy. The profile from the integrated light is scaled by looking at the results of overlapping regions where the completeness of both techniques is adequate (e.g., Barker et al., 2009). That way, a continuous profile can be recovered for disk+halo modelling.

For galaxies further away where stellar populations cannot be resolved, deep low surface brightness surveys are relied on to uncover the stellar halos. The Dragonfly Nearby Galaxies Survey observed stellar halos of eight spiral galaxies (7 < D < 18 Mpc) (Merritt et al., 2016). The galaxies were observed to depths as low as 31 mag arcsec$^{-2}$ and radial distances as high as 70 kpc from the centre. Interestingly, the authors found that 3 out of 8 galaxies observed do not appear to have a detectable stellar halo in their data. The state–of–the–art wide–field deep optical surveys are the key to analyse galaxies beyond the Local Volume (D > 5 Mpc) through diffuse light.

1.2.3 Modelling Stellar Halos with Simulations

The substructures and streams in halos can also be modelled in N–body galaxy formation simulations without restrictions that emerge from observations. However, stellar halo modelling in simulations is met with similar obstacles as the surveys that observe the stellar halos. The stellar halo is a sparse component of the galaxy, and its substructures are even sparser, leading to difficulties in resolving them. N–body simulations were used to show the evolution of dark matter halos from infalling satellites. Earlier on, the stars were “painted” onto the accreted halos after DM simulations by considering mass–to–light ratios from equivalent observed substructures. It was aimed that the characteristics of late–time infalling objects such as velocity dispersions and radial profiles would match the results from surveys of dwarf galaxies (e.g., Bullock & Johnston, 2005). A simulated galaxy from the Bullock & Johnston (2005) simulations is shown in
Figure 1.2: Stars in a simulated galaxy, figure taken from (Bullock & Johnston, 2005). The stellar streams and shells resultant from mergers can be seen in the stellar halo.
The stellar streams and shells are seen in the outskirts of the stellar halo – these are the remnants of the accreted dwarf galaxies onto the host galaxy.

Nevertheless, as computational power dedicated to simulations increased, so did the resolution of dark matter and stellar particles. The simulations became more physical, allowing more streamlined direct comparisons with results from observations (Johnston et al., 2008). Even though the resultant substructures in the models will not fully match the ones we observe, the physicality of their characteristics can be tested.

The hydrodynamical zoom–in simulations can be used for direct comparisons with observations in multiple ways. For example, Sanderson et al. (2018) analysed Milky Way dark matter halo–mass galaxies in the FIRE–2 suite simulations to compare against the aforementioned deep diffuse light Dragonfly survey (Merritt et al., 2016). The authors emulated diffuse light observations of simulated galaxies and reproduced the reduction steps as done by Merritt et al. (2016). They found that while the stellar halo masses are reproduced consistently when compared to actual observations, the simulated observations underestimate the accreted component by up to a factor of 10. This is due to the fact that a significant fraction of the accreted mass is centrally concentrated and its mass contribution is therefore subtracted along with the disc during the data reduction process.

In addition, simulations can be used to make mock catalogues of stars. The AURIGA suite of magnetohydrodynamical zoom–in simulations of galaxies in Milky Way–sized dark matter halos was utilised to create mock stellar catalogues of Gaia data (Grand et al., 2018). The mock catalogues provide a means to directly test the methods of analysis on a functionally equivalent dataset produced with theoretical predictions. This seamless way of comparison between observations and simulations will likely be implemented more often in the future.

A major strength of simulations is the higher availability of rare types of galaxies as opposed to observations, where there are few massive galaxies nearby for in–depth observations. With this advantage, trends and correlations in various properties of simulated galaxies can emerge more clearly, as statistics of the high–mass end galaxies is better due to higher numbers available. For example, Monachesi et al. (2019) uncovered a correlation between stellar halo mass and metallicity using the AURIGA suite of simulations.

\[^{1}\]The annotated version of the image was taken from [https://caltechletters.org/](https://caltechletters.org/science/stellar-hello)
Simulations can also give insight to origins of mergers and substructures observed. For example, hydrodynamical simulations from the EAGLE suite were compared against Gaia and APOGEE observations to estimate the likely mass and time of accretion given the observed remnants of a major merger in the Milky Way (Mackereth et al., 2019). The Milky Way mergers will be discussed further in the next section. In addition, large volume cosmological hydrodynamical simulations such as Illustris can be utilised to recreate the full accretion and stellar halo assembly histories of actual galaxies through cosmic time (Elias et al., 2018).

Simulations can also provide predictions in domains not yet accessible with observations. Many studies of the Milky Way stellar halo are limited within ~50 kpc from the Galactic centre (e.g., Fernández-Alvar et al., 2015; Naidu et al., 2020). Using FIRE–2 simulations, Yu et al. (2020) predict that the very outer domains of Milky Way stellar halo (50 – 300 kpc) may be populated by in–situ stars at a total population fraction of up to 40%. The in–situ stellar populations would originate through mechanisms of stellar outflows driven by supernovae. This certainty of this prediction depends on our current knowledge of stellar feedback, but it sets expectations for observations once they are capable of testing this hypothesis.

1.3 Key results in the Local Volume

1.3.1 The Milky Way

The Milky Way, being the closest galaxy available for stellar halo studies, has been studied rigorously. The system comprises three main structures: the Milky Way and two nearby satellite galaxies – the Large and Small Magellanic Clouds. In addition, there are numerous dwarf galaxies and GCs orbiting this system (e.g., Koposov et al., 2008; Harris, 2010; McConnachie, 2012).

The knowledge of the Milky Way stellar halo has been considerably expanded by the revolutionary SDSS survey (Jurić et al., 2008), PS1 (Drlica-Wagner et al., 2020), DES (Pieres et al., 2020) and Gaia DR2+EDR3 (Martin et al., 2022a). Figure 1.3 shows the multitude of streams and other substructures in a single image known as the SDSS Field of Streams (Belokurov et al., 2006). Many more

\[2\]The annotated version of the image was taken from https://people.ast.cam.ac.uk/~vasily/sdss/field_of_streams/dr6/
faint dwarf galaxies were found as well \citep{Willman2005}. The SDSS also started a new era of the low surface brightness universe observations by detecting a new class of objects – the ultra faint satellites \citep{Willman2010}. Thanks to the discoveries of the most DM–dominated objects, the number of known satellites in the Milky Way has more than doubled.

The stellar halo of the Milky Way has little to no metallicity gradient in the range of 10–50 kpc from the galactic centre \citep{Carollo2007, Ivezic2008, deJong2010}. However, new findings show that separate kinematic components of the Galactic halo exhibit different behaviours metallicity–wise \citep{Dietz2020}. The retrograde component exhibits no metallicity gradient while the prograde population shows a strong radial metallicity decline. The prograde population has likely come from an early major merger which will be described later in this section (Gaia–Sausage–Enceladus). Moreover, the outer halo appears to have a sudden shift in metallicity at $r > 40$ kpc, going from mean $[Fe/H] \sim -1.6$ to $-2.0$. It may be the transition point from inner halo–dominated populations ($[Fe/H] \sim -1.6$, \citealp{Fernandez-Alvar2015}) to outer halo–dominated populations ($[Fe/H] \sim -2.2$, \citealp{Carollo2010}). On the other hand, this sharp change in metallicity may also be explained by yet another merger in the outer halo (Sequoia), visited later in this section.

The decline of its density profile is governed by a power–law, but it is not clear
how steep the power-law is, with current estimates ranging around $2 < \gamma < 4$ (e.g., Jurić et al., 2008; Bell et al., 2008; Newberg & Yanny, 2005). It is likely that the large differences in estimated radial profiles are due to the smooth halo component being probed with incident overdensities or diffuse substructures, thus introducing unexpected selection bias (Schönrich et al., 2014).

The smooth halo component of the Milky Way appears to be not smooth at all, with a power-law profile breaking at about 27 kpc from the centre (Deason et al., 2011). One of the explanations for this emergent pattern is that a single massive accretion event happened in the past, with the assimilated stars piling up at the apocenters of their orbits (Deason et al., 2018). By examining the 3D velocities (both radial and tangential) of stars in the vicinity, a previously unseen coherent structure was discovered. The progenitor has been dubbed the Gaia-Sausage (Belokurov et al., 2018) or Gaia-Enceladus (Helmi et al., 2018) – a massive ($M_* \sim 10^8-10^9 M_\odot$) galaxy that would have merged with MW 10 Gyr ago. It is suggested that the stellar content that came from this merger dominates the inner Galactic stellar halo.

It is argued that Gaia DR2 has uncovered yet another early accretion event in the outer halo – a progenitor dwarf galaxy Sequoia. The first evidence for this accretion was the FSR 1758, a GC with a highly retrograde orbit and unusually large size ($\sim 10$ pc) (Barbá et al., 2019). It was speculated that the GC was accreted into the halo due to its orbit (Simpson, 2019). Combined with other six GCs (including $\omega$ Centauri) following a similar region as FSR 1758 in dynamical quantity space, as well as other retrograde stellar substructures in energy space, the remains of the Sequoia put it at a lower mass regime than Gaia–Enceladus–Sausage – about $M_* \sim 10^7 M_\odot$ (Myeong et al., 2019). Overall, Myeong et al. (2019) suggest that Gaia–Sausage built the inner halo, while Sequoia built the outer halo. There are counterpoints that a single merger may not have made such outer halo structures alone, and yet another accretion, Thamnos, may have happened along Sequoia (Koppelman et al., 2019). Many more merger events are claimed to have happened according to the motion of GCs and stars, each offering a different grouping of GCs (e.g., Fernández-Trincado et al., 2019; Kruijssen et al., 2020; Naidu et al., 2020). The current state of the Galactic merger history is highly uncertain, and any newly discovered Galactic merger events should be approached with caution. As Gaia data releases more proper motion data, it is expected that a better consensus on the Galactic merger history should be reached (Monty et al., 2020).
So far, most substructures in the stellar halo have been observed within 20–50 kpc. The lack of tidal streams in regions closer to the centre may be explained by an overcrowding of dispersed stellar streams where none of them could be separated, although some streams were found near the Galactic bulge (Bernard et al., 2014) and the general inner regions of the Milky Way (Ibata et al., 2019). For completeness, the collated list of all currently known MW streams is written by Mateu (2022). For detections further out from 50 kpc, it may be that the satellites caught by the Milky Way’s potential have not yet started forming tidal tails due to long orbital periods (Newberg, 2016). It is suggested that the fraction of stars in substructures increases with distance, so we should expect to detect many more of them in the future (Ivezić et al., 2012). The Vera C. Rubin Observatory is expected to uncover a myriad of streams within 50 kpc and push further beyond the limit (Martin et al., 2014).

The LMC and SMC surroundings have a massive dataset from the SMASH survey, which observed out to 50 kpc from the LMC (Nidever et al., 2017). It was found that there are extremely extended anomalous stellar populations at about 50 kpc of distance from the LMC (Nidever et al., 2019). They are likely to be tidally stripped from the LMC itself, but the possibility of them being an overdensity of the disc has not been ruled out either (Mackey et al., 2016). However, low–mass dwarf galaxies recently discovered nearby might also imply active hierarchical accretion occurring at a smaller scale (Drlica-Wagner et al., 2016; Koposov et al., 2015).

1.3.2 M31 - Andromeda

The M31 group is the second group of galaxies closest to us after the Milky Way. Both of these groups are considered to make up the Local Group. The main galaxy of the group – Andromeda (M31) – is a spiral galaxy of similar mass within the order of magnitude (e.g., Carignan et al., 2006; Phelps et al., 2013; Yuan et al., 2022) and morphology (e.g., Sandage & Tammann, 1981) to the Milky Way. Likewise, it has many tidal streams, substructures and dwarf galaxies, hinting at an eventful merger history (e.g., McConnachie et al., 2009). Therefore, it is ideal for testing all hypotheses drawn from the results of the Milky Way’s stellar halo observations. It is at a sufficient proximity ($D \sim 770$ kpc) for effective use of the resolved stellar population techniques (Conn et al., 2016). Because of its fairly edge–on orientation, the halo stars are minimally obscured by its disc.
Figure 1.4: CMD of point sources from the PAndAS survey. The middle selection box encloses the M31 group RGB halo stars. Fiducial tracks of RGB stars with various metallicities ranging from \([\text{Fe/H}] = -1.91\) dex to \([\text{Fe/H}] = -0.2\) dex. Figure taken from Ibata et al. (2014).

Overall, M31 is a key element that bridges local and external knowledge of halos. At present, our knowledge of the outer halo of M31 is far better than the Milky Way’s. The latter suffers from contamination of foreground stars which obscure both the CMDs and spatial maps, making the detection of sparse outer halo populations hardly feasible (Ferguson & Mackey, 2016). The M31 is at galactic latitude low enough to suffer from significant foreground contamination as well. Nevertheless, the M31 halo stars can be separated from Milky Way’s stellar halo and disc populations by examining them in the colour-magnitude domain (see Figure 1.4 taken from Ibata et al. 2014).

Studies of the M31 stellar halo metal content found that it has a clear metallicity gradient present from the inner halo at 10 kpc through to the extended component of up to 160 kpc (Koch et al., 2008), which was later extended to 175 kpc (Gilbert et al., 2014). The wide-field Pan-Andromeda Archaeological Survey (PAndAS) (Ibata et al., 2014) has shown that M31 has a wide variety of streams, clouds and dwarf galaxies. The authors stated that the substructure must be disentangled from the halo first before examining the remaining smooth halo component. They found that a significant metallicity gradient is present when analysing both the
smooth halo component separately and the halo as a whole. The full halo has a steady decrease of metallicity from $[Fe/H] \sim -0.7$ dex at 27.2 kpc down to $[Fe/H] \sim -1.5$ dex at 150 kpc. The smooth halo component shows a similar behaviour, although the metallicities are about 0.2 dex lower at same discrete radii compared to the full halo. As for the radial density profile of the M31 halo, the radial density decline is shallow, with most studies estimating the power–law fit at around $\gamma \sim 2$ (Gilbert et al., 2012; Ibata et al., 2014).

With the discovery of the Giant Stellar Stream (GSS) with the INT survey, it became evident that M31 has an evident active past of hierarchical merging (Ibata et al., 2001; Ferguson et al., 2002). M31 is suspected to have endured an ancient major merger $9 - 10$ Gyr ago (Hammer et al., 2013). This event significantly reshaped the stellar halo and triggered a starburst, while the disc stayed mostly intact. Nevertheless, the merger history of the M31 group has been a matter of debate. Because it had a more violent merger history compared to the Milky Way, it boasts a substantially larger number of visible substructures. Even so, it is not entirely agreed how the system has formed. Some studies suggest that a single major merger was the cause of the most prominent substructures (Hammer et al., 2018), a scenario which is favoured by hydrodynamical simulations (e.g., D’Souza & Bell, 2018). Other studies argue that multiple accretion events had to occur around $3 - 4$ Gyr (McConnachie et al., 2018), a scenario supported by the GC population in the M31 stellar halo (Mackey et al., 2019a). About $35 - 60\%$ of GCs in the stellar halo can be associated with substructure coming from accreted dwarf galaxies at late times. The GC populations suggest two major accretion epochs that have happened in M31 (Mackey et al., 2019b).

The differences between M31 and Milky Way stellar halos show that their formation mechanism may result in a variety of outcomes. To find out what properties would describe an “average” halo, it is important to observe more distant galaxies of similar mass and characterise their stellar halos. This is one of the primary aims of this PhD thesis.

1.4 GCs as Probes of Stellar Halos

As the stellar halo of a host galaxy accumulates stellar mass through both major and minor mergers, it also inherits the GC systems from its stripped counterparts. The GCs residing in the stellar halo provide an excellent method of analysing this
sparse region because the GCs are brighter than individual stars, especially when the galaxy itself is too far away to observe through resolved stellar photometry (e.g., Peng & Lim 2016). Moreover, measurements of velocities of RGB stars are not yet feasible beyond the Local Group while it is not the case for GCs.

Most galaxies with significant GC populations exhibit a distinct bimodality in their colour and/or metallicities (e.g., Zinn 1985; Peng et al. 2006). In the context of the large galaxies such as Milky Way and M31, the blue metal-poor GCs tend to be more sparsely distributed outwards into the stellar halo with no coherent rotation, while the red metal-rich GCs are more spatially concentrated towards the centre and co–rotating with the Milky Way (e.g., Perrett et al. 2002). This does not apply to all galaxies – M31 appears to be unimodal in terms of its colour and metallicity (e.g., Huxor et al. 2014; Mackey et al. 2019a).

It is suggested that for bimodality to occur, two distinct GC origins are required. The blue GCs would form in early galaxies, which would then hierarchically merge with other galaxies through cosmic time which drives the build–up of the blue population. On the other hand, the red population is said to then either form as an aftermath of wet mergers during a starburst phase (Ashman & Zepf 1992), or later on once the disk of the resultant galaxy has settled (Forbes et al. 1997). There are contrasting claims – some advocate that both red and blue populations result from major mergers (Li & Gnedin 2014), though this does not explain the bimodality of the Milky Way GCs, as the Milky Way has not had a recent major merger like the M31 (e.g Belokurov et al. 2018). Others suggest that the blue GCs are accreted, and red GCs are formed in–situ (Côté et al. 1998).

To shed light on the solution to this problem, formation channels of GC populations are tested through simulations. In particular, a zoom–in simulation study by Renaud et al. (2017) attempts to recreate the GCs in a Milky Way–like galaxy that forms a disc and experiences a major merger at z = 2. Indeed, the bimodality is reproduced – the blue clusters were formed and accreted from low mass galaxies, while red clusters came from more massive galaxies accreted at later times, but the majority of them were formed in–situ. It was also found that the in–situ clusters experience significantly stronger tidal disruption than the accreted counterparts, typically 4 times stronger. This is true for both the present day and the average disruption over the lifetime of the GCs. Undoubtedly, this difference is heavily influenced by the fact that the blue GCs reside in farther reaches of the stellar halo, and are accreted at earlier times than their red counterparts, thus resulting in lower tidal disruption over time.
Due to tidal disruption, GCs deposit a fraction of their stars in the stellar halo. The stars in GCs exhibit a specific light element abundance pattern – an increase in N, Na and Al as well as decrease of C, O and Mg (e.g., Piotto et al., 2015). Therefore, stars detected in the stellar halo with such chemical signatures would imply that they may have originated from a disrupted GC. At present, testing of this scenario can only be done in the Milky Way and nearby dwarf galaxies, as stars in external galaxies are too faint for the high resolution spectroscopy required. It was found that 2.6% of stars have the characteristic abundance pattern, suggesting that only 11% of halo stars come from disrupted clusters, accounted for stellar loss due to intrinsic GC evolution, bias and completeness (Koch et al., 2019). This is assuming that the only formation channel for such stars comes from GCs. However, recent E–MOSAICS simulations state that no more than 2–5% of mass in Galactic halo field stars have come from GCs (Reina-Campos et al., 2020).

Going outside of the Milky Way, the stellar halo of M31 also has an abundant assemblage of GCs. In particular, the outer halo (25 < r < 150 kpc) has 92 known GCs (Huxor et al., 2014; Mackey et al., 2019a). As previously mentioned in Section 1.3.2, it was found by Mackey et al. (2019a) that about 35–60% of GCs in the outer halo have been accreted at late times with their host dwarf galaxies. On the other hand, no spatial association was found between the other 40% of GCs and outer halo substructures. The spatial distribution of this population closely follows the density profile of the smooth halo, suggesting that they have been accreted at early times when M31 was growing through major mergers. Figure 1.5 (taken from Mackey et al., 2019b) shows the distribution of M31 GCs associated with substructures (stars) and not associated with any substructures (circles). The two separate groups have their own coherent rotational kinematics, implying that two separate major mergers may have built the stellar halo of M31. At 30–50 kpc in particular, there is an overdensity of GCs which directly follows the behaviour of the metal-poor field halo previously observed by Ibata et al. (2014). These findings suggest that the halo GC populations may have been built entirely through external mergers.

Detections of GC streams in M31 could provide better insight on the underlying dark matter substructure. While it is still impossible to detect any GC streams outside the Milky Way system due to their faintness, it is predicted that the new generation of space telescopes, in particular the Roman Space Telescope will be capable of detecting of GC streams in the M31 system (Pearson et al., 2022).
Figure 1.5: M31 PAndAS survey, figure taken from Mackey et al. (2019b). The gray points show the distribution of metal–poor RGB stars, while GCs are marked with symbols. GCs associated with substructures are shown as stars, while GCs not associated with substructures are shown as circles. Each GC is colour–coded by its spectroscopically measured Andromeda–centric velocity. The dashed circles show projected distances of 25 and 150 kpc from the centre of M31.
Within the Local Volume ($D < 5$ Mpc), simultaneous analysis of both resolved stellar halo populations and GCs is viable, thus providing substantial statistical strength for testing and improving galaxy formation models. Both components of the stellar halo would have to be reproduced to accurately represent the observed galaxies, leading to a more rigorously tested galaxy formation model (e.g., Beasley et al., 2003).

1.5 Ultra Diffuse Galaxies

As well as GCs, stellar halos also host populations of dwarf satellite galaxies. A particularly interesting type of dwarf satellite galaxy are the ultra–diffuse galaxies (UDGs) which are distinguished by their low central surface brightnesses and large sizes. A commonly used, albeit rather arbitrary definition is that they have effective radii $R_{\text{eff}} \geq 1.5$ kpc and central surface brightnesses fainter than $\mu_g(0) \gtrsim 24$ mag arcsec$^{-2}$ (e.g., van Dokkum et al., 2015; Koda et al., 2015). Although systems with these properties have been known to exist for decades (e.g., Sandage & Binggeli, 1984; Caldwell & Bothun, 1987; Impey et al., 1988), there has been a recent resurgence in interest in them due to the sheer abundance of such objects being discovered in modern deep imaging surveys. They appear particularly common in dense environments (e.g., van Dokkum et al., 2015; Koda et al., 2015; Mihos et al., 2015; Janssens et al., 2017; Iodice et al., 2020), but are also found in low density groups and in the field (e.g., Merritt et al., 2016; Román & Trujillo, 2017; Greco et al., 2018; Müller et al., 2018).

Studies of UDGs in the last few years have yielded important new information about the properties of these unusual galaxies. It has been established that many UDGs have round isophotes and radial distributions of starlight that follow an exponentially declining or flatter profile (e.g., Yagi et al., 2016; Cohen et al., 2018; Alabi et al., 2020). Their star formation properties are observed to vary, with systems which ceased to form stars a long time ago dominating in cluster environments while the field contains examples where star formation has continued until recent epochs (e.g., Leisman et al., 2017; Greco et al., 2018; Prole et al., 2019).

Much debate has centered on the dark matter content of UDGs and, again, this seems to be a property with considerable variance. There have been extremely dark matter-dominated UDGs reported as well as systems that appear to have
very little dark matter at all (e.g., Toloba et al., 2018; Lim et al., 2018; Danieli et al., 2019; Forbes et al., 2020). A common way to infer the amount of dark matter in a UDG is to exploit the relationship between the number of GCs in a system and the host halo mass (e.g., Spitler & Forbes, 2009; Harris et al., 2013; Forbes et al., 2018). While this is in principle a simple technique, results can vary considerably depending on how it is applied in practice. For example, while van Dokkum et al. (2017) find the Coma cluster UDG DF44 to have \(\sim 75\) GCs associated with it, Saifollahi et al. (2021) use the same dataset to argue that this number should instead be \(\sim 21\). Other studies support the idea that the GC systems of UDGs are generally consistent with them being dwarf galaxies with normal dark matter content (e.g., Amorisco et al., 2018; Lim et al., 2018).

Several explanations for the origin of UDGs have appeared in the literature. Firstly, they may be rapidly rotating normal dwarf galaxies, resulting in a very extended profile for their stellar mass (Amorisco & Loeb, 2016). Alternately, their large sizes may result from tidal stripping and heating experienced through interactions with massive neighbouring galaxies (Carleton et al., 2019; Doppel et al., 2021) or through formation in tidal debris (Bennet et al., 2018). Other possible scenarios for the origin of UDGs are that they are puffed-up dwarf galaxies that have experienced gas loss due to star formation–driven outflows (Di Cintio et al., 2017; Jiang et al., 2019) or that they are “failed” galaxies that did not manage to build–up their expected stellar mass (van Dokkum et al., 2015). Ram–pressure stripping may play a further role in transforming gas–rich blue UDGs into red ones (e.g., Junais et al., 2021). While it is likely that the present day UDG population results from a variety of these formation channels, the question of which is the dominant channel remains open.

Local universe examples of UDGs are particularly valuable since their proximity allows for much greater insight into their properties compared to more distant systems. Some very low surface brightness extended dwarf galaxies have been uncovered in the nearby universe. Toloba et al. (2016) discuss the NGC 253 satellite Scl-MM–Dw2 which has \(R_{\text{eff}} = 2.9\) kpc, \(\mu_V(0) = 27.7\) mag arcsec\(^{-2}\) and \(M_V = -12\), while Martin et al. (2016) find the M31 satellite And XIX to have \(R_{\text{eff}} = 3.1\) kpc, \(\mu_V(0) = 29.3\) mag arcsec\(^{-2}\) and \(M_V = -10\) mag and Torrealba et al. (2019) find Antlia 2, a Milky Satellite with \(R_{\text{eff}} = 2.92\) kpc, \(\mu_V(r < r_{\text{eff}}) = 31.9\) mag arcsec\(^{-2}\) and \(M_V = -9\) mag. These may be extreme examples of the UDG category but they are not direct analogues of the dominant population of UDGs seen at greater distances.
1.6 Outline of the Thesis

The thesis is structured as follows: in Chapter 2 I present my study of the stellar halo of the M81 galaxy using resolved stellar populations from wide-field Subaru Hyper Suprime-Cam images. In Chapter 3 I continue on with the HSC M81 galaxy survey, presenting a discovery of a > 60 kpc long tidal tail emanating from F8D1, a UDG in the M81 Group. In Chapter 4 I present the results from the NGC 1052 survey done with CFHT MegaCam on the GC search in the NGC 1052 stellar halo. In Chapter 5 I summarise my findings and briefly give future prospects of this work and beyond.
Chapter 2

Project Bubilas: The Stellar Halo of M81

Bubilas is the Baltic god of honey and bees. Beekeepers sacrifice honey to him to have a better honey yield.

2.1 Introduction

The M81 Group is at a distance of 3.6 Mpc (Radburn-Smith et al., 2011). The three main galaxies in this group are M81, M82 and NGC 3077, although there are many more dwarf counterparts discovered in the recent years (e.g., Chiboucas et al., 2013; Smercina et al., 2017; Okamoto et al., 2019). The M81 Group stands out from other nearby galaxy groups due to the fact that the three main galaxies are undergoing a major merger, with the first near pass–by undergone already, resulting in a tidal interaction. This major tidal interaction event is suspected to have happened about 200–300 Myr ago, which is clearly visible in HI gas observations in Figure 2.1 (see also Yun, 1999; de Blok et al., 2018). Due to this recent close encounter, multiple young tidal structures have been distributed around the system (e.g., de Mello et al., 2008; Mouhcine & Ibata, 2009). Some of the most prominent ones are the Arp’s Loop (AL) and Holmberg IX (HoIX). It is suggested that AL and HoIX may actually be newly formed tidal dwarf galaxies (Makarova et al., 2002).

It is not clear how the M81 Group turned out to be in the configuration it is at
the present. The only constraint for reproducing this state in simulations is the tidal debris that dates the close encounter back to $200-300 \text{ Myr}$. According to simulations, this system is highly unlikely to have been in a three-body bound state after deducing that both M82 and NGC 3077 were at a pericentre distance of 30 kpc to M81 within the recent 500 Myr (Oehm et al., 2017). If this was indeed the case, the lifetime of this system until the end of the merger event is about $1.3-1.7 \text{ Gyr}$. On the other hand, a more favourable scenario is that either or both galaxies (M82 and NGC 3077) were initially unbound and came from a far distance, increasing the lifetime of this system to $5.6-7 \text{ Gyr}$. Such simulations require additional constraints to reduce the amount of likely scenarios.

M81 is an analogue to the Milky Way and M31 as it is also a massive spiral galaxy. The stellar halo of M81 was found to be populated by old RGB stars, and it also contains young stellar populations that formed from gas ejected due
Figure 2.2: DSS coloured image of the M81 galaxy (NGC3031) with GHOSTS survey fields overlaid. Figure taken from Monachesi et al. (2016). The green fields were observed in the first part of the survey with the HST/ACS camera (Radburn-Smith et al., 2011), while the yellow fields were observed with either HST/ACS or HST/WFC3 cameras in the second part of the survey (Monachesi et al., 2016).

to the close encounters (Okamoto et al. 2015).

The first wide field resolved stellar population surveys of the M81 stellar halo started emerging at the end of the last decade when Southeast and Northwest regions of the disc and halo were observed (Mouhcine & Ibata 2009; Barker et al. 2009). The former survey used the CFHT/Megacam, and found young Main Sequence (MS) stellar populations closely following the HI filaments extending down to NGC 3077. The authors concluded that these stellar clumps are likely to be of tidal origin. The latter survey presented by Barker et al. (2009) used the Suprime–Cam on the 8m Subaru telescope, observing the northern part around M81 out to projected distances of 30 kpc. The radial profile measurements were fit well by a disk and bulge model (Möllenhoff 2004). The outer part of the profile showed evidence of an extended component, and therefore the profile was also fit by a Hernquist halo model (Syer & White 1998). The power–law fit for
the extended component turned out to be shallow, with $\gamma \sim 2$. The authors did not succeed to distinguish whether the extended component was dominated by a stellar halo or an extended thick disc. By assuming that the RGB halo stars are 10 Gyr old, they found the peak metallicity to be about $[Fe/H] \sim -1.1$ dex.

Later, the GHOSTS (Galaxy Halos, Outer disks, Substructure, Thick disks, and Star clusters) survey of resolved populations in stellar halos of 14 disc galaxies was done, including the M81. The fields were observed with the Hubble Space Telescope Advance Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3). Because of the pencil–beam field–of–view of the HST (3.4 arcmin a side), the survey risked biases from observing such small regions. To lower the risk of accidentally sampling single stellar streams, the observations were done along the major and minor axes. Nevertheless, it was emphasised that these observations still depend on the panoramic surveys to properly analyse the halos and their characteristic substructures. The M81 halo was observed up to projected radius of $\sim 50$ kpc from the centre. In total, 28 fields were observed from both surveys, as shown in Figure 2.2.

One of the papers of the GHOSTS survey tested the models of galaxy formation, in which they studied the M81 exclusively. It was found that the M81 halo shows no metallicity gradient in its metallicity profile within the range of 15 to 50 kpc, similarly to the Milky Way. The CMDs of RGB stars in individual fields were compared to CMDs drawn from simulated stellar halos. Even though the simulated CMDs were drawn from stellar populations ranging from 6 to 13.5 Gyr, the scatter was extremely narrow. This was argued to be the result of the age–colour degeneracy. After applying statistical noise that would come from observations, the RGB stars in simulated CMDs matched the observed ones remarkably well. This comparison shows that a substantial contribution to scatter in RGB colour comes from the errors in the observations. In addition, the simulations of the stellar halo also predicted no colour gradient, and therefore a flat metallicity gradient, in agreement with observations. Lastly, it was estimated that the median metallicity of M81’s stellar halo is $[Fe/H] \sim -1.2$ dex. This puts M81 in between M31 and Milky Way, which have metallicities of $[Fe/H] \sim -0.8$ and $[Fe/H] \sim -1.6$ dex respectively within the same physical range of 15–50 kpc. The study also agrees with earlier deep photometry from the HST ACS observations at the distance of 19 kpc along the southwestern minor axis.
et al. (2010), which estimated that the mean age of the RGB stars was $9 \pm 2$ Gyr, and the metallicity peaked around $[Fe/H] \sim -1.15$ dex.

A later GHOSTS survey study investigated the radial profiles of six galaxies, including M81 (Harmsen et al., 2017). However, the estimated properties of the M81 stellar halo profile are in significant disagreement with Barker et al. (2009). The estimated stellar mass of the halo is $1.1 \pm 0.5 \times 10^9 M_\odot$, which is $2 \pm 0.9\%$ of the overall stellar mass of M81, compared to the 10–15% in Barker et al. (2009). The power-law fit to the halo is much steeper in Harmsen et al. (2017) at $\gamma \sim 3.5$, while the one in the earlier study is $\gamma \sim 2$.

The given reason for the discrepancy was that the resolved star number densities were scaled in Barker et al. (2009) to match the integrated light measurements closer to the centre of the galaxy. While this is a valid technique, Harmsen et al. (2017) claim that the Galactic foreground stars heavily contaminate the inner parts of the halo, further confirmed by Muñoz-Mateos et al. (2015) observations with the S4G 3.6$\mu$ surface brightness profile. They state that the surface brightness from diffuse light was measured too high due to unsubtracted cirrus, resulting in a shallower power-law slope. In contrast, the results from the GHOSTS survey directly converted the number densities of resolved stars to surface brightness measurements by using a $[Fe/H] = -1.2$ dex metallicity 10 Gyr old Padova isochrone (Marigo et al., 2017), thus avoiding the bias introduced by the foreground.

The same group followed up their results with wide-field ground-based observations with the Hyper Suprime-Cam (HSC) on the 8.2m Subaru telescope (Smercina et al., 2020). They agree that the Harmsen et al. (2017) profile was oversubtracted, as the control fields were situated in locations where the contribution of M81 stellar halo stars was dominating over the background level. Their measured power-law slope ($\gamma = -2.59$) was closer to Barker et al. (2009) ($\gamma \sim -2$) rather than Harmsen et al. (2017) ($\gamma = -3.53$). Smercina et al. (2020) also confirmed that there is no colour gradient along the Eastern minor axis of M81. They also estimated that the stellar halo of M81 contains a low amount of stellar mass ($1.16 \times 10^9 M_\odot$), suggesting a quiet merger history of M81 so far. However, these conclusions are drawn from measurements of a single minor axis, which may not reflect the global properties of M81.

In this chapter, I will present the analysis of a nearby ($D \sim 3.6$ Mpc) galaxy M81, in particular its stellar halo using resolved stellar data state-of-the-art
observations from Hyper Suprime–Cam. The proximity of the M81 Group has advantages, but also brings some challenges. For example, the close distance means that the group takes up a large portion of the sky, requiring an extensive survey area-wise.

## 2.2 The Data

The primary dataset consists of observations obtained with HSC on the Subaru Telescope. The HSC imager consists of a mosaic of 104 CCDs, sampling a field–of–view (FOV) of $1.76 \text{ deg}^2$ with 0.17″ pixels (Miyazaki et al., 2018). The M81 Group survey covers $\sim 12$ square degrees and reaches roughly two magnitudes below the tip of the RGB at the distance of M81. The survey footprint is centered on M81 and comprises seven HSC pointings in total, extending to a projected radius of $\sim 130$ kpc from the centre of M81 (see Fig. 2.3). The data were obtained in the course of various classical and queue-mode runs during the period 2015–2019. The survey uses the $g$– and $i$–band filters to image to depths of $g \sim 27.5$ and $i \sim 26.5 \ (5\sigma)$, with seeing ranging from 0.6″ to 1.0″. This depth corresponds to more than two magnitudes below the tip of the RGB at the distance of M81.

In this chapter, I focus on a subset of the HSC M81 Group survey, namely fields 1–4. Table 2.1 summarises the observations. The raw image data was reduced by a collaborator (S. Okamoto) from our research team and photometry was measured using DAOPHOT/ALLSTAR. The end product was provided to me in catalogue form with all detected objects and their parameters listed after the initial cull of contaminants. The 4 fields alone are sufficient for initial analysis of the M81 halo.
Figure 2.3: The M81 Group survey footprint (7 HSC pointings) overlaid on an SDSS image. The red circles indicate the pointings used in this chapter. Note that SDSS did not cover the North-Western portion of the survey. Each HSC pointing has a diameter of 1.5 degrees and the known galaxies within this area are marked. The scalebar reflects the physical scale at the distance at M81. North is up and east is to the left.
The reduction and photometric extraction is fully described in Okamoto et al. (2015, 2019). Here I provide only a brief summary of the steps involved. Images with good seeing (≤1") were processed with a dedicated pipeline hscPipe, version 4.0.0 (Bosch et al., 2019). This pipeline is based on the framework developed for processing images from the Vera C. Rubin Observatory. Initial steps include correcting for bias, creating dark, flat and sky fields for each individual CCD. After the initial corrections, source detection and photometry is performed on each CCD image. Then stacking of multiple frames and mosaicking follows. PSF photometry on the final science-ready images was done using DAOPHOT/ALLSTAR as implemented in IRAF (Stetson, 1987). The resultant catalogue of sources was culled according to their respective quality parameters (sharpness, crowding, and signal-to-noise) to remove extended sources while retaining stellar-like sources. The photometry is on the HSC filter system in AB magnitudes. The source catalogue has ∼1.4 million sources in total.

Figure 2.4 shows the measured photometric error against magnitude. The catalogue was further culled of any sources that had errors beyond ∼0.55 mag. For the RGB stars that are analysed in this chapter, the $i$-magnitude domain spans from 24.15 to 25.2 mag (marked with black dashed lines), in which most sources are within errors of 0.2 mag on the bright side, and 0.25 mag on the faint side.

The M81 Group lies in a part of the sky with significant and highly variable extinction from foreground dust. In Figure 2.5 I show the magnitude of foreground extinction in the $g$-band towards the M81 field as derived from the Schlegel et al. (1998) reddening map with corrections from Schlafly & Finkbeiner.
Figure 2.5: Foreground extinction in the four HSC fields analysed in this chapter. This is derived from the Schlegel et al. (1998) map, calibrated with coefficients from Schlafly & Finkbeiner (2011) and the HSC filter coefficients provided by Rodrigo & Solano (2020). The three main galaxies of the M81 Group are marked. In the Schlegel map, M81 has been excised and replaced with median values of surrounding pixels.
and the HSC filter coefficients provided by Rodrigo & Solano (2020). M81 has been excised from the map and replaced with median values of surrounding pixels. As Barker et al. (2009) noted, this means that the internal extinction of M81 is not corrected for but this is not a problem given my interest in RGB halo stars. The values of $A_g$ reach up to 0.5 mag in some regions, therefore it is necessary to do a star–by–star extinction correction. I use the extinction–corrected PSF magnitudes for the remainder of this paper, which will be referred to as $g_0$ and $i_0$ hereafter.

2.3 Completeness Tests

While the M81 Group survey is photometrically deep and reaches 1.5 mag below the tip of the Red Giant Branch (TRGB), not all stars in this magnitude range are detected, leaving the catalogue incomplete. While there are numerous reasons for failing to detect stars, the main driving factor in the vicinity of galaxies is stellar crowding. The fraction of stars missed in the catalogue increases with magnitude, as fainter stars are inherently more difficult to detect.

The completeness of a stellar photometric catalogue can be quantified in two ways – either through artificial star tests (ASTs) or a direct comparison with a deeper survey that covers a common area of the sky. Due to lack of development of tools for ASTs specifically tailored to HSC data, the first approach was difficult for a dataset of this volume. To assess the completeness of the HSC catalogue in a broader way, I conduct comparisons to archival HST pointings that fall within the HSC field–of–view.

Before examining the positioning of the HST pointings, I define the spatial coordinates that I use. The Equatorial Coordinate System is the most commonly used system for specifying object locations in the sky as it is virtually independent of time and location of the observer. The objects are placed on a celestial sphere, with longitude and latitude measured by Right Ascension and Declination respectively. However, spatial maps of objects are almost always shown as 2D projections, which may cause distortion problems if the field of interest is large and far from the celestial equator. To avoid projection warping, a Standard Coordinate System can be adopted instead (e.g., Green 1985). This requires projecting the equatorial coordinates ($\alpha, \delta$) onto a tangent plane centered on a given point ($A, D$).
Figure 2.6: HST fields used for completeness tests overlaid on the HSC RGB stellar map (see Sec. 2.4). The magenta fields are above the 0.015 stars arcsec$^{-2}$ density threshold, and the cyan fields are below. The larger and smaller fields were taken with the ACS and WFC3 respectively.
\((\xi, \eta)\) derived as:

\[
\begin{align*}
\xi &= \frac{\cos \delta \sin (\alpha - A)}{\sin D \sin \delta + \cos D \cos \delta \cos (\alpha - A)} \\
\eta &= \frac{\cos D \sin \delta - \sin D \cos \delta \cos (\alpha - A)}{\sin D \sin \delta + \cos D \cos \delta \cos (\alpha - A)}
\end{align*}
\] (2.1) (2.2)

I selected 24 Advanced Camera for Surveys (ACS) and Wide Field Camera 3 (WFC3) pointings from GO 9353, 10523, 10915, 10136, 10584, 10604 and 11613 which consist of exposures in the F606W and F814W passbands (see Fig. 2.6). These data are largely drawn from the GHOSTS survey and have been presented in Radburn-Smith et al. (2011) and Monachesi et al. (2016). These HST ACS/WFC3 datasets detect stars to roughly three magnitudes below the TRGB and hence are about a magnitude deeper than the HSC dataset. As a result, they can be considered to be 100% complete relative to the ground–based RGB photometry over the magnitude range of interest.

To analyse the data, I used the dedicated reduction pipeline DOLPHOT (Dolphin, 2016), tailored to reduce raw HST images to catalogues. The photometry was done on flc images, which means that the images were calibrated for charge–transfer efficiency and flat–fielded. The reduction process is as follows. Firstly, bad pixels are masked in every image. Then, the images are split into two, as there are two CCDs on both the ACS and WFC3 cameras. For each CCD image, a sky image is created. After preparatory steps, the main DOLPHOT routine is run. The images are drizzled and stacked, and PSF photometry is performed on the stacked images.

This routine gives a catalogue of sources together with a multitude of quality parameters for each source, including a object type classification. The sources are classified into stars, extended objects and sharp objects (noisy pixels). The catalogues were culled to minimise contamination from foreground and background sources using the parameters from Radburn-Smith et al. (2011) for ACS and Monachesi et al. (2016) for WCS3 images. The catalogues have photometric magnitudes in their native bands (F606W, F814W) and their closest equivalent Johnson–Cousins bands (V, I) both in the Vega system. For the completeness tests, the native bands were used. The final catalogue was made after correcting for the foreground extinction with Schlegel et al. (1998) maps and Schlafly & Finkbeiner (2011) coefficients for the HST filters.
To be able to use these data to assess the completeness of the HSC catalogues, the magnitudes had to be transformed onto the HSC AB system. As there are no photometric transformations available from the HST to HSC photometric system, they had to be derived from scratch.

Following the procedure outlined in Komiyama et al. (2018), the magnitudes can be reliably transformed between the filter systems if a colour factor is also used from the original system, HST F606W–F814W in this particular case. First off, the transmission curves of HSC and HST filters were convolved with stellar spectra from the Gunn & Stryker (1983) and Pickles (1998) spectral atlases. The atlases contain 175 and 131 spectra respectively and sample all spectral types of interest. This allowed me to extract synthetic photometry and derive transformations between the HSC and HST systems across a broad range of colour.

Figures 2.7 and 2.8 show the difference in derived magnitudes between the two filter systems as a function the F606W–F814W colour. A quadratic polynomial fit was found to be sufficient to describe the conversion between the two red bands:

\[
i_{\text{HSC}} - F_{814W} = 0.384 + 0.088(F_{606W} - F_{814W}) + 0.011(F_{606W} - F_{814W})^2 \quad (2.3)
\]

The difference between the blue bands exhibits a break at F606W–F814W ~ 1, requiring two separate quadratic polynomial fits:

\[
g_{\text{HSC}} - F_{606W} = -0.124 + 0.892(F_{606W} - F_{814W}) + 0.322(F_{606W} - F_{814W})^2 \quad (2.4)
\]

for F606W – F814W < 1.0, and
Figure 2.7: Conversion from the HST F814W (Vega) to $i_{\text{HSC}}$ (AB) filter systems using a quadratic fit to the F606W–F814W colour. The top panel shows the magnitude difference of the atlas stars as black points while the bottom panel shows the residuals of the same stars from the quadratic fit.
Figure 2.8: Conversion from the HST F606W (Vega) to $g_{\text{HSC}}$ (AB) filter systems using a quadratic fit to the F606W–F814W. Divergent behaviour is seen beyond F606W–F814W = 1.0, thus requiring a separate quadratic fit in this region. The top panel shows the magnitude difference of the atlas stars as black points while the bottom panel shows the residuals of the same stars from the quadratic fit.
\begin{align*}
g_{\text{HSC}} - F_{606W} &= 0.507 + 0.742(F_{606W} - F_{814W}) - \\
&- 0.15(F_{606W} - F_{814W})^2 \quad (2.5)
\end{align*}

for \(F_{606W} - F_{814W} > 1.0\). In all cases, the HSC magnitudes are on the AB system and the HST magnitudes are on the Vega system.

The \(i\)-band fit has very low scatter – the residuals are typically less than 0.025 mag even at the reddest colours. While there is some higher-order behaviour at colours bluer than \(F_{606W} - F_{814W} = 0.75\) which my polynomial fit fails to capture, this level of precision is not required for my purposes. On the other hand, the \(g\)-band fit exhibits higher residuals at all colours, ranging from \(\sim 0.075\) mag at colours bluer than \(F_{606W} - F_{814W} = 1.0\) to \(\sim 0.2\) mag beyond this limit. This is not unexpected given that \(g_{\text{HSC}}\) is considerably bluer in transmission than \(F_{606W}\). Nonetheless, this description is adequate for my study.

I searched for positional matches between stellar sources in the HST catalogue and those in the HSC catalogue. Any match within 1 arcsec in both catalogues was classed as a matched detection. If there were multiple matches, the one that is photometrically closest in the colour–magnitude space was adopted.

As a qualitative demonstration of both the photometric transformation and matching algorithms, Figure 2.9 shows CMDs of the matched HST sources in the \(F_{606W} - F_{814W}\) bands, the same sources transformed to the HSC \(g - i\) system, and the matched sources from the HSC catalogue. Visually, the HST and HSC colour–magnitude diagrams (CMDs) are strikingly similar after transformation to the HSC photometric system.

The HST fields are situated along the northern major axis and the eastern minor axis except for four fields, as shown in Figure 2.6. Because of this, there is a clear variation of stellar densities sampled which translates to different completeness levels. The fields were grouped into dense and sparse groups, with the limiting threshold set to 0.015 stars arcsec\(^{-2}\) or 667/412 stars in an ACS/WFC3 field. The threshold was selected arbitrarily to isolate the dense fields expected to be found in the vicinity of M81 and along the Northern major axis. These are indicated in cyan and magenta respectively. Unsurprisingly, the densest fields are located near the main bodies of M81 and M82. While a radially–varying completeness function estimation would have been a more correct approach, the statistical noise due to
Figure 2.9: Left panel: stars matched between the HST and HSC catalogues in the HST photometric system (HST catalogue). Centre: stars matched between the HST and HSC catalogues transformed from the HST photometric system to the HSC photometric system (HST catalogue). Right panel: stars matched between the HST and HSC catalogues in the HSC photometric system (HSC catalogue).
Figure 2.10: Magnitude-dependent 1D completeness. The fitted completeness models are overlaid as solid lines. Left panel: $i$-band. Right panel: $g$-band.

the small areas of fields made this option unreliable. Instead, only the sparse fields were used to give an average correction as the completeness corrections are primarily intended for the analysis of the low density outer regions of the galaxy rather than the disc.

I bin the stellar sources from all low-density fields in varying $g$- and $i$-band magnitudes separately, both within the colour limit of $1.0 < (g-i)_0 < 3.0$ to encompass the RGB stars. For each bin, I determine the fraction of the HSC sources which appear in the HST catalogue, $\eta(m)$, and characterise the behaviour by fitting Equation 7 from Martin et al. (2016) to the recovered fraction of stars as a function of magnitude:

$$\eta(m) = \frac{A}{1 + \exp\left(\frac{m-m_{50}}{\rho}\right)}$$

where $m$ is the magnitude, $A$, $\rho$ are fitted constants, and $m_{50}$ is the magnitude at which the catalogue would be 50% complete if $A$ was exactly 1, otherwise it is the characteristic limiting magnitude. Using this approach, I find that the $i$-band catalogue reaches the 50% completeness limit at 25.12 mag, while the $g$-band catalogue is 50% complete until 25.84 mag. I show the fractions of stars recovered as well as fitted completeness curves in Figure 2.10.
Figure 2.11: Composite g–i completeness solution in CMD space. The RGB selection box is overlaid in red. The white line delineates the 50% completeness threshold. Left panel: completeness derived from HST fields, this work. Right panel: completeness taken from Okamoto et al. (2019).

The two completeness functions can be combined to create a 2D completeness map in the CMD space, where the completeness fraction at each colour and magnitude coordinate is governed by the completeness function that is lower in that discrete location. The continuous completeness function fits in $g$– and $i$–band can be used simultaneously in colour–magnitude space for every discrete colour and magnitude. For example, should the completeness level be lower in $g$–band than $i$–band at a given colour and magnitude, the assigned completeness fraction is then taken from the $g$–band completeness fit. By iterating this method through various points on the CMD, a 2D completeness map is made. The resultant map is shown on the left panel in Figure 2.11. The colour–dependent 50% completeness line is shown in white. Using this method, I find that the RGB stars of interest (red polygon) all lie below the 50% completeness curve. I explain how the RGB star polygon is defined in Section 2.4. This result was surprising given the long exposures that the program was designed with, which should have led to good completeness on the RGB. Although many further tests were carried out, I could not find any reason for the low completeness recovered by this method. It may simply reflect low number counts in the HST or that perhaps the initial HSC culling was too severe.

While some reasons for the lower than expected completeness obtained were explored, the problem was never fixed. As a contingency, I resorted to using the
results of the ASTs provided to me by S. Okamoto and which were used in the analyses of Okamoto et al. (2015) and Okamoto et al. (2019). The completeness solution provided uses the sigmoid function instead of Equation 2.6 but otherwise works essentially in the same way as my method. The completeness is estimated using ASTs for six different areas in the four HSC fields, with some overlap. The 2D completeness map for the segment covering the Southeastern region of the M81 halo is shown in Figure 2.11 right. This 50% completeness line has a significantly larger portion of RGB stars above it than my estimate, as is expected given the exposure times of HSC observations used for this project. Note that while my method for completeness estimation did not provide satisfactory results for M81, it was successfully used in Chapter 3. The completeness curve in Figure 2.11 (right) is used for correcting the stellar density radial profiles in Section 2.5 and stellar metal content analyses in Section 2.6.

2.4 Colour–Magnitude and Spatial Distributions

Figure 2.12 shows the CMD of the catalogue. Several distinct stellar population features can be seen, although some of the features are not associated with M81. To guide the eye, isochrones of varying ages and metallicities have been overlaid on the CMD. The isochrones were taken from PARSEC+COLIBRI tracks (CMD input form version 3.6, PARSEC version 1.2S) with Kroupa initial mass function (IMF) (Kroupa 2001; Bressan et al. 2012; Marigo et al. 2013). A distance modulus correction \((m - M)_0 = 27.8\) was applied to the isochrones so as to bring them to the distance of M81 (Freedman et al. 1994). Guided by the isochrones, I defined polygons to isolate the distinct stellar populations of interest by drawing them around the isochrones. Note that for all evolutionary stages except for RGB, the polygons are drawn purely for visual purposes and are not used for the subsequent analysis. The green and orange polygons in Figure 2.12 show the distribution of Main Sequence (MS, green polygon) and Red Supergiant Stars (RSG, orange polygon) in colour–magnitude space. These stars have recently formed either in the main bodies of the galaxies or in extratidal gas from a close recent encounter 200–300 Myr Myr ago (Yun 1999).

The most relevant domain of the CMD for this chapter is the RGB population, located in the red polygon. Figure 2.13 shows Hess diagram of the CMD which better depicts the distribution of stars in the RGB box as well as nearby overdensities unassociated with the RGB. The stars located in this region are
Figure 2.12: The Colour–Magnitude diagram of all point–sources in the M81 dataset (Fields 1–4, ∼1.4 million sources). Each dot represents a single object from the catalogue. White contours are supplied in regions where the density of objects is too large. The distinctive stellar evolutionary stages of populations of the M81 Group are indicated with polygons and labeled. An isochrone of metallicity $[M/H] = -0.7$ dex and age of 220 Myr traces the young Main Sequence (MS) population, while the isochrones tracing the Red Supergiant (RSG) populations are overlaid with varying ages of 10, 40, 100 Myr and metallicity of $[M/H] = -0.7$ dex.
Figure 2.13: Colour–Magnitude diagram of all point–sources in the M81 dataset (Fields 1–4, ∼1.4 million sources). The same point–source catalogue objects are depicted here as in Figure 2.12 but in the form of a Hess diagram (2D histogram). The distinctive stellar evolutionary stages of populations of the M81 Group are indicated with polygons and labeled. Isochrones of age 10 Gyr tracing the old RGB population are overlaid with varying metal content ([M/H] = −2.0 (magenta), −1.5 (blue), −1.0 (lime green), −0.5 (orange) dex.)
typically old (2 − 13 Gyr) and metal–poor (−2.0 < [M/H] < −0.7 dex). The colour width of the population is primarily driven by the variation in metal content rather than age. I assume an age of 10 Gyr and vary the metallicity of the isochrones, as shown in Figure 2.13. All curves of different colours end at the top of the RGB box which is the tip of the RGB. The RGB polygon is defined to encompass the CMD area spanned by the isochrones to sample the domain of stars with metallicities in the range of (−2.0 < [M/H] < −0.7 dex). The bottom threshold is ∼ 1 magnitude below the tip of the RGB.

Figure 2.14 depicts the spatial distribution of recently formed Main Sequence stars. The stars located outside the main bodies of galaxies trace the path of ongoing close interactions between the galaxies, akin to the expelled HI gas they were formed in (e.g., de Blok et al., 2018). These young stellar populations are traced by the $[M/H] = −0.75$ dex, 10 Myr isochrone which is shown as a light green line in Figure 2.12. Similarly, the bright stars populating the orange polygon of the CMD are the Red Super-Giants (RSG) which are a population of evolved young massive stellar populations. Figure 2.15 shows their spatial distribution which is more concentrated in the galaxies themselves as opposed to MS populations. In Figure 2.12 they are traced by the light orange $[M/H] = −0.75$ dex, 40, 100 and 220 Myr isochrones.

The RGB stars trace the stellar halo as it comprises old stellar populations accreted from major and minor mergers in the past. Figure 2.16 shows the spatial distribution of RGB stars. The RGB star map also uncovers the dwarf galaxy members of the M81 Group as low–mass dwarf galaxies are dominated by old stellar populations. The RGB stars trace the stellar halos in the outer extents of the three main galaxies of the M81 Group. It has been shown by Okamoto et al. (2015) that the stellar halos are significantly affected by the ongoing interaction, resulting in bridging structures which join the stellar halos together. To better visualise the sheer extent of the stellar halos traced through resolved stellar populations, colour images of the main bodies of M81, M82 and NGC 3077 from SDSS are embedded on the map. Notably, the size of NGC 3077 at low surface brightness appears as large as that of the other two systems, while the main body size reported in the literature is significantly smaller than its counterparts. This calls to question whether a significant fraction of luminosity was underestimated in the past due to undetected stellar populations at large radius.

The stars located above the bright end of RGB are the thermally–pulsing Asymptotic Giant Branch (AGB) stars. These stars are of intermediate age (0.5−5
Figure 2.14: A map of MS stars in the M81 Group from the 4 HSC pointings. North is up and east is left.

Figure 2.15: A map of RSG stars in the M81 Group from the 4 HSC pointings. North is up and east is left.
Figure 2.16: A map of RGB stars in the M81 Group from the 4 HSC pointings. North is up and east is left. False-colour images from SDSS are overlaid on M81, M82 and NGC3077 inner regions.

Figure 2.17: A map of AGB stars in the M81 Group from the 4 HSC pointings. North is up and east is left.
Figure 2.18: Hess diagram of objects from the point–source catalogue that are not in the vicinity of any known galaxy. The spatial distribution of sources in the green and magenta boxes are shown in Figure 2.19. Note that the RGB box (red) is more affected by background galaxy contaminants than foreground stars.
Figure 2.19: A map of contaminating sources in the M81 group from the 4 HSC pointings. North is up and east is left. Left panel: Background contaminants – unresolved galaxies. Right panel: Foreground contaminants – Milky Way disc and halo stars.

Gyr) and are found in both the major galaxies and some dwarf galaxies. In Figure 2.17 I show how they are spatially distributed in the M81 survey. While these populations are brighter than RGB, they are not as numerous on account of their shorter lifetimes and they do not trace the ancient stellar populations of galaxies in the outer regions. The isochrones representing the AGB stars are not depicted in Figure 2.13 as they follow a disorderly path.

A significant challenge is posed as the RGB stars populate an area in the CMD near where unresolved background galaxies lie. While the bulk of the background galaxies are in the bluer and fainter region peaking at \((g - i)_0 \sim 0.2\) (see Fig. 2.13), their distribution extends into the blue (low \((g - i)_0\)) metal–poor region of the RGB stars, thus requiring extra care when performing any analysis involving RGB star selection. Without correcting for this contamination, this may result in a perceived overabundance of metal–poor RGB stars.

In Figure 2.18 I show a CMD of regions of the HSC survey that are far removed from the bright galaxies. As a result, the sources here are likely to be contaminants. I highlight selected areas in colour–magnitude space where there is a high density of contaminants of either foreground or background origin. The left panel of Figure 2.19 shows the spatial distribution of the background galaxy population which appears uniform throughout the field, except in the vicinity of the large galaxies due to stellar crowding. In these crowded regions, large photometric errors cause RGB stars to be scattered out of the RGB selection.
Figure 2.20: Left panel: Placement of the contamination sampling areas (red boxes), overlaid on the RGB stellar map. Right panel: Measured surface density in each contaminant area following East to West (top) and South to North (bottom). The dashed lines are the average surface density of contaminants.

The two bright vertical sequences that are at both sides of the RSG box in Figure 2.12 are of foreground origin. The bluer (lower $g - i$) column contains the metal–poor Galactic halo populations while the red (higher $g - i$) column is populated by metal–rich Galactic disc stars. I define two polygons that sample the two populations in 2.18. In the right panel of Figure 2.19, I show that the spatial distribution of the foreground stars is uniform, with some very minor structure visible around the three major galaxies, again due to crowding effects resulting in photometric scatter. In the next section, I explain how I minimise the contamination caused by the background galaxies and foreground stars simultaneously, which is necessary to quantitatively study the structure of the extended stellar populations.

### 2.4.1 Background contamination

The aforementioned contaminant sources impact all measurements in the data, and therefore must be accounted for. Any gradients in the contaminant population will influence the extracted stellar halo profile, while the pedestal level of the contaminants will inflate the surface brightness measures. As shown in Figure 2.19, the contamination is essentially uniform throughout the halo region.
of interest both along East to West and South to North with some statistical variation and hence can be treated as a constant correction. To quantify the level of this correction, I define 10 square fields, each 12 arcmin on a side, in regions where no known galaxies or features that belong to the M81 Group exist. I show the distribution of the fields in the left panel of Figure 2.20, superimposed on a map of RGB stars. The sources in each field falling within the RGB box are counted and expressed in terms of surface density ($\log_{10}(N_{\text{contaminants}}) \text{ arcmin}^{-2}$). The distribution of contaminants appears random and the locations are discrete, therefore the errors of contaminant counts are Poissonian, i.e. $\Delta N = \sqrt{N}$. As shown in the right panel of Figure 2.20, the resultant contaminant densities vary slightly, but show no evidence of systematic gradients along $\xi$ nor $\eta$ and have an average stellar density of $\log_{10}(N_{\text{contaminants}}) = 1.45 \pm 0.2 \text{ arcmin}^{-2}$.

The contaminant level defined here will be used throughout all subsequent RGB star analyses to account for contamination in a consistent way. In cases where a selection by colour is required instead of stellar densities (e.g. Section 2.6), the colour–magnitude values of the contaminant sources will be used instead.

2.5 Radial Profiles

2.5.1 Diffuse Light

The stars in the inner regions of the main M81 Group galaxies are not resolved due to immense crowding. However, the inner regions are crucial for accurate estimation of total light, and in turn the total stellar mass of the galaxy, as well as for photometric calibration of the halo star count profile. As resolved stellar population methods are unsuitable for the inner regions, pixel images are used instead to analyse the diffuse light.

The most obvious images to use for this analysis are the HSC images that form the basis of the M81 Group survey. However, these proved unsuitable as the background subtraction in hscPipe optimised the detection of point sources and removed large portions of the diffuse galaxy light.

To facilitate integrated light analysis of the inner regions of M81, I instead use a deep image in the $g$–band that was acquired with the 1.1 square degree MegaCam imager on the 3.6m Canada-France-Hawaii Telescope (CFHT). The image was
Figure 2.21: Ellipses fitted by AutoProf on the CFHT $g$–band image. To minimise crowding, only every fourth fitted ellipse is drawn on the image. The diffuse features outside the disc do not belong to the M81 group and are due to foreground cirrus.
Figure 2.22: Fitted ellipse parameters for the CFHT g–band M81 image with AutoProf. Left panel: position angle. Right panel: axis ratio.

obtained using an observing technique that is optimised for low surface brightness (LSB) surveys at CFHT by our collaborator Jean–Charles Cuillandre. The image was processed by Cuillandre following the procedures outlined in Ferrarese et al. (2012) and Duc et al. (2015). This involves making a sky image from a set of images with large (> 10”) dithers and using this for background subtraction. The final stacks have a pixel size of 0.561”/pixel and have a limiting surface brightness of ∼28.6 mag in the g–band.

I then proceeded to use the AutoProf software (Stone et al., 2021) to construct the surface brightness profile for the deep CFHT g–band image of M81. AutoProf provides an end–to–end pipeline for non-parametric profile extraction, including masking, sky determination, centroiding and isophotal fitting. AutoProf is based on the earlier isophotal–fitting routine of Jedrzejewski (1987) and includes new regularization techniques from machine learning which allow it to deliver more stable and robust profiles. In my analysis, I use it in default mode to fit elliptical isophotes at a series of radii and extract the surface brightness profile.

Once the centre is selected, AutoProf then fits a series of isophotes which extend until they reach below 2 times the pixel level SNR, which in my case is a semimajor axis of ∼15 arcmin. When the limit of isophotal fitting is reached, AutoProf can sample the profile further out by assuming the average of the outer fit values of position angle (PA) and ellipticity (defined as $\epsilon = 1 - b/a$, where $b/a$ is the ratio between the minor and major axes lengths) (see Stone et al., 2021, for more details). The fitted ellipses are overlaid on the g–band image in Figure 2.21.

In Figure 2.22 I show the variation of the ellipse parameters as a function of semimajor radius. The ellipticity and PA vary strongly in the inner regions due
Figure 2.23: Comparison of diffuse light profiles of the M81 main body. This work uses the red profile made using a deep LSB–optimised CFHT $g$–band image with AutoProf. This profile covers a larger radial range and reaches to a deeper surface brightness limit than any other profile published to date.
to the bulge and spiral arm structures, but settle to $b/a = 0.53 \pm 0.16$, $\theta = -26.9^\circ \pm 0.3^\circ$ by the last successfully fitted isophote. Using the estimated ellipse parameters, the surface brightness is then extracted in the elliptical apertures and the background contamination is subtracted. The foreground extinction was corrected for by subtracting a single average value, $E(B-V) = 0.26$ mag, derived from the Schlegel et al. (1998) map, calibrated with coefficients from Schlafly & Finkbeiner (2011).

The surface brightness profile can be measured out to $\sim 25$ arcmin with AutoProf, as seen in Figure 2.23. In the very inner regions ($\sim 2$ arcmin) the profile sharply declines in surface brightness due to the presence the bulge, whereas the outer parts of the profile fall off more slowly due to the exponential disc. For qualitative comparison, previously published surface brightness profiles in various photometric bands from Barker et al. (2009) (Subaru Suprime–Cam V), Muñoz-Mateos et al. (2015) (Spitzer 3.6 $\mu$m) and Jarrett et al. (2019) (WISE W1) are overlaid. As can be seen, the surface brightness profile measured in this work is now the most extended integrated light profile of M81 constructed to date. All profiles exhibit a similar shape, but the AutoProf profile covers a wider radial range and samples more frequently which in turn gives finer details on the profile and reaches fainter depths. The improvement of the diffuse light profile over the previous measurements is due to a combination of a deeper, low surface brightness–optimised image and AutoProf’s ability to work at low surface brightness.

Note that my profile does not have any visible uncertainties because the AutoProf routine was run on an image that was background–subtracted beforehand. As the background is the main driver of uncertainties, the uncertainties shown in Figure 2.23 are heavily diminished. The other profiles do not have errors provided in their respective publications or had negligible errors within the reliable range shown in this figure, and are therefore not shown.

2.5.2 Star Count Profiles

The diffuse light profile does not probe far into the stellar halo, meaning that other methods must be pursued. To extend the radial profile beyond the main body of M81, resolved stellar populations are used instead. In particular, the RGB stellar populations are used to trace the extent of halo, as they contribute about $\sim 43\%$ of the light in the halo. This was estimated by using a simulated
Figure 2.24: Padova luminosity function assuming a 10 Gyr, $[M/H] = -1.13$ dex stellar population. The red vertical lines delineate the range of magnitudes encompassed by the RGB selection box used in this chapter. Left panel: relative number density. Right panel: relative flux density.

The luminosity function, assuming a 10 Gyr, $[M/H] = -1.13$ dex stellar population from the Padova database (Kroupa 2001, Bressan et al. 2012, Marigo et al. 2013). The luminosity functions are shown in Figure 2.24. Starting with the relative number density on the left panel, each bin is scaled by its flux output from its given central magnitude. This way, the relative flux density is obtained, shown in the right panel. By isolating the magnitude range enclosed by the RGB selection box used in this chapter, the relative flux coming from the RGB stars is integrated and compared against the whole luminosity function. The estimated fraction shows that the RGB stars contribute $\sim 43\%$ of the light in this stellar population.

Using both diffuse light and star counts will allow me to probe the surface brightness profile of M81 from inner regions to the outer halo, which is required so as to decompose the profile into consistent structures.

The analysis done in this section and further chapters utilise my own Python code for capturing objects inside ellipses given the position angle, axis ratio and central position using mathematical prescriptions. For further information, the algorithm is described in more detail in Appendix A.

The first step is to decide the shape and geometry of the apertures to use for the star count analysis. Generally, stellar halos are expected to be roughly spherical while flattened features, like in the case of the inclined M81 disc, appear elliptical.
Figure 2.25: Ellipses derived from moments analysis overlaid on the RGB stellar density map (black dots).
Figure 2.26: Ellipse parameters derived from moments analysis (orange). For comparison, parameters derived from diffuse light measurements with AutoProf are shown in blue. Left panel: position angle. Right panel: axis ratio.

when projected on the sky. To determine the shape of the M81 stellar halo, I used the RGB star distribution to calculate the characteristic moments as described in McConnachie & Irwin (2006) and Higgs et al. (2021). This method starts with estimation of the first moment – the centroid position (X, Y) – but for the purpose of this analysis I skip this step and keep the centre of M81 fixed to (0, 0) in standard coordinates (ξ, η), for consistency with the centroid for diffuse light profiles. The moments σ_{XX}, σ_{YY} and σ_{XY} are estimated by:

\[
\sigma_{XX} = \frac{\sum x_i^2 I_i}{I_{tot}} \quad (2.7)
\]

\[
\sigma_{YY} = \frac{\sum y_i^2 I_i}{I_{tot}} \quad (2.8)
\]

\[
\sigma_{XY} = \frac{\sum x_i y_i I_i}{I_{tot}} \quad (2.9)
\]

where (x, y) is the relative position of each image pixel with respect to the centre, \(I_i\) is the intensity of each discrete pixel and \(I_{tot}\) is the total intensity of the image.

The intensity weighting is repurposed for resolved stellar populations by defining a 2D grid where each bin is a box, 0.2 arcmin a side. The magnitudes of the RGB stars located in the bins are converted to flux and summed together to emulate the intensities as if they came from pixel images. Here, with the second moments, the PA and ellipticity can be determined:

\[
PA = \frac{1}{2} \arctan \frac{2\sigma_{XY}}{\sigma_{YY} - \sigma_{XX}} \quad (2.10)
\]
\[
\frac{b}{a} = \sqrt{\frac{1-e}{1+e}} \quad \text{where} \quad e = \frac{\sqrt{(\sigma_{XX} - \sigma_{YY})^2 + 4\sigma_{XY}}}{\sigma_{XX} + \sigma_{YY}}
\]  

(2.11)

To calculate the moments, we begin by constructing circular annuli in the range 4–34 arcmin. Each annulus is 2 arcmin wide. The moments are estimated for each annulus separately. From these moments the position angles and axis ratios are obtained, and then iterated with the new parameters until the solution converged.

The ellipses calculated by the moments analysis are overlaid on a map of M81 RGB stars in Figure 2.25. The inner regions are poorly characterised due to lack of stars as a result of crowding, however in these regions I will rely on diffuse light. In the very outer regions, the ellipses become elongated due to contamination by RGB stars in the halos of M82 and KDG061, as is evident from the position angles of outermost ellipses aligning closely with the positions of those systems. In the intermediate region, the ellipses are stable and relatively round and visually seem to be a good match to the star count distribution. Comparing the moments analysis solutions of the axis ratio and position angle with the ones estimated by \textit{AutoProf} in Figure 2.26, the position angle is consistent in both methods, but the axis ratio is clearly larger for the resolved stellar populations, indicating a rounder distribution. The star counts inside \(\sim 20\) arcmin may still be quite incomplete due to crowding and this may be the reason of the offset. Another reason for the offset may be that I have used a \(g\)–band image for the diffuse light analysis, which is most sensitive to light from much younger stars than RGB stars. I adopt the average of the ellipse parameters from the moments analysis in the range 15–26 arcmin, excluding the last three annuli due to influence from M82 and KDG061. I extract the stellar halo profile using elliptical apertures with \(b/a = 0.73 \pm 0.02\) and position angle \(PA = -22.9^\circ \pm 3.7^\circ\).

The contaminating presence of the neighbouring galaxies, M82 and NGC 3077, heavily limit the ability to construct azimuthally–averaged star count profiles at large radius. The stellar halo can be probed further with resolved stars if traced along several directions separately. Due to the high number of RGB stars in the halo, the statistical signal is strong enough for probing partial sections of the azimuthal annuli. A particular interest is in the minor and major axis profiles. I adopt annular wedges of angular width 40° along the minor axes while an angular width of 10° is used along the major axes due to positioning of M82, NGC3077 and KDG061. In Figure 2.27 I show the annular wedges used for the analysis in magenta. The footprint of the present dataset poses further limitations to the
Figure 2.27: Wedges used in radial profile construction along the principal axes of M81. The principal axes are labeled by cardinal directions.
profiles – the Western minor axis can only be traced to a projected radius of 40 arcmin, while the Northern major axis can be traced to 46 arcmin before reaching the edge of the field. Both of these profiles will be extended further when a full reduction of all fields of the M81 Group survey is done in the future. The other two axes can be extended to much larger radii for this analysis, their extent will be limited solely by the background starting to dominate in the outer regions.

The width of the radial bin sizes along the annular wedges is initially set to be 1 arcminute each. Beyond 40 arcmin, the bin size is increased to 2 arcmin to compensate for declining star counts. In constructing the profiles, several corrections are applied to the star counts. Each star is corrected for completeness, i.e. if a star is located in a 50% completeness bin of the CMD, the star is counted twice, while a star with estimated 33% completeness is counted thrice. The counts are also corrected for contaminants by subtracting the expected amount for the area covered by the annular bin (see Section 2.3).

The counts are then converted to densities (counts arcsec$^{-2}$) and expressed logarithmically. All four profiles are shown together in Figure 2.28. The uncertainties come from combination of Poisson uncertainties and background subtraction. The profiles cannot be constructed within $\sim$10 arcmin from the centre of the galaxy due to crowding. They may also be unreliable within 15 arcmin as the completeness correction I have applied was derived from sparser regions and so will underestimate the true stellar density. Nevertheless, in those very crowded regions out to 20 arcmin, the profiles generally agree well, reflecting the presence of the disc.

The profiles show more variance at large radii. The most noticeable discrepancy is the sharp peak at $\sim$32 arcmin in the Southern major axis profile. This is because this radial range captures a significant part of KDG061, which lies directly along this axis. The major axes do not agree with each other in the outer radii due to several reasons. Firstly, the Northern major axis enters a region where a significant contribution of stars from the M82 halo is present as can be seen in the shoulder in the profile around 22 arcmin. The profile also steeply drops in density beyond 38 arcmin due to fall-off in areal coverage.

The minor axis profiles exhibit similar behaviour through the whole radial range until the Western profile reaches the edge of the field. Beyond 70 arcmin, the stellar density measured along the Eastern axis increases which I suspect may be due to tidal debris from M82 and NGC 3077 contaminating the profile. Indeed, a
Figure 2.28: Radial RGB stellar density profiles along the principal axes in log counts. The widths of the profiles represent the uncertainties estimated from combination of Poisson uncertainties and background subtraction.
weak density enhancement in this region can even be seen in the star count maps of Figures 2.16 and 2.27.

The major and minor axes profiles are clearly offset in terms of stellar density, with major axes consistently above the minor axes in the outer radii. This is particularly apparent in the Eastern minor and major Southern profiles which can be traced to the largest radii. The Southern major axis profile stays significantly higher in density compared to the Eastern minor axis profile throughout. This could reflect the fact that the axis ratio of the halo has been incorrectly estimated because of residual contamination from NGC 3077 along the Southern major axis. For the subsequent analysis, I choose to focus on the minor axis profiles as these are the least contaminated directions. I take the mean minor axis profile as the average of the two.

2.5.3 Composite Profile

The diffuse light and star count profiles can be joined together to make a composite surface brightness profile that probes both the bright inner regions of the galaxy and the faint outer regions in the stellar halo. The stellar density profile is first multiplied by a factor of $-2.5$ to turn it into a pseudo–surface brightness profile. For M81, the overlap range of the two profiles is $10 < r < 25$ arcmin, i.e. 15 arcmin in length, which can be used to bring the profiles onto a common scale (see Fig. 2.29). I choose a smaller range of 14–20 arcmin. This ensures that neither the diffuse light nor the stellar density profiles are affected by background subtraction uncertainties or crowding. As the profiles are now both expressed in terms of mag arcsec$^{-2}$, they can be joined up via a zeropoint correction applied to the star count profile, i.e. a constant value will be added to the stellar density profile. A constant correction for the missing light in the luminosity function assumes a single luminosity function is a good approximation at all radii. This seems reasonable for the outer halo where the star formation history is not expected to strongly vary.

One can also use stellar models to estimate the zeropoint correction (e.g., Harmsen et al. 2017, Smercina et al. 2020), but this requires many assumptions. To find the optimal zeropoint correction, I used a numerical minimiser routine from the PYTHON library SciPy (Virtanen et al. 2020). The surface brightness and stellar density were not measured at the exact same radii, so an interpolation of the measurements had to be done. After running the routine, the best–fitting
Figure 2.29: CFHT $g$-band azimuthally-averaged diffuse light profile (blue) joined with the averaged minor axes RGB stellar density profile (red) through a zeropoint correction. The range used for calculating the zeropoint is denoted by black dashed lines. A zoom-in of the overlap region is displayed in the top right corner.
zeropoint correction for the M81 star count profile was estimated to be 30.89. Due to the nature of interpolation and minimiser routine usage as well as the lack of any actual model being fit, the uncertainty in the zeropoint correction was not measured. However, it is visually clear from Figure 2.29 that the uncertainty should not be larger than 0.1–0.2 mag. Both profiles capture the small–scale variations of the profiles in the overlap range well, further confirming the reliability of the joint profile method. As expected, stellar densities fall below where surface brightness can be measured to the left of the range, and vice versa to the right. I choose the transition radius to be 20 arcmin, at which diffuse light profile measurements are switched to stellar densities. The composite profile can be traced from ~15 mag arcsec$^{-2}$ in the core of the galaxy to ~29.5 mag arcsec$^{-2}$ in the outskirts of the stellar halo, making it one of the deepest and most extended surface brightness profiles ever measured.

2.5.4 Quantitative fits

The composite profile spans a wide range of radii, and reflects the surface brightness of multiple components of the galaxy, in particular the bulge, disc and the stellar halo. Looking at the composite profile, it is clear that the profile is not simple, and therefore will require multiple models to describe the nature of the galaxy. The disc of an L$^*$ spiral galaxy is often fit with an exponential profile (e.g., Freeman, 1970):

$$I_{\text{disc}}(r) = I_c \exp \left(-r/r_h\right)$$

(2.12)

where $I_c$ is the central flux density and $r_h$ is the scale radius. On the other hand, the stellar halo is often characterised by a power law (e.g., Irwin et al., 2005):

$$I_{\text{halo}}(r) = cr^\gamma$$

(2.13)

where $\gamma$ is the power of the profile, the key parameter defining the shape of the halo. There are other models that may be used for the stellar halo, such as a Hernquist profile (Hernquist, 1990) which was used by Barker et al. (2009) to describe the M81 halo. The bulge is usually fit with a Séréic profile (Sersic, 1968), which can be expressed as:
Figure 2.30: Decomposition of the joint M81 surface brightness profile into its constituent parts – bulge, disc and stellar halo. The diffuse light points are shown as blue circles, complemented beyond 20 arcmin by the stellar density points as black triangles. The flattening of the profile at ~18–20 arcmin seen by Barker et al. (2009) using only partial coverage of the halo persists in this profile.
Table 2.2: Fitted parameters of M81 component models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{c,\text{disc}}$ (mag arcsec$^{-2}$)</td>
<td>19.47 ± 0.03</td>
</tr>
<tr>
<td>$r_{h,\text{disc}}$ (arcmin)</td>
<td>2.43 ± 0.02</td>
</tr>
<tr>
<td>$I_{\text{eff, bulge}}$ (mag arcsec$^{-2}$)</td>
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</tr>
<tr>
<td>$c_{\text{halo}}$ (mag arcsec$^{-2}$)</td>
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</tr>
<tr>
<td>$\gamma_{\text{halo}}$</td>
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</tr>
<tr>
<td>$M_{\text{abs, disc}}$ (mag)</td>
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</tr>
<tr>
<td>$M_{\text{abs, bulge}}$ (mag)</td>
<td>-19.22 ± 0.02</td>
</tr>
<tr>
<td>$M_{\text{abs, halo}}$ (mag)</td>
<td>-18.6 ± 0.4</td>
</tr>
<tr>
<td>$L_{\text{disc}} (L_\odot)$</td>
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</tr>
<tr>
<td>$L_{\text{bulge}} (L_\odot)$</td>
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</tr>
<tr>
<td>$L_{\text{halo}} (L_\odot)$</td>
<td>2.55 ± 1 × 10$^9$</td>
</tr>
<tr>
<td>$M_{\text{disc}} (M_\odot)$</td>
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</tr>
<tr>
<td>$M_{\text{bulge}} (M_\odot)$</td>
<td>9.25 ± 0.15 × 10$^9$</td>
</tr>
<tr>
<td>$M_{\text{halo}} (M_\odot)$</td>
<td>5.1 ± 1.8 × 10$^9$</td>
</tr>
</tbody>
</table>

\[ I_{\text{bulge}}(r) = I_{\text{eff}} \exp \left( -b_e \left[ \left( \frac{r}{r_{\text{eff}}} \right)^\beta - 1 \right] \right) \]  

(2.14)

where $b_e = 1.9986/\beta - 0.327 \approx 2n - 0.33$ (Caon et al., 1993). The parameter $n$ represents the central concentration of the profile – the larger the $n$, the more centrally concentrated the profile is. Following Barker et al. (2009), I take the M81 bulge parameters from M"ollenhoff (2004) – effective radius $r_{\text{eff}} = 0.75$ arcmin and scale parameter $\beta = 0.75$ estimated for a $V$–band profile. Due to slight differences between $V$– and $g$–bands, a re–estimation of the effective intensity $I_{\text{eff}}$ is required. For the disc, I take the scale radius ($r_h = 2.7$ arcmin) from Barker et al. (2009) as a starting parameter. I begin by fitting to fit the disc and the bulge only in the range out to 17 arcmin from the centre, assuming that these components completely dominate the profile in this range. In total, three parameters are fit – $I_{\text{eff, bulge}}$, $I_{\text{eff, bulge}}$ and $r_{h,\text{disc}}$. The models are fit with a PYTHON routine curve_fit from the SciPy library (Virtanen et al., 2020). The function is given the model, data and its uncertainties which it uses a non–linear least squares fit method to find the best–fitting parameters. The scale radius of the disc is found to be smaller than that estimated by Barker et al. (2009) using the $V$–band, $r_h = 2.43 \pm 0.02$ arcmin.

With the bulge and disc successfully fit, the halo model can be included in the composite profile. The halo profile was not fit simultaneously with the other two profiles as the halo profile is a power law, and power laws grow to infinity.

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when approaching \( r = 0 \), which would have favoured and entirely halo-dominated profile fit. With disc and bulge fit constrained, the halo profile fit no longer dominates the inner region. I now use the full range from 0 to 70 arcmin to fit the power law to the halo, holding disc and bulge parameters constant. The halo is best fit with \( \gamma = -1.6 \pm 0.1 \). The combination of all three models describes the M81 surface brightness extremely well throughout, as shown in Figure [2.30]. The fitted parameters are listed in Table [2.2].

2.5.5 **Luminosity and Stellar Mass of the Halo**

The decomposition of the M81 surface brightness profile into its constituent parts provides a means to derive the stellar luminosity and mass contribution from the separate components. In particular, the mass fraction of the stellar halo provides insight on the amount of satellite accretion, assuming this is the dominant mode of formation.

The profiles are first integrated separately to find their total luminosity contributing to the composite profile. For Sérsic profiles, I adopt the analytical solution provided by Graham & Driver (2005) to calculate the integrated absolute magnitude:

\[
M_{\text{total}} = \langle \mu \rangle_{e, \text{abs}} - 2.5 \log(2\pi R_{e, \text{kpc}}^2) - 36.57,
\]

where \( \langle \mu \rangle_{e, \text{abs}} = \mu_e - 2.5 \log[f(n)] - (m - M)_0 \),

\[
\text{where } f(n) = \frac{ne^b}{b^{2n}} \Gamma(2n)
\]

This is used for both the bulge and disc profile, as the exponential disc is an \( n = 1 \) Sérsic profile. For the power law describing the halo, I integrate the profile numerically with the SciPy quad package [Virtanen et al., 2020]. As the power law diverges towards \( r = 0 \), a discrete integration range must be chosen. The halo starts dominating from 20 kpc onwards, which I choose to be the starting point of integration. Ibata et al. (2014) have integrated the M31 halo to 150 kpc to which they were confident the smooth stellar halo extends to. 150 kpc is my chosen integration upper limit. M31 and M81 have comparable virial radii – 300 kpc for M31 (Klypin et al., 2002) and 210 kpc for M81 (Oehm et al., 2017). This means that integrating to 150 kpc will extend to \( \sim 71\% \) of M81’s virial radius. All integrations were done assuming a 3.63 Mpc line-of-sight distance [Freedman
et al., 1994). The contributions of the bulge, disc and halo are $-19.22 \pm 0.02$, $-21.04 \pm 0.05$ and $-18.6 \pm 0.4$ mag respectively. Therefore, the stellar halo contributes $8.0 \pm 2.5\%$ of the light to the galaxy. This value should be considered a lower limit to halo luminosity fraction as it misses the contribution inside 20 kpc.

These measurements can be expressed in terms of Solar luminosities. The absolute magnitude of the Sun is $M_g = 5.11$ mag (Willmer 2018). By converting the magnitudes to fluxes and dividing by solar flux, I find that the bulge, disc and stellar halo stellar population luminosities in solar units are $L = 5.4, 28.83, 2.55 \times 10^9 L_\odot$, respectively.

Old globular clusters that have a similar metallicity to the stellar halo could be used as a proxy to empirically estimate the approximate M/L. Taking a selection of a few well studied Milky Way globular clusters – NGC 7089, 6093, 1904, 3201, 5286 and 4147 – from Harris (1996) catalogue of GC parameters, I took their M/L values from Baumgardt et al. (2020) which range from 1.42 to 2.01. On average, the M/L for this set of GCs is $1.71 \pm 0.22$. I use this to directly convert the stellar luminosity to stellar mass for the halo as well as for the disc and bulge.

Converting luminosities to masses, I find that the bulge, disc and the halo are $M = 9.25 \pm 0.15 \times 10^9, 4.93 \pm 0.25 \times 10^{10}, 5.1 \pm 1.8 \times 10^9 M_\odot$ respectively. The difference in colour between the stellar halo and other components changes the halo contribution to the mass compared to the light. As the same M/L value was used for all components, the stellar halo contributes a minimum of $8.0 \pm 2.5\%$ of stellar mass to the galaxy.

### 2.6 The Metallicities of the M81 Stellar Halo

The colour of an RGB star depends on both metallicity and age, and this is known as the age-metallicity degeneracy. However, the colour is more sensitive to metallicity rather than age (e.g., Ferguson & Mackey, 2016). By assuming a fixed age (~10 Gyr), as typical for stellar halos, the RGB stars provide excellent tracers of metal content ($[M/H]$).

To estimate photometric metallicities, a set of finely spaced 10 Gyr isochrones is used, ranging from $-2.2$ to $-0.3$ dex in metal content ($[M/H]$). To ensure a satisfactory resolution of metal content, the spacing between each isochrone
Figure 2.31: Metallicity distribution functions (MDFs) measured radially along the Eastern minor axis of M81. The blue bars represent the contaminant subtracted stellar population, the orange bars represent the contaminant population. The blue bars are fit with a Gaussian (red line). In the top left corner of each plot, the mean $[M/H]$ from the Gaussian fit is displayed. Below is the width of the Gaussian fit. On the top right corners is the radial semimajor axis distance from the centre of M81 in both arcmin and kpc. Note that the y–axis changes for each row.
Figure 2.32: The Colour–Magnitude diagram of objects in the Eastern minor axis at a semimajor radius distance 20–35 arcmin in the form of a Hess diagram. Isochrones of age 10 Gyr tracing the old RGB population are overlaid with varying metal content ($[M/H] = -2.0, -1.5, -1.0, -0.5$). The stars used for metallicity analysis are located within the red polygon isolating the RGB population. The most populated region in the CMD centred at $(g - i)_0 \sim 0.3$, $i_0 \sim 26$ mostly contains background galaxies which are avoided for this analysis.
is 0.05 dex. As the isochrones are extracted as discrete values in colour and magnitude, this requires interpolation to turn them into continuous functions. Each star contained in the RGB selection box gets assigned its $[M/H]$ value by finding the closest corresponding interpolated isochrone on the CMD. In practice, this was done by holding the magnitude fixed and finding the nearest isochrone in colour. The metallicity of that isochrone is then assigned to the star. If an object is further away from any isochrone by more that 0.1 mag in colour, it is omitted from further analysis. This only affects a few stars at the extremes of the distribution.

The assigned metallicities can then be used to create a metallicity distribution function (MDF) which reflects the relative number of stars as a function of metal content. Figure 2.31 shows this for the Eastern minor axis. The histogram bins are set to encompass three isochrones each to enhance the statistical strength whilst retaining a relatively high resolution. The objects in the background estimation fields (see Fig. 2.20) are also run through the same algorithm to assess how contaminants contribute to the MDFs. A histogram containing all of the background objects is subtracted from the histogram of RGB stars, scaled by the relative areas. The contaminant–subtracted MDF is then fit using a Gaussian function to estimate the peak $[M/H]$ and spread $\sigma$ of the population.

The uncertainty in the mean $[M/H]$ of the population is estimated by re–sampling each star. The re–sampling is done via these steps:

- Each star is modelled by assuming a Gaussian distribution, where the magnitude of the star is the mean ($\mu$) of the Gaussian, and the magnitude uncertainty is width ($\sigma$) of the Gaussian.
- $N = 2000$ numbers are drawn from a normal (Gaussian) distribution with the aforementioned parameters individually for each star. These are the re–sampled magnitudes of the stellar population.
- The same algorithm is run for each star again, this time considering their colours and colour uncertainties instead. This makes $N = 2000$ colour–magnitude samples.
- The metal content estimation method used for the original sample is run for all $N = 2000$ re–sampled stellar populations.
- The standard deviation of the resultant mean $[M/H]$ of all $N = 2000$ re–sampled populations is the error in estimated mean $[M/H]$ for the original
Figure 2.33: Radial metallicity profiles for all principal axes of M81. Each axis was fit by a linear metallicity gradient. While the stars within 20 arcmin were not used to estimate the gradient, the fitted line is extrapolated into the inner regions for the purposes of visual comparison. Note that the x–axis range is shorter for the Northern and Western axes. (a): Northern major axis. (b): Southern major axis. (c): Eastern minor axis. An additional gradient measured for the inner $r < 20$ arcmin region is added in red. (d): Western minor axis.

To examine how the stellar halo metallicity varies with radius, the RGB stars are binned in annular wedges along the major and minor axes. While the stars within 20 arcmin were not used to estimate the gradient, the fitted line is extrapolated into the inner regions for the purposes of visual comparison. The radial bins are spaced in steps of 3 arcmin until 40 arcmin in semimajor radius, and steps of 5 arcmin beyond that threshold. As established in the previous section, the stellar halo starts to dominate the light from 20 arcmin. Therefore, I focus on stars that are at a distance of 20 arcmin in semimajor radius from the centre or further. As an example, a CMD of stars captured along the Eastern minor axis in the semimajor radius range 20–35 arcmin is shown in Figure 2.32. The RGB box is well separated from contaminants such as background galaxies which occupy
bluer regions \((g - i)_0 \sim 0.3\) mag.

Figure 2.33 shows the measured metallicities along the principal axes. The \([M/H]\) values exhibit a radial gradient along all principal axes of M81. As with the star count profiles in Figure 2.28, the Northern major axis begins to suffer from contamination by M82 at approximately 25 arcmin, evident by the sudden dip in the metallicities. A sharp increase in uncertainty in the outer radii is caused by small number statistics as a result of the footprint edge. Over the radial range of 20–40 arcmin, the stellar halo in the Northern axis shows a metallicity gradient of \(-0.027 \pm 0.008\) dex/kpc. The Southern major axis shows peaks and troughs in metallicity as the profile is traced near NGC3077 and KDG061. The profile stabilises beyond 50 arcmin where it remains constant with no evidence for a constant metallicity gradient. Overall, the gradient along the Southern major axis is \(-0.005 \pm 0.002\) dex/kpc, but his axis profile covers a wider range (10–70 arcmin) than the aforementioned Northern axis (10–45 arcmin). It is difficult to interpret these differing metallicity gradients along the major axes due to the contamination from the dwarf galaxy halos, which are clearly more metal–poor.

Both minor axis profiles also show radial gradients in metallicity going from \([M/H] \sim -1\) dex at 10 armin to \(-1.5\) dex at 30–35 arcmin. The Eastern minor axis can be traced beyond this point to 70 arcmin, however there is no discernible gradient in this region \((-0.002 \pm 0.002\) dex/kpc). The mean metallicity measured from 27 to 70 arcmin for the Eastern minor axis is \([M/H] \sim -1.46 \pm 0.07\) dex. At 30 kpc along the minor axis, the metallicity is \(-1.47 \pm 0.1\) dex (Eastern) and \(-1.43 \pm 0.13\) dex (Western). These broadly similar minor axis metallicities will be relevant for the discussion in Section 2.7.3.

### 2.7 Discussion

In this chapter, I have examined the stellar halo of M81 using a state–of–the–art resolved star dataset obtained with HSC on Subaru. While the M81 halo has been explored before \(\{\text{Barker et al. 2009, Durrell et al. 2010, Harmsen et al. 2017, Smercina et al. 2020}\}\), the analysis presented here provides the widest field–of–view and deepest coverage so far, enabling star counts along all the principal axes to be studied.
2.7.1 Stellar Halo Shape

While the measured axis ratio in the inner regions of the M81 stellar halo cannot be determined due to the heavy contamination of the disc, I have examined the moments of the star count distribution to show that the stellar halo \((b/a = 0.73 \pm 0.02)\) beyond a radius of 15 arcmin is considerably flattened but more spherical than the inclined disc \((b/a = 0.53 \pm 0.16)\).

Comparing against other studies, Harmsen et al. (2017) found that the projected axis ratio of the M81 stellar halo (defined as \(c/a_{25}\)) is 0.61. They define \(c/a_{25}\) as the indicative projected axis ratio which is measured from the ratio of stellar densities estimated along the major and minor axes. The ratio is measured by estimating the densities from the power law fits at a distance of 25 kpc.

However, there are important caveats to keep in mind about their measurement. This study comes from an HST pencil–beam survey which is susceptible to substructures in the stellar halo. Moreover, the background subtraction of such observations is difficult, as the reference fields used are embedded in the outer halo. Therefore, they may include real stars together with contaminant sources. Indeed, the authors do acknowledge that the axis ratio measurements may be influenced by substructures. The risk of contamination by substructures is especially important since the M81 halo is clearly distorted by a recent close encounter. For example, the Northern major axis profile shown in Fig. 5 of Harmsen et al. (2017) is clearly influenced by the stellar halo of M82. While the authors do acknowledge that their profile is affected by this in the range of 25–40 kpc, it is unclear whether the contamination also affects the 40–50 kpc range which they relied on to estimate the shape of the halo.

One unresolved issue from my study is the fact that even with my adopted axis ratio, the densities along the major axes are higher than along the minor axes (Fig. 2.28). With the data presented here, it is not possible to determine if this is due to major axis contamination from M82, NGC 3077 and KDG 061, or if it is an indication that the halo flattening has been underestimated. My estimated structural stellar halo properties \((b/a = 0.73 \pm 0.02, \ PA = -22.9^\circ \pm 3.7^\circ)\) will be improved in the future through a homogeneous analysis of the whole survey dataset (7 fields). That way, a 2–dimensional modeling of the stellar halo profile can be performed instead of 1–dimensional radial profiles along the principal axes and will be less susceptible to the substructure in the halo.
2.7.2 Stellar Halo Metallicity Gradients

The nearest massive galaxies – the Milky Way and M31 – have highly contrasting stellar halos mainly due to the activity in their accretion history. The smooth stellar halo component of the Milky Way galaxy has little to no evidence of a radial metallicity gradient (e.g., Carollo et al. 2007; Ivezić et al. 2008; de Jong et al. 2010) and is generally considered to be metal–poor ([Fe/H] \sim \sim -1.6, Fernández-Alvar et al. 2015). In contrast, the smooth stellar halo component of M31 is more metal–rich and has a strongly negative radial metallicity gradient (–0.01 dex/kpc) going outwards (Gilbert et al. 2014; Ibata et al. 2014). The radial density profile of the M31 stellar halo is well–defined by a power law of \sim 2 < \gamma < \sim 2 (Gilbert et al. 2012; Ibata et al. 2014), whilst there is no consensus regarding the slope of the Milky Way (–2 < \gamma < –4) (e.g., Jurić et al. 2008; Bell et al. 2008; Newberg & Yanny 2005). While the characterisation of the Milky Way stellar density profile is still in flux, there is good evidence that the profile has a break at \sim 27 kpc, beyond which the rate of stellar density decline is significantly steeper (e.g., Deason et al. 2011), although some studies have failed to confirm this (e.g., Sesar et al. 2011).

With more stellar halos of galaxies outside the Local Group characterised, it has been suggested that the Milky Way and M31 stellar halos may be at the extreme ends of metrics, and therefore are a good testbed to compare against. I compare my results against the Milky Way and M31 in this and further subsections.

The lack of a metallicity gradient in the Eastern minor axis has also been seen by Monachesi et al. (2013) and Smercina et al. (2020) using HST and HSC datasets respectively. While both have searched for a colour gradient in RGB populations instead of metallicity, it is still closely representative of the metal content in these regions. Both studies have found that the outer portion of the Eastern minor axis (r > 20 kpc) exhibits no colour gradient. My findings agree with the lack of a metallicity gradient for the axis in question and extend the measurements further to 70 kpc. In addition, I see evidence for an enhancement in metallicity \sim 60’, coinciding with the enhancement in stellar density, which may be due to tidal debris from the M82 and NGC 3077 interaction. A similar enhancement is seen at \sim 38’, which may be further tidal debris.

On the other hand, the Western minor axis appears to show a shallow metallicity gradient (–0.018 ± 0.002 dex/kpc) beyond 20’. The origin of this discrepancy
is unclear, but there are three possible reasons. Firstly, as noted before, the Eastern minor axis may be contaminated by the M82 and NGC 3077 interaction, thus erasing the evidence of the intrinsic M81 stellar halo metallicity gradient. Secondly, it may be that both minor axes are indeed showing the true nature of the stellar halo, but the stellar halo itself is not symmetric. Finally, the Western minor axis has a smaller sampling range than its counterpart, and therefore the results may suffer from edge effects where coverage is lacking. These three hypotheses will be tested in the future when all seven fields of the M81 Group survey are reduced together.

2.7.3 Global Stellar Halo Metallicity

Using deep HST/ACS data, Durrell et al. (2010) estimate a metallicity of \([M/H] = -1.15 \pm 0.11\) dex on the Western minor axis at a semimajor distance of 18 arcmin. Figure 2.30 shows that this position is still dominated by the disc component of M81 and not measuring the halo. Nevertheless, my metallicity measurement at 17 arcmin along the Western minor axis is \([M/H] = -1.15 \pm 0.07\) dex, perfectly consistent with the Durrell et al. (2010) measurement.

On the other side – the Eastern minor axis – I estimate the mean metallicity of the Eastern minor axis to be \([M/H] = -1.46 \pm 0.11\) dex, measured from 27 to 70 arcmin. However, this is quite a bit lower than Smercina et al. (2020) who found a constant metallicity of \([M/H] = -1.2\) dex in the Eastern minor axis to 60 kpc. With the assumption of no alpha enhancement ((\([\alpha/Fe]\) = 0.0), they translate this to \([Fe/H] = -1.2\) dex. Their \([M/H]\) measurement was obtained by directly converting the average colour \((g-i)_0\) to metallicity with the use of the calibration of Streich et al. (2014). The authors acknowledge that while the conversion is not rigorously defined, the method is validated by the fact that their \([M/H]\) estimate is similar to the one measured by Durrell et al. (2010). As mentioned before, this may not be a good metric, as the Durrell et al. (2010) measurement is not sampling the halo. Indeed, note that measuring the metallicity of the halo at 30 kpc along each minor axis gives the same metallicity, even though the gradients are different.
2.7.4 Stellar Halo Radial Density Profile

The stellar density profile of M81 constructed in this work covers an unprecedented semimajor radius range of 70 arcmin. The diffuse light and star count profiles used in tandem have provided a view on the M81 structure from its inner bulge-dominated regions to the outskirts of the stellar halo. I find that the stellar halo does not have a break in its profile as has been suggested for the Milky Way stellar halo (e.g., Deason et al., 2011), but has a steady decline like M31 (Ibata et al., 2014). Nevertheless, the overall profile appears to gradually flatten beyond 18–20 arcmin, which is where the halo starts to dominate (see also Barker et al., 2009). The composite surface brightness profiles in Harmsen et al. (2017) and Smercina et al. (2020) also appear to have breaks in the profiles, but they are likely to be artificial as the breaks happen exactly at the radius where the diffuse light and resolved star profiles are joined in their work. It should be noted that they use diffuse light profiles from Spitzer and WISE that only extend to 17′ and 10′ respectively.

The estimated slope of the stellar halo power law \( \gamma = -1.6 \pm 0.1 \) is shallow compared to the recent measurements from Harmsen et al. (2017) \( \gamma = -3.53 \pm 0.18 \) and Smercina et al. (2020) \( \gamma = -2.59 \). These two measurements (which come from the same group) come from HST pencil beam studies and wide-field resolved star counts respectively and both focus on the Eastern minor axis as done here. In Smercina et al. (2020), the group state that the Harmsen et al. (2017) slope has been affected by an oversubtraction of the background and that the value of \( \gamma = -2.6 \) (provided with no uncertainty) is more reliable. Barker et al. (2009) have characterised their profile of M81 with a power law of \( \gamma \sim -2 \). My measurement for M81 \( \gamma = -1.6 \pm 0.1 \) is much closer to this than the Harmsen et al. (2017) and Smercina et al. (2020).

Comparing these results to the Local Group counterparts, the M31 halo has a power law fall-off of \( \gamma = -2.08 \pm 0.02 \) (Ibata et al., 2014), and the Milky Way has a power law fall-off of \( \gamma = -2.3 \pm 0.1 \) which has been suggested to break into a steeper power law of \( \gamma = -4.6 \pm 0.2 \) beyond 27 kpc (Deason et al., 2011). These values are similar but slightly steeper than the value of \( \gamma = -1.6 \pm 0.1 \) that I have found for M81.
Figure 2.34: Stellar halo mass–metallicity relation. The magenta points represent AURIGA simulations (Monachesi et al., 2019) and the green points are observations from Harmsen et al. (2017). The measurements for the Milky Way outer stellar halo are taken from Sesar et al. (2011) and Fernández-Alvar et al. (2017) (cyan), while the measurements from the H3 and APOGEE surveys are shown in purple (Mackereth & Bovy, 2020; Conroy et al., 2019). For M31, the photometric measurements are from Gilbert et al. (2014) (black), while the spectroscopic metallicity in yellow is from Escala et al. (2020). My measurements for the M81 halo are shown in red and orange, while those of Smercina et al. (2020) are shown in blue.
2.7.5 Stellar Halo Mass

The Spitzer S4G survey estimated that M81 has stellar mass of $6.025 \times 10^{10} M_\odot$ \cite{Muinoz-Mateos2015}. My measurement of the disk+bulge stellar mass is $5.86 \pm 0.25 \times 10^{10} M_\odot$, meaning that the estimated stellar masses are consistent and within 1σ.

\cite{Smercina2020} estimated that the stellar halo of M81 makes only a small contribution to the stellar mass ($1.16 \times 10^9 M_\odot$), suggesting that the most massive major merger M81 has endured is meager in comparison with the mergers with M82 and NGC 3077 that are now ongoing. The authors argue that M81 in its current state is much alike the Milky Way in terms of its stellar halo properties, i.e. the relatively low metallicity and mass of the stellar halo. In contrast, my estimated halo mass is $5.1 \pm 1.8 \times 10^9 M_\odot$, roughly 4 times higher, while my measured metallicity is somewhat lower.

My estimate of the $8.0 \pm 2.5\%$ of total light and stellar mass contributed by the stellar halo to the M81 galaxy is rather high, and may be partially explained by the interaction with M82 and NGC 3077. However, a more in–depth analysis will be required to disentangle their contribution to the stellar halo of M81 to draw such conclusions.

Similar to the dwarf galaxy luminosity–metallicity relation \cite{Kirby2013}, a correlation has been suggested between stellar halo mass and its metallicity \cite{Harmsen2017}. At 30 kpc and beyond, the contribution of stars from accreted galaxies is expected to dominate over the in–situ counterparts \cite[e.g.,][]{Abadi2006,Pillepich2015}. Monachesi et al. \cite{Monachesi2019} combine GHOSTS measurements for nearby galaxies taken from \cite{Harmsen2017} with Auriga simulations and demonstrate the broad agreement between the two.

To explore how my measurements of the M81 halo compare to this trend, I take the average metallicity of my Eastern and Western axis measurements at 30 kpc ($[M/H] = -1.45 \pm 0.13$) and transform $[M/H]$ to $[Fe/H]$. I use the $[M/H]–[Fe/H]$ relation provided by \cite{Salaris1993} and consider two cases – no alpha enhancement ($[\alpha/Fe] = 0.0$) and modest alpha enhancement ($[\alpha/Fe] = 0.2$):

$$[M/H] = [Fe/H] + \log 10(0.638 \times 10^{[\alpha/Fe]} + 0.362) \quad (2.16)$$
This results in $[Fe/H]$ of $-1.45 \pm 0.13$ and $-1.59 \pm 0.13$. These values are plotted along with my measurement of stellar halo mass in Figure 2.34 (red and orange stars). The measurement from Smercina et al. (2020) is also shown (blue). As noted before, compared to Smercina et al. (2020), my halo mass estimate is higher and metallicity is lower. The higher halo mass stems in part from the shallower profile.

However, the stellar mass–metallicity relation here is defined by results from high-mass galaxies from AURIGA simulations (Monachesi et al., 2019) (magenta), and lower mass galaxies from pencil-beam HST surveys (Harmsen et al., 2017, green). While both earlier results of the Milky Way outer halo (cyan Sesar et al., 2011 Fernandez-Alvar et al., 2017) and more recent H3 and APOGEE Milky Way surveys (purple Conroy et al., 2019, Mackereth & Bovy, 2020) both agree with the relation, the M31 results show some disagreement. For example, the M31 photometric measurements (black) from Gilbert et al. (2014) follow the relation well, but there are more recent spectroscopic studies of M31 (yellow) that suggest far lower metallicities at 30 kpc than photometrically estimated before (Escala et al., 2020). The spectroscopic result is more metal-poor, thus pulling M31 far off of the relation. Therefore, while the stellar mass–metallicity relation is a good testbed for comparison of results, it may not be iron-clad.

My measurement of the stellar halo mass sits firmly in the middle of the Milky Way and M31 and has smaller uncertainties than Smercina et al. (2020). While my metallicity is lower, it is comparable to some measurements for the Milky Way and M31. It is clear that the behaviour of this plot is highly dependent on the particular datasets used for comparison and it is premature to draw strong conclusions. Analyses of the full HSC dataset will allow the stellar halo to be studied to large radii in all directions. They will be crucial in order to firmly place it on the stellar halo mass–metallicity relation.
Chapter 3

Project Bangpūtyts: F8D1: A Tidally-Disrupting Ultra-Diffuse Dwarf Galaxy in the M81 Group

Bangpūtyts is the Baltic god of sea and storm. He is considered a vindictive and wrathful god, worshipped by fishermen and seamen.

3.1 Introduction

In this chapter, I examine an ultra–diffuse galaxy (UDG) in the M81 Group that represents the best local example of this galaxy type. While most famously known for its triplet of interacting galaxies (M81–M82–NGC3077), the nearby M81 Group (D = 3.6 Mpc; Radburn-Smith et al. 2011) hosts a low luminosity galaxy with properties that unequivocally place it in the UDG realm. F8D1 was discovered more than 20 years ago by Caldwell et al. (1998, hereafter C98) during a CCD survey for M81 Group analogues to Local Group dwarf elliptical galaxies. It has a luminosity of $M_V \sim -14$ or $\sim 4 \times 10^7$ L$_\odot$ and lies roughly 2 degrees in projection from M81 in a region that is heavily contaminated by Galactic cirrus (Sandage 1976). Although C98 remarked on the fact that its low central surface brightness ($\mu_V(0) \sim 25.4$ mag arcsec$^{-2}$) and large effective radius ($R_{\text{eff}} \sim 2.5$ kpc) were in stark contrast to those of most galaxies known at that time, F8D1 has barely received any attention beyond its initial discovery.
Figure 3.1: Left: The M81 Group survey footprint (7 HSC pointings) overlaid on an SDSS image. Each HSC pointing has a diameter of 1.5 degrees and the known galaxies within this area are marked. The red circle indicates the pointing containing F8D1, which is the focus of this chapter. Right: A portion of a deep $i$–band image taken with CFHT/MegaCam that shows a zoom–in on the central region of the red–circled HSC pointing. Highly–structured cirrus is present throughout this region of the sky which greatly complicates integrated light studies of the low surface brightness emission of F8D1 and its neighbours. F8D1 appears projected over a particularly bright ISM filament. The scalebar in both panels reflects the physical scale at the distance at M81. North is up and east is to the left.
Using *Hubble Space Telescope* Wide Field Planetary Camera 2 (HST/WFPC2) data, C98 were able to resolve the upper two magnitudes of the red giant branch (RGB) of F8D1 and use the luminosity of the RGB tip to firmly place it at the distance of the M81 Group (see also Karachentsev et al., 2000). They also used the colour of the RGB to measure the mean metallicity of the galaxy as $[Fe/H] = -1.0 \pm 0.26$ dex, with no significant radial abundance gradient and showed that it hosts a considerable population of luminous asymptotic giant branch (AGB) stars. Such a population is a testament to an extended period of star formation; C98 argued that roughly 30% of the stellar population was of intermediate age, with the youngest stars having formed only 3–4 Gyr ago. A single globular cluster candidate was identified near the centre of the galaxy. This object was selected on the basis of its semi–resolved morphology and integrated colour. It is rather blue ($V - I \sim 0.76$) which could be indicative of a low metallicity. On the other hand, Chiboucas et al. (2009) report a radial velocity of $-125 \pm 130$ km s$^{-1}$ for this object which leaves open the possibility it is a background galaxy. Unfortunately, there has been no published radial velocity for F8D1 yet.

### 3.2 The Data

#### 3.2.1 HSC Observations and Data Reduction

In this work, I focus on one particular HSC pointing from the M81 Group survey analysed in Chapter 2 – the Southwest field highlighted in the left panel of Fig. 3.1 which contains F8D1 near its Southwestern edge. The total exposure time for this field is 6160s (28 $\times$ 220s) and 6900s (32 $\times$ 210s) in the $g$– and $i$–filters, respectively. This field also includes two additional M81 Group members, the low mass spiral NGC 2976 and the dwarf galaxy F12D1 (also known as [KK98] 077).

The HSC data were processed entirely by me using the native image reduction pipeline `hscPipe 8.4` (Bosch et al., 2019), developed as a precursor to the Rubin Observatory data reduction pipeline (Axelrod et al., 2010; Jurić et al., 2017; Ivezić et al., 2019). The images were corrected for bias, dark count and flat-fielding, and the sky was modelled internally and subtracted from each frame. The frames in each filter were then mosaicked and co–added after photometrically and astrometrically calibrating against Pan–STARRS1 (Magnier et al., 2013). The final photometry is in the HSC filter system and in AB magnitudes.
I also used hscPipe to perform point spread function–fitting (PSF) photometry on the co–added $g$– and $i$–band frames, forcing the photometry on the $i$–band at the positions of the $g$–band (primary) detections. Experimentation revealed that source detection across the field was optimised when an aggressive 32–pixel (5.4′′) mesh was used to subtract the sky from each frame. While this removed the local sky very well and aided in point source detection, it rendered the co–adds unusable for diffuse light analyses. The source catalogue was initially cleaned by retaining only sources that have signal–to–noise ratio (SNR) $\geq 5$ in both bands. Extended sources were subsequently excluded by considering the PSF to cmodel flux ratio. Cmodel flux is fitted by a combination of S´ersic profiles with S´ersic indices $n = 1$ and $4$, used for extended sources such as galaxies. Following Pucha et al. (2019), I classify an object as point–like if the $f_{PSF}/f_{cmodel}$ ratio is within $1\sigma$ of unity at the respective magnitude.

3.2.2 Corrections to the Stellar Catalogue

To assess the completeness of the HSC catalogue, I conduct comparisons to archival HST pointings that fall within the HSC FOV. I select three Advanced Camera for Surveys (ACS) pointings from GO 16191 which consist of exposures of 1103s and 1153s in the F606W and F814W passbands, respectively. These HST/ACS datasets detect stars to roughly three magnitudes below the TRGB and hence are about a magnitude deeper than my HSC dataset. As a result, they can be considered to be 100% complete relative to my ground–based RGB photometry. While the 50% completeness limits of the HST data used in this work are unknown, a first–order estimate can be deduced from the GHOSTS survey results Monachesi et al. (2016), which have already been discussed in Section 2.1. Field 17 of the M81 GHOSTS survey is in the area of similar stellar density as the F8D1 fields, and it is 50% complete down to F814W$_0 \sim 26.5$ mag. This field was observed for 680s in F814W band. The F8D1 HST fields were observed 2715s in F814W band, meaning that the 50% completeness limit will be significantly fainter than F814W$_0 \sim 26.5$ mag, and can therefore be interpreted as 100% complete for this study.

The chosen HST/ACS fields sample a distance range of 6–14 arcmin from the centre of F8D1. Two of the fields lie to the Northeast of F8D1, along the major

\footnote{The particular datasets used are: JEEA32010, JEEA32020, JEEA33010, JEEA33020, JEEA35010, JEEA35010.}
axis and are roughly coincident with the feature I discuss in Sec. 3.3, whereas the third field lies Southeast of the centre along the minor axis. After conducting photometry on the flc images using DOLPHOT (Dolphin, 2016), I searched for positional matches between stellar sources in the HST/ACS catalogue (selected using the criteria defined in Radburn-Smith et al., 2011) and those in my HSC catalogue. I then convert the HST/ACS F606W and F814W magnitudes of the sources onto the HSC $g$- and $i$-band filter system using transformations that I derived and presented in Chapter 2. Finally, I merge the catalogues of stars in the three HST/ACS fields into one, thus ensuring that the completeness curves do not suffer from statistical noise in less populated magnitude bins. I bin the stellar sources in varying $g$- and $i$-band magnitudes separately, both within the colour limit of $1.0 < (g-i)_0 < 3.0$ to encompass the RGB stars. For each bin, I determine the fraction of the HSC sources which appear in the HST catalogue and characterise the behaviour by fitting Equation 7 of Martin et al. (2016) to the recovered fraction as a function of magnitude. I find that the $i$-band catalogue reaches the 50% completeness limit at 25.35 mag, while the $g$-band catalogue is 50% complete until 27.06 mag. I use these completeness curves to produce a 2-D histogram that represents the completeness fraction as a function of magnitude and colour and in the subsequent analyses I correct the HSC photometric catalogue where appropriate. It is worth noting that all the analyses in this chapter concern RGB stars above the 50% completeness level, so these corrections are never dominant.

The M81 Group lies in a part of the sky with significant and highly variable extinction from foreground dust. In Fig. 3.2, I show the magnitude of foreground extinction in the $g$-band towards the F8D1 field as derived from the Schlegel et al. (1998) reddening map with corrections from Schlafly & Finkbeiner (2011) and the HSC filter coefficients provided in Rodrigo & Solano (2020). The values of $A_g$ reach up to 0.6 mag in some regions and so it was necessary to do a star-by-star extinction correction. I use the extinction-corrected PSF magnitudes for the remainder of this chapter, which will be referred to as $g$ and $i$ hereafter.

### 3.2.3 Ancillary Low Surface Brightness Data

As previously mentioned, the sky subtraction method I have adopted within hscPipe optimises the detection of point sources but removes large portions of diffuse galaxy light. I found that reprocessing the data using a global sky
subtraction (which corresponds to super–sky pixels of 1000 × 1000 pixels in hscPipe) still results in a visible oversubtraction of the galaxy light. To facilitate integrated light analysis of the main body of F8D1, deep images were acquired by our collaborator Jean–Charles Cuillandre in the $g,r,i$ filters with the 1.1 square degree MegaCam imager on the 3.6m Canada–France–Hawaii Telescope (CFHT) between Feb 6 and Mar 3 2022. The images were obtained using an observing technique that is optimised for low surface brightness (LSB) surveys at CFHT (e.g., Ferrarese et al. 2012; Duc et al. 2015).

The right panel of Fig.3.1 shows the central high SNR portion of the CFHT stacked $i$–band image (the sky area covered by all 7 exposures from the LSB set), with the main galaxies in the field indicated. This deep image also serves to beautifully illustrate the complex nature of the F8D1 field in terms of galaxy locations and foreground cirrus. It demonstrates precisely why the wide–field resolved star approach described in Sec. 3.2.1 is the only means to study stellar features in the M81 Group at extremely low surface brightness levels. As expected, the cirrus features in the right panel of Fig.3.1 generally agree with the areas of high extinction seen in Fig. 3.2.

### 3.3 A Stream from F8D1

Fig. 3.3 shows the spatial density distribution of candidate RGB stars across the HSC field in a standard coordinate projection anchored to the pointing centre. The sources are selected from the stellar catalogue to lie within a polygonal region on the colour–magnitude diagram (CMD). This region is defined to isolate old metal–poor stars ([M/H]$=−2.0$ to $−1.0$ dex and $\sim 10$ Gyr) and extends down to $i = 25.5$, where I have $\gtrsim 50\%$ completeness (see Fig. 3.4). As the three galaxies in the field are all low mass systems, this metallicity range captures the bulk of the RGB stars in the field.

The most striking feature in this map is a giant stream of stars which extends from F8D1 to the Northwest, in the direction of NGC 2976 and M81. This feature can be visibly traced for at least a degree on the sky (and $\approx$ two–thirds of the HSC field), and can be seen on both sides of NGC 2976. Along with F8D1 and its tidal stream, NGC 2976 and F12D1 also appear as prominent overdensities in this field, both of which have stellar extents that are considerably larger than previously thought (Karachentsev et al. 2000; Simon et al. 2003). To illustrate
Figure 3.2: Foreground extinction in the F8D1 HSC field derived from the Schlegel et al. (1998) map, calibrated with the HSC $g$–band coefficients from Schlafly & Finkbeiner (2011). The large white circle shows the approximate footprint of the HSC pointing analysed here, with the main galaxies marked. The small white circle delineates $3 R_{\text{eff}}$ around F8D1 derived from my results.
this, a DSS cutout of the main optical body of NGC 2976 is superposed on the star count map of Fig. 3.3 (left); this is the only one of the three galaxies that is of high enough surface brightness to be seen in the DSS. All three galaxies have voids in their central regions where the \texttt{hscPipe} failed to return good resolved star photometry due to crowding and the high brightness background.

The right panel of Fig. 3.3 shows a deep false–colour image created from combined CFHT $g, r$ images with the contours from the RGB map overlaid. These contours have been created by binning the star count map into 0.5 arcmin bins and gaussian–smoothing with a kernel of 1 arcmin, and represent levels of 0.7, 1, 2 and $3\sigma$ above the background. This visualisation underscores the fact that the tidal tail I have uncovered via star counts is completely impossible to discern on a deep integrated light image due to the bright cirrus in the field. Indeed, while there is an apparent distortion of F8D1 towards the Northeast in integrated light (also noted by \textcite{C98}), this feature is complicated by Galactic cirrus since its position angle is offset somewhat from that of the tidal stream. In contrast to F8D1, the outer star count contours of NGC 2976 and F12D1 are well–behaved and show no evidence that these systems are tidally distorted in their outer regions.

Fig. 3.4 shows various Hess diagrams constructed from the stellar catalogue with PARSEC isochrones (\textcite{Bressan12}) with fixed age of 10 Gyr and varying metallicity $[M/H]$ of $-2.0$ to $-1.0$ overlaid. The 50% completeness level is shown as a yellow line and the polygonal region used to select RGB stars is delineated in red. The top left panel shows sources across the full HSC field. In addition to the conspicuous RGB around $0.7 \leq (g - i)_0 \leq 2.0$, the other obvious sequence that can be seen is due to unresolved background galaxies which populate bluer colours, $-0.5 \leq (g - i)_0 \leq 0.7$. The top right panel shows the Hess diagram for a circular region of radius 6 arcmin which is centered on F8D1, and bottom left panel shows a region extending from 6 to 24 arcmin away from F8D1 along the tidal stream. Compared to the Hess diagram of a similarly–sized reference field (bottom right) that lies far from the main galaxies and tidal stream, these panels show prominent RGBs. The Hess diagram of F8D1 shows no evidence of recent star formation in the form of young MS stars, although it does reveal a significant population of luminous AGB stars above the RGB tip, as earlier pointed out by \textcite{C98}
Figure 3.3: Left: The RGB star count density across the HSC pointing. A giant tidal stream can be seen emanating from F8D1, which is located at the Southwestern edge. The stream can be traced for more than a degree ($\gtrsim 60 \text{ kpc}$) towards the Northeast, in the direction of NGC 2976 and M81. A DSS image of NGC 2976 is superposed for scale and the hollow centres of the galaxies indicate regions where the pipeline failed to return photometry. Right: A CFHT false–colour image created from combined $g, r$–band observations with the RGB stellar density contours representing $0.7, 1, 2$ and $3 \sigma$ from the left panel overlaid. Diffuse emission from Galactic cirrus covers the whole field.
Figure 3.4: (a): The Hess diagram of stellar sources across the full HSC field. (b): The Hess diagram of stellar sources within a circular radius of 6 arcmin of F8D1. (c): The Hess diagram of a region extending from 6 to 24 arcmin away from F8D1, along the direction of the tidal stream. (d): The Hess diagram of a reference field with circular radius 9 arcmin, located well away from the tidal stream and main galaxies. The RGB star selection box (red) and 10 Gyr isochrones of varying metallicity ([M/H] = -2.0, -1.5, 1.0) are overlaid in each case. Note the RGB populations in the area of F8D1 and its stream are not visible in the reference field. The solid yellow line shows the 50 percent completeness threshold.
3.3.1 TRGB Distances

While the distances to F8D1 and NGC 2976 have previously been determined using various HST datasets (e.g., Caldwell et al. 1998; Karachentsev et al. 2000; Dalcanton et al. 2009), I decided to rederive these in a consistent manner with my HSC dataset. I use the tip of the RGB (TRGB) method (e.g., Lee et al. 1993; Sakai et al. 1996) and follow the procedure described in Okamoto et al. (2019).

I begin by defining regions around the galaxies that are to be used for analysis. For F8D1, I select all stars lying within 6.6 arcmin of my adopted center (see Sec. 3.3.2) and for NGC 2976 I use stars lying within a radius of 10 arcmin. For each system, I select stars with colours in the range \((g - i)_0 < 2.25\) and with photometric errors smaller than 0.5 mag. I then construct their luminosity functions which are convolved with a Sobel filter (Kanopoulos et al. 1988). The same method is also applied to stellar sources in empty reference fields of the same area so that I can subtract off the foreground and background contamination.

The highest peaks in the convolved luminosity functions are determined to be \(i_{\text{TRGB}} = 24.28 \pm 0.03\) and \(24.18 \pm 0.02\) for F8D1 and NGC 2976, respectively. The luminosity functions of the main body of F8D1 and the reference field are shown in Figure 3.5. The red line represents the output of a Sobel filter used on a reference field-subtracted F8D1 main body luminosity function. The highest peak represents the best-fitting TRGB magnitude, corresponding to a line-of-sight distance of \(D = 3.67\) Mpc.

Okamoto et al. (2019) used PARSEC v1.2 stellar models to explore how the \(i\)-band absolute magnitude of the TRGB varies with \((g - i)_0\) colour assuming metallicities of \([M/H] < -1.0\) and 10–13 Gyr ages. I measure a median colour of \((g - i)_0 = 1.87 \pm 0.12\) for TRGB stars in F8D1 which using Eqn. (1) of Okamoto et al. (2019) translates into \(M_{i_{\text{TRGB}}} = -3.55 \pm 0.02\). Therefore, the distance modulus to F8D1 is \((m - M)_0 = 27.82 \pm 0.03\), corresponding to \(D = 3.67\) Mpc \(\pm 0.06\) Mpc. This is in excellent agreement with the distance moduli of 27.82–28.88 which have been derived from previous HST studies (Karachentsev et al. 2000; Ferrarese et al. 2000; Dalcanton et al. 2009).

Similarly, I measure a median colour of \((g - i)_0 = 1.89 \pm 0.08\) for TRGB stars in NGC 2976 which translates to \(M_{i_{\text{TRGB}}} = -3.55 \pm 0.02\) and a distance modulus of NGC 2976 is \((m - M)_0 = 27.72 \pm 0.02\), or \(D = 3.50\) Mpc \(\pm 0.04\) Mpc. This is also in very good agreement with the literature value of 27.76 derived by Dalcanton et al. (2009). The uncertainties on my measurements include photometric errors, the
Figure 3.5: Luminosity functions of the main body of F8D1 and a reference field. The result from applying the Sobel filter to a reference field–subtracted luminosity function of F8D1 is depicted as a red curve. The highest peak represents the best–fitting TRGB magnitude, corresponding to a line–of–sight distance of $D = 3.67$ Mpc.
$M_{	ext{TRGB}}$ calibration uncertainty and the reddening uncertainty. I do not include uncertainties arising from the assumption of a single fixed age, or the variance in TRGB luminosity according to different stellar models, which are likely to be far larger.

These measurements confirm that F8D1 and NGC 2976 lie at different distances, separated along the line–of–sight by $\sim 170$ kpc. The angular distance between F8D1 and NGC 2976 is 0.53 degrees, which corresponds to a projected separation of 34 kpc and a 3D distance of 173 kpc. There are insufficient stars near the TRGB for me to be able to measure a distance gradient along the stream itself but it seems safe to assume that this feature lies well behind NGC 2976 along the line–of–sight.

### 3.3.2 Structural Analysis of F8D1

Before proceeding to analyse the properties of the stream, I revisit the properties of the main body of F8D1 and update its measured structural parameters. As the stars in the inner parts of the galaxy are poorly detected due to aforementioned issues, a structural analysis using resolved stars is not viable and I need to utilise diffuse light instead. However, as mentioned in Sec. 3.2.3, my implementation of hscPipe does not preserve the LSB emission of galaxies, leaving F8D1 with a large fraction of diffuse light missing in the final stack. Instead, I investigate the structure of the main body of F8D1 using the MegaCam LSB images.

I use the AutoProf software (Stone et al., 2021) to construct the surface brightness profile of F8D1. Based on visual inspection, the contaminating cirrus is less severe in the $i$–band image (the galaxy gets brighter while the cirrus gets fainter with respect to the higher sky brightness) and hence I decided to use that as the primary image for fitting the isophotes and extracting surface photometry. The ellipse parameters derived from this run of AutoProf were then applied to the $g$– and $r$–band images.

To assess the impact of contamination by foreground cirrus in the vicinity of F8D1, the images were compared against WISE 12 $\mu$m observations using the highest resolution maps from Meisner & Finkbeiner (2014). Our collaborators produced cirrus–corrected MegaCam images through an iterative scaling process that flattens the background around F8D1 on the $g,r$ images. The $i$–band was found to be unaffected and so does not require any correction. Comparing the
Table 3.1: Properties of F8D1 measured in this chapter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.A. (J2000.0)</td>
<td>09:44:45.95</td>
</tr>
<tr>
<td>Dec (J2000.0)</td>
<td>+67:26:27.7</td>
</tr>
<tr>
<td>$M_{g0,\text{direct}}$ (mag)$^a$</td>
<td>$-13.42 \pm 0.03$</td>
</tr>
<tr>
<td>$M_{g0,\text{Sérsic}}$ (mag)$^b$</td>
<td>$-13.70 \pm 0.04$</td>
</tr>
<tr>
<td>$(g-r)_0$ $^c$</td>
<td>$0.764 \pm 0.003$</td>
</tr>
<tr>
<td>$(r-i)_0$ $^c$</td>
<td>$0.310 \pm 0.004$</td>
</tr>
<tr>
<td>$(m-M)_0$</td>
<td>$27.82 \pm 0.03$</td>
</tr>
<tr>
<td>$D$ (Mpc)</td>
<td>$3.67 \pm 0.06$</td>
</tr>
<tr>
<td>$E(B-V)$</td>
<td>$0.11$</td>
</tr>
<tr>
<td>$[\text{M/H}]$ (dex)</td>
<td>$-1.14 \pm 0.09$</td>
</tr>
<tr>
<td>$\sigma[\text{M/H}]$ (dex)</td>
<td>$0.37$</td>
</tr>
<tr>
<td>PA (deg)$^d$</td>
<td>$90.4 \pm 5.1$</td>
</tr>
<tr>
<td>$\epsilon^d$</td>
<td>$0.12 \pm 0.01$</td>
</tr>
<tr>
<td>$M_*$ ($M_\odot$)$^e$</td>
<td>$\sim 6.8 \times 10^7$</td>
</tr>
</tbody>
</table>

$^a$ The measured magnitude of the main body of F8D1 inside a radius of 3.6 arcmin.

$^b$ The inferred total magnitude of the main body of F8D1 through extrapolation of the Sérsic profile.

$^c$ The mean colour inside a radius of 3.6 arcmin.

$^d$ Average over the radial range 0.5–1.5 arcmin.

$^e$ Main body stellar mass calculated using the inferred total magnitude.
Table 3.2: Sérsic fits and derived parameters for the main body of F8D1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>g</th>
<th>r</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>0.53 ± 0.01</td>
<td>0.56 ± 0.01</td>
<td>0.56 ± 0.01</td>
</tr>
<tr>
<td>$\mu(0)$</td>
<td>25.69 ± 0.01</td>
<td>25.08 ± 0.01</td>
<td>24.68 ± 0.01</td>
</tr>
<tr>
<td>$R_h$ (arcsec)</td>
<td>119 ± 0.6</td>
<td>119 ± 0.8</td>
<td>125 ± 1.1</td>
</tr>
<tr>
<td>$R_{\text{eff}}$ (arcsec)</td>
<td>100 ± 0.8</td>
<td>105 ± 1.2</td>
<td>109 ± 1.6</td>
</tr>
<tr>
<td>$M_{0,\text{Sérsic}}$ (mag)$^a$</td>
<td>−13.70 ± 0.04</td>
<td>−14.32 ± 0.04</td>
<td>−14.82 ± 0.04</td>
</tr>
</tbody>
</table>

$^a$ The inferred total magnitude through extrapolation of the Sérsic profile.

**AutoProf** photometry extracted from the $g, r$ images with and without this cirrus correction shows no change to the profiles. However, it did reveal a slight artificial boosting of the surface brightness due to cirrus, requiring a correction of +0.22 mag to the $g$–band profile and +0.20 mag to the $r$–band profile.

In Fig. 3.6 I show the three extracted surface brightness profiles (top) and the colour profiles (bottom). These have been corrected for foreground extinction using a single average value of $E(B-V)=0.11$. The uncertainties returned by **AutoProf** are purely statistical in nature. Systematic effects, such as those due to residual cirrus contamination and/or sky residuals, are likely to be several times higher. I also overplot the surface brightness of profile of C98 transformed to the $g$–band using the equations in Komiyama et al. (2018) and adjusted for my assumed extinction. This shows very good agreement with my own profile. The most significant departure is seen at radii $\gtrsim$2 arcmin, where the C98 profile shows a knee in the profile that I do not see in my data. While there are no strong colour gradients within the inner few arcmin of F8D1, there is a gradual trend to redder colours with increasing radius. Table 3.1 reports the mean colours of F8D1 measured within 3.6 arcmin. The ellipticity and position angle derived by **AutoProf** are essentially constant over the fit range, averaging to 0.12 ± 0.01 and 90.4 ± 5.1 degrees, respectively.

I fit a Sérsic profile ($I = I_0 e^{-(R/R_0)^{1/n}}$) to the surface brightness profiles, leaving all parameters free (Sersic, 1968). These fits, which are overlaid in Fig. 3.6, can be seen to provide a good description of the light profile across the main body of F8D1, out to roughly 3.5 arcmin. The values of the central surface brightness, $\mu(0)$, and the semimajor axis scale radius, $R_h$, are reported for each band in Table 3.2. The effective radii, $R_{\text{eff}}$, are also listed, which are obtained from the fit parameters using $R_{\text{eff}} = R_h b^n$, where $b = 2n - 0.324$ (Ciotti, 1991). Adjusting for my derived distance, I find that the effective radii slightly increase towards
redder bands, going from 1.7 kpc in the $g$–band to 1.9 kpc in the $i$–band. These values lie in between the initial value of 2.45 kpc found by C98 and the smaller value of 1.2 kpc reported by Chiboucas et al. (2009) from their $r$–band CFHT survey. When combined with my central surface brightnesses of $\mu(0) \sim 24.7–25.7$ mag arcsec$^{-2}$, it is clear that F8D1 has photometric and structural properties which firmly place it in the realm of UDGs.

I also revisit the luminosity of F8D1 using two different methods. Firstly, I sum the cumulative flux measured by AutoProf within the last measured isophote at 3.6 arcmin ($\sim 2.2 \ R_{g,\text{eff}}$) and find $M_g = -13.42 \pm 0.03$. Alternately, I can use the Sersic fits to infer the total magnitude using eqn. 12 of Graham & Driver (2005). This yields the slightly larger value of $-13.70$ in the $g$–band (see Table 3.2), as expected given that it extrapolates beyond the last directly measured datapoint. I adopt these two measures as the lower and upper limits on the true luminosity of the main body of the system. The latter value compares reasonably well to the total magnitude reported by C98 which, when transformed from $V$ to $g_{\text{hsc}}$ and adjusted for my measured distance and extinction, yields $M_g = -13.9$ mag. With the $i$–band magnitude and $(g-i)_0$ colour, I use eqn. 8 of Taylor et al. (2011) to calculate that F8D1 contains $\sim 6.8 \times 10^7 M_\odot$ in stellar mass.

### 3.3.3 Stream Profile

Visual inspection of Fig. 3.1 suggests that the tidal tail may have some curvature along its length, as projected on the sky. To quantify this, I consider the RGB star counts in $20 \times 6$ arcmin wide bins aligned with the direction of the tail. By fitting a Gaussian in the transverse direction, I find the peak RGB star density location in each bin which I take to represent the stream locus (Fig. 3.7). Bins lying 24 to 42 arcmin along the stream length are contaminated by stars from NGC 2976 and are omitted. I find that the stream curves $\sim 0.8$ arcmin ($\sim 0.9$ kpc) West of the main body at small radii (6–24 arcmin), and changes direction at larger radii, curving $\sim 1.1$ arcmin ($\sim 1.2$ kpc) to the east at distances of 40–60 arcmin. This is consistent with the S–shaped behaviour that is commonly seen in satellites that are being tidally stripped by a massive companion (e.g., Johnston et al. 2002).

I next investigate the stellar density profile along the tail. For this, I calculate the RGB surface density in $15 \times 6$ arcmin rectangular bins aligned along the direction of the tail. The $\sim 15$ kpc width of these bins matches well the visible width of
Figure 3.6: (Top panel) The extinction–corrected, background–subtracted surface brightness profiles of F8D1, derived from a diffuse light analysis of the MegaCam LSB data. Sérsic fits are overlaid. For comparison, I also show the $V$–band surface brightness profile of C98, which has been converted onto the HSC photometric system and adjusted for extinction (blue points). (Bottom panel) The extinction–corrected $(g - r)_0$ and $(g - i)_0$ colour profiles.
Figure 3.7: Peak RGB star density across the width of the stream, in bins placed sequentially along its length. The locations of the transverse peak densities are measured relative to that of the first bin, which corresponds to $\sim 4R_{g,\text{eff}}$ from F8D1. The region corresponding to $\sim 24$–$42$ arcmin along the length of the stream is omitted due to contamination from NGC 2976. Clear curvature can be seen.
the stream. The bins begin at a distance of 6 arcmin from the centre of F8D1 to avoid the regions where the crowding is severe and completeness corrections are very large. The distance range 24 – 36 arcmin is omitted due to the presence of NGC 2976. The stars counted are completeness corrected. A correction is made for contaminants using the mean source density inside the RGB selection box in nine 12 × 12 reference fields positioned far from the obvious overdensities in the HSC pointing. Fig. 3.8 shows the resultant profile, with the stream clearly traced to ≈ 60kpc. The error bars reflect the combination of Poissonian uncertainties on the RGB and contaminant source counts. The logarithmic stellar density profile can be described reasonably well by a Sérsic model with $R_h \sim 28$ arcmin and $n \sim 0.8$. Alternately, the outermost four points can be explained by a power-law fall off, with $\gamma \sim -3$.

I can calculate the luminosity of the stream by summing up the stellar light along its length. I first consider two large rectangular bins that span 6–24 arcmin and 42–60 arcmin along the tail, each of width 15 arcmin. These bins encompass the visible extent of the stream while avoiding the region contaminated by NGC 2976. I convert the $g$–band magnitudes of the RGB stars in each bin to flux and sum up the collective light, while also correcting for completeness of each RGB star. I then correct for light from contaminants using the mean contaminant density appropriately scaled to the size of my rectangular bins. To account for stars with magnitudes fainter than the RGB selection box, I simulate the luminosity function of a 10 Gyr stellar population with [$M/H$] = −1.1 using the Padova isochrones (Bressan et al., 2012). Once shifted to the F8D1 distance, the luminosity function shows that the RGB selection box encompasses 43% of total luminosity of the population. I therefore divide by this fraction to correct for unresolved stars.

Using the average of the luminosities in the two bins as a proxy for that in the 24–42 arcmin bin that is contaminated by NGC 2976, I calculate that the luminosity contained in the visible stream is $M_g =-12.03$ mag or $7.17\times10^6$ $L_{\odot}$. The luminosity of the main body of F8D1 is estimated to be $2.58-3.34\times10^7$ $L_{\odot}$, depending on whether the directly measured flux inside of 3.6 arcmin or the extrapolated total magnitude is used. These calculations make use of the absolute $g$–band magnitude of the Sun, $M_{g,\odot} = 5.11$, provided by Willmer (2018). The HSC imagery currently only captures one side of the F8D1 stream but I make the assumption that an analogous tail exists to the Southwest. Multiplying the stream luminosity by a factor of two to account for this, I infer that 30–36% of F8D1’s light is contained in the extratidal features. I also calculate that the average surface brightness of the observed stream over the defined area is $\mu_g \sim 32$. 

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Figure 3.8: The RGB stellar density profile along the stream length constructed using 8 arcmin wide bins at intervals of 6 arcmin and corrected for contaminants. The bins at ~24–36 arcmin were omitted due to the presence of NGC 2976 at this location. The dashed line shows a Sérsic fit to the profile.
Figure 3.9: The completeness–corrected and contaminant–subtracted MDF (blue) of the main body of F8D1, constructed using RGB stars lying within $3R_{\text{eff}}$ of the galaxy centre. The peak metallicity is derived from a Gaussian fit to the MDF after subtracting the contribution of contaminants.

mag arcsec$^{-2}$, which is significantly fainter than any previous integrated light studies of this area have reached. I note that it is not possible to directly join the star count profile of the stream (Fig. 3.8) with the integrated light profile of the main body (Fig. 3.6) since there is no radial range where the two profiles overlap.

### 3.3.4 Metallicity of F8D1 and its stream

I investigate the metallicity distribution function (MDF) of resolved stars in the main body and tidal stream of F8D1 using their photometric metallicities ($[M/H]$). I select PARSEC isochrones of age 10 Gyr and spanning a metallicity range of $-2.2$ to $-0.3$ dex in intervals of 0.05 dex, and shift them to the distance of F8D1. Each star within the RGB selection box is matched to the closest isochrone in colour (for its magnitude) and assigned that metallicity if the colour difference is $\leq 0.05$ mag. The same procedure is performed on a reference field, far removed from the stream, to allow construction of the MDF of the contaminant population.
Figure 3.10: The completeness–corrected and contaminant–subtracted MDF in bins along the length of the F8D1 stream, constructed in a similar way to that shown in Fig. 3.9. In the top left corner of each plot, the mean metallicity is displayed. Below it is the dispersion of the Gaussian fit. On the top right corners is the distance from the main body of F8D1 along the stream in both arcmin and kpc.
I note that the metallicities of the contaminant population are meaningless, since these sources are either background galaxies or Milky Way foreground stars and hence not at the distance of F8D1.

To calculate the main body MDF, I consider RGB stars lying within \( \sim 3R_{\text{g,eff}} \). Fig. 3.9 shows the completeness–corrected and contaminant–subtracted MDF (blue) which exhibits a clear peak and significant dispersion. The orange histogram represents the distribution of the contaminants in reference field, scaled to the same area. To characterise the MDF, I fit a Gaussian to estimate the mean metallicity and dispersion which I find to be \( \langle [M/H] \rangle \) of \(-1.14 \pm 0.09\) dex and \( \sigma([M/H]) = 0.37 \). The errors come from sampling the selected stars from a Gaussian distribution where the width was chosen to be the photometric error of each star centred on the measured magnitude, repeated for \( N = 2000 \) times. The mean metallicity and dispersion compare reasonably well to the values of \( \langle [Fe/H] \rangle = -1.0 \pm 0.15 \) dex and \( \sigma([Fe/H]) = 0.26 \pm 0.03 \) estimated by C98 although the metallicity scales are different between these studies. It should also be kept in mind that the MDF for the main body of F8D1, while based on a sample of several hundred stars, suffers from significant incompleteness. As seen in Fig. 3.4 this is most likely to affect stars with the reddest colours and hence highest metallicities for a fixed 10 Gyr age.

Fig. 3.10 shows the completeness–corrected and contaminant–subtracted MDFs along the stream, using the same rectangular bins as used to construct the stream radial profile (Sec. 3.3). Again, I use Gaussian fits to characterise the mean metallicity and dispersion in each bin. Beyond \( \sim 20 \) kpc, the stream MDFs become increasingly noisy although a clear excess of stars above the expected contaminant population is present in all cases. From inspection of the panels, it is clear that there is no obvious metallicity gradient present. This suggests that the main body of F8D1 was chemically well–mixed prior to disruption, consistent with the lack of any significant colour gradient in the main body.

Fig. 3.11 shows where F8D1 (stars) lies relative to the luminosity–metallicity relation defined by Local Group dwarfs (black dots) and Local Group UDGs (coloured triangles Collins et al., 2020; Ji et al., 2021). I have taken the spectroscopic metallicities and the fit relationship from Kirby et al. (2013). The luminosity of F8D1 is transformed from the HSC \( g \)–band to V using the conversion factors of Komiyama et al. (2018). To convert my measured \([M/H]\) to \([Fe/H]\), I use eqn. 3 of Salaris et al. (1993) that requires knowledge of the alpha enhancement \([\alpha/Fe]\). While there are no \([\alpha/Fe]\) measurements for F8D1,
Figure 3.11: Luminosity–metallicity relation of Local Group dwarf galaxies and F8D1. The black points are taken from Kirby et al. (2013), including the best-fit and rms lines from eqn. 3 in the paper. The red and blue stars represent F8D1 with $\alpha/Fe = 0.0$ and 0.4 dex, respectively. The lower luminosity points include the main body light only, the higher luminosity represent the main body with added light from the two tidal tails. The known Local Group UDGs are shown as coloured triangles.
Ruiz-Lara et al. (2018) find that the average $\left[ \alpha/Fe \right]$ for their UDGs is $\sim 0.4$. I place F8D1 on this diagram assuming both $\left[ \alpha/Fe \right] \sim 0.0$ (red) and $\left[ \alpha/Fe \right] \sim 0.4$ (blue). In the case for $\left[ \alpha/Fe \right] \sim 0.4$ (blue), F8D1 falls on the same side of the relation as the known Local Group UDGs. While F8D1 lies more than 1$\sigma$ off the relationship in the case for $\left[ \alpha/Fe \right] \sim 0.4$, it falls directly on the relationship if there were no alpha enhancement ($\left[ \alpha/Fe \right] \sim 0.0$). This is true whether I consider just the present main body luminosity or the luminosity if I add in the contribution of two tails. Until a more precise spectroscopic measurement of $[Fe/H]$ can be made for F8D1, the extent to which it remains an outlier on the luminosity–metallicity relation remains inconclusive.

3.4 Discussion

I have uncovered a previously–unknown giant tidal stream from the ultra–diffuse galaxy F8D1. Considering its visible extent of $\sim 60$ kpc projected on the sky (Fig. 3.1) and the fact that it contains $\sim 30$–$36\%$ of the main body light, it is clear that the galaxy is undergoing heavy tidal disruption. The two most likely tidal disruptors of F8D1 are its closest projected neighbour, the dwarf spiral NGC 2976, or the more massive central galaxy M81. Inspection of HI maps of the M81 Group show a large filament pointing in the direction of NGC 2976 and that the HI distribution of NGC 2976 is more extended in the direction of M81 (de Blok et al. 2018; Sorgho et al. 2019). This suggests a tidal interaction between these two systems but there are no HI features around NGC 2976 that could be connected to a possible tidal interaction with F8D1. HI has not been detected in F8D1 thus far. Sorgho et al. (2019) notes that a cloud is visible in the Southeast side of NGC 2976, but it is unlikely to be tied to the disruption of F8D1 located in the Southwest.

Our estimated line–of–sight distances to F8D1 and NGC 2976 show that these galaxies appear near each other only because of their projected positions on the sky. Their actual 3D separation is 173 kpc, with F8D1 lying further away. M81 lies at an angular distance of 1.91 degrees from F8D1. Taking this together with a distance of 3.63 Mpc for this system (Freedman et al. 1994), I calculate that the 3D distance between M81 and F8D1 is 128 kpc. The total masses of M81 and NGC 2976 are not well known but their stellar masses have been reported to be $63.8 \times 10^9 M_\odot$ and $1.2 \times 10^9 M_\odot$ (Sorgho et al. 2019), respectively. The stellar mass–halo mass relation of Behroozi et al. (2013) implies that their halo
masses differ by roughly one order of magnitude, and hence that the tidal force exerted on F8D1 by M81 will be at least 20 times stronger than that due to NGC 2976. The identification of M81 as the primary disruptor is also consistent with the fact that NGC 2976 shows no obvious distortion in its outermost stellar isophotes. There is no radial velocity measurement available for F8D1 but given its advanced state of disruption it is natural to surmise that it has had at least one pericentric passage to date. The fact that I see luminous AGB stars in F8D1 (see also C98) indicates that star formation has taken place within the last few Gyr. I speculate that this pericentric passage must have happened fairly recently and that it has been responsible for the stripping the galaxy of its remaining cold gas and quenching star formation.

There are several interesting and important implications of my findings. Firstly, I can deduce that F8D1 has played a hitherto unrecognised and potentially important role in the interaction history of the M81 Group. Most famously known for its interacting triplet, all previous studies of the dynamical evolution of the group have focused on the inner trio of M81, M82 and NGC 3077 alone. These three galaxies are strongly interacting at the present day, with bridging structures of HI evident between them (Yun et al., 1994; de Blok et al., 2018) as well as very extended and perturbed stellar halos that are linked by a large stream of tidal debris (Barker et al., 2009; Okamoto et al., 2015; Smercina et al., 2020).

Early modelling of the dynamical evolution of M81, M82 and NGC 3077 involved studying the pairwise interactions between M81–M82 and M81–NGC 3077. This suggested pericentric passages about 220 and 280 Myr ago and could match the HI observations reasonably well. However, this was not full N–body modelling so did not capture the effects of dynamical friction. More recently, Oehm et al. (2017) have revisited the problem using N–body modelling. Based on the current positions and velocities of the three inner galaxies, and imposing the requirement that M82 and NGC 3077 experienced pericentric passages within 30 kpc of M81 in the last 500 Myr, they find it highly unlikely that the current configuration of the system can be long–lived. Indeed, they argue that at least one or both of M82 and NGC 3077 must have been initially unbound and that we are observing the M81 Group at a special time, with a merger set to take place within the next 1–2 Gyr. On the other hand, for the three galaxies to be in an orbital configuration that is long–lived, they require that the amount of dark matter in the galaxies must be significantly less than would be expected on the basis of their stellar masses. It will be interesting to explore if future modelling efforts that include F8D1 change
Table 3.3: Comparison of F8D1 with NGC1052–DF2 and DF4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>F8D1&lt;sup&gt;a&lt;/sup&gt;</th>
<th>NGC1052–DF2&lt;sup&gt;b&lt;/sup&gt;</th>
<th>NGC1052–DF4&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{eff}}$ (kpc)</td>
<td>1.70 ± 0.03</td>
<td>2.28± 0.03</td>
<td>1.63± 0.04</td>
</tr>
<tr>
<td>$\mu_g(0)$</td>
<td>25.69 ± 0.01</td>
<td>24.7 ± 0.1</td>
<td>24.3± 0.1</td>
</tr>
<tr>
<td>$(g - r)_0$</td>
<td>0.764 ± 0.003</td>
<td>0.6 ± 0.01</td>
<td>0.63 ± 0.01</td>
</tr>
<tr>
<td>$n$</td>
<td>0.52 ± 0.01</td>
<td>0.58± 0.02</td>
<td>0.8 ± 0.04</td>
</tr>
<tr>
<td>$b/a$</td>
<td>0.88±0.01</td>
<td>0.89 ± 0.01</td>
<td>0.86 ± 0.01</td>
</tr>
<tr>
<td>$M_g$ (mag)</td>
<td>−13.70 ± 0.04</td>
<td>−14.89± 0.04</td>
<td>−14.65± 0.04</td>
</tr>
</tbody>
</table>

<sup>a</sup> Derived in this chapter.
<sup>b</sup> Taken from Román et al. (2021) and using the Danieli et al. (2020) distance.
<sup>c</sup> Taken from Román et al. (2021) and using the Shen et al. (2021b) distance.

The realisation that F8D1 is in an advanced state of tidal disruption provides an explanation for the peculiar properties of this system, as first commented on by C98. In particular, F8D1 has an unusually large size and metallicity for its luminosity and central surface brightness, and C98 noted that it is offset from the scaling relationships that are defined by dwarf galaxies in the Local Group. I have shown that accounting for the visible stream, and assuming that a similar feature lies on the side of the galaxy unprobed by the observations, the luminosity of F8D1 is at least $\sim 43$–$56\%$ times larger (corresponding to $M_g \sim −14$ mag) than would be inferred from measuring the main body light. I note that this is likely to be a lower limit on its original luminosity, as it may have experienced repeated earlier bouts of stripping as it has orbited around M81. This moves the system closer to the expected scaling relation behaviour, suggesting that initially, it may have been a relatively normal galaxy.

The unveiling of F8D1 as a tidally–disrupted system also raises the question of whether the properties of other UDGs can be explained in this way. In Table 3.3, I compare the properties of F8D1 that I have derived in this chapter with those of two very well–studied UDGs, the systems NGC1052–DF2 and NGC1052–DF4. These systems have attracted much recent attention as examples of UDGs that have little to no dark matter and unusually luminous globular cluster systems (e.g., van Dokkum et al., 2018a, 2019a). I use the photometric and structural parameters from Román et al. (2021) for DF2 and DF4, adjusted for their respective distances reported by Danieli et al. (2020) and Shen et al. (2021b). It can be seen that while F8D1 has a somewhat lower central surface brightness and luminosity than these systems, their structural properties compare...
surprisingly well. In particular, all systems have effective radii $\gtrsim 1.6$ kpc, Sérsic indices smaller than unity and rather circular isophotes in their central regions. Recently [Keim et al. (2022)] have used new deep imaging data from the Dragonfly Telephoto array to show that NGC1052–DF2 and DF4 exhibit position angle twists and increasingly elongated isophotes when surface brightness levels of $\mu_g \sim 30$ mag arcsec$^{-2}$ are reached (although see [Montes et al. (2021)]. While they see no evidence for the strong signatures of ongoing disruption that I have uncovered in F8D1, I note that the F8D1 tail has an even lower mean surface brightness ($\mu_g \sim 32$ mag arcsec$^{-2}$) than Dragonfly has reached. Indeed, the F8D1 tail lies well below the surface brightness limit of all integrated light studies of individual UDGs carried out to date\[1\]. This leaves open the possibility that many of these systems could have relatively regular shapes and radial profiles in their inner regions, yet still be undergoing significant tidal stripping.

Tidal stripping and heating have been discussed by several authors as a mechanism for producing UDGs (e.g., [Carleton et al. (2019); Jiang et al. (2019); Sales et al. (2020); Benavides et al. (2022)]. These papers have mostly focused on galaxies residing in dense environments but they have also discussed UDGs in groups and in the field. They generally show that satellite galaxies born in $\sim 10^{10}–10^{11} \, M_\odot$ haloes can suffer a dramatic reduction in surface brightness and expansion in size due to tidal stripping and heating. However, this is not the only way to form UDGs in the simulations, and many are also born as intrinsically low surface brightness extended dwarfs. [Jiang et al. (2019)] argue that roughly half of the population of group UDGs have started off as normal dwarfs on highly eccentric orbits. For these systems, one pericentric passage is sufficient for the system to puff up, and lose its gas due to ram pressure stripping. The presence of a few Gyr old AGB stars in F8D1 is interesting in this respect, suggesting the pericentric passage around M81 occurred on this timescale. A precise measurement of the star formation history of F8D1 through modelling its CMD will further constrain this, and will also help distinguish between competing formation scenarios. For example, [Carleton et al. (2019)] predict that the mean stellar age for UDGs with effective radii between 1.5–3 kpc is 4.8 Gyr, while [Sales et al. (2020)] predict that tidal UDGs should be significantly older. Thus far, the available age measurements for UDGs are consistent with ages $\gtrsim 7$ Gyr, albeit with large uncertainties (e.g., [Gu et al. (2018); Ferré-Mateu et al. (2018)].

\[1\]Mowla et al. (2017) stack 231 UDGs in the Coma cluster and find no evidence of an S–shaped tidal feature to $\gtrsim 30$ mag arcsec$^{-2}$. However, this may not be unexpected given that tidal features are likely to exhibit a variety of morphologies and sizes around individual galaxies, which stacking will cancel out.
Furthermore, a spectroscopic measurement of F8D1’s metallicity will clarify if it really is an outlier on the luminosity–metallicity relationship as would be expected in the tidal–stripping scenario (e.g., Sales et al. 2020).
Chapter 4

Project Žvaigždikis: A Globular Cluster Search in the Halo of NGC 1052

Žvaigždikis is the Baltic god of light. People call for him to provide light for the crops, grass and the animals at the right time.

4.1 Introduction

Moving on from the M81 Group, the other system studied in this work is the NGC 1052 Group. The central galaxy NGC 1052 is a typical massive elliptical galaxy in a small group of galaxies. It is at a distance of $D = 19.2$ Mpc, or $(m - M)_0 = 31.42$ mag (Tully et al. 2016). NGC 1052 has a dark matter halo completely consistent with the stellar mass–dark matter halo mass relation (SHMR) (Forbes et al. 2019). The stellar mass of NGC 1052 is $\log(M_*) = 11.02$ M$_\odot$, measured using 3.6µm Spitzer imaging (Forbes et al. 2017).

The NGC 1052 system has been a major focus point in the last 5 years, with interest sparked by discovery of not one, but two ultra–diffuse galaxies completely devoid of any dark matter – NGC 1052–DF2 and NGC 1052–DF4 (van Dokkum et al. 2018b, 2019b). The argument was initially drawn from the globular cluster (GC) populations, in particular their velocities as well as velocity dispersions of galaxies. There have been numerous arguments against this claim, thus bringing
to light several other ways to prove the absence of dark matter in these bodies (Martin et al., 2018; Trujillo et al., 2019).

This scientific endeavour loops back to the original method – the need to improve the knowledge of the GC populations in the system. The main galaxy of the Group – NGC 1052 has 76 discovered and spectroscopically–confirmed GCs (Forbes et al., 2001, 2019). Currently, the UDGs DF2 and DF4 have 12 spectroscopically confirmed GCs each (Shen et al., 2021a).

In this chapter, I will search for halo GCs in NGC 1052 using CFHT MegaCam multi–band images in the 𝑢𝑔𝑖 filters. The CFHT MegaCam wide field camera was previously introduced in Chapter 2 of this thesis. To recap, it has 40 CCDs with a pixel scale of 0.185 arcsec/pix. 36 CCDs form a rectangular shape, and the remaining 4 are situated on the shorter sides of the resultant rectangle as its “ears”. Overall, the camera covers 1 deg² of the sky, or 320 × 320 kpc², assuming the line–of–sight distance D~19.2 Mpc to NGC1052 (Tully et al., 2016). The large area covered by the observations meant that a single CFHT field was sufficient to cover the area of interest, shown in Figure 4.2.

Previous work has shown how combining deep 𝑢–band observations with 𝑔– and 𝑖–band data can prove to be very effective for identifying GC candidates around nearby galaxies (e.g., Muñoz et al., 2014; Lim et al., 2017). These filters cover distinct parts of the GC spectrum as shown in Figure 4.1. The most important filter is the 𝑢–band filter which has an unprecedented transmission of 96% measured together with the instrument response. This is extremely crucial for detecting the blue horizontal branch (BHB) stellar population light that is abundant in GCs. Indeed, old metal–poor GCs universally show these features which are composed of low–mass core helium burning stars. Moreover, the background galaxies that are often mislabeled as GC candidates in 2–filter extragalactic GC search surveys can be easily separated through the use of a third filter. The 𝑢–band filter works best for this task, as a typical background galaxy spectral energy distribution is much fainter in the 𝑢–band than a GC with a BHB stellar population. This is well illustrated by a comparison of spectra against the filter transmission curves shown in Figure 4.1. The GC spectrum is of NGC 5272, a Milky Way GC that contains a significant fraction of BHB stars (Thomas et al., 2018), taken from Usher et al. (2017) survey. The background galaxy spectrum is constructed from the stellar population synthesis models of Bruzual & Charlot (1993)¹. Specifically, the spectrum shown is for a galaxy that had a starburst 10

Figure 4.1: CFHT filter+instrument response transmissions compared to GC and galaxy spectra. The GC is NGC5272, which has a blue horizontal branch, and is taken from the WAGGS survey (Usher et al. 2017; Thomas et al. 2018). The galaxy spectrum is a model of a galaxy that had a starburst 10 Gyr ago which exponentially decreased with folding time of 1 Gyr (Bruzual & Charlot 1993). Both spectra are normalised by taking the median at 5500 ± 100 Å. The GC spectrum is significantly brighter than the galaxy spectrum in the $u$–band filter, demonstrating why the $u$-band is so powerful for selecting GC candidates.

Gyr ago which exponentially decreased thereafter with a folding time of 1 Gyr. Hence, with deep wide field $ugi$–band imagery of NGC 1052, I have a powerful means to study its extended halo GC population, and that of its closest satellites.

4.2 Observations

As established by the PAndAS survey of M31, GCs can be found out to projected distances of at least 150 kpc from the centre of a massive galaxy (Mackey et al. 2019a). For the NGC 1052 line–of–sight distance of $D \sim 19.2$ Mpc (Tully et al. 2016), the survey covers distances of up to ~160 kpc from NGC 1052, and hence is well–matched to this expectation. As this system is too far away to be studied through resolved stellar populations from the ground, analysing the GC populations instead is the next most viable method to probe the outskirts of astronomical-catalogs/the-bruzual-charlot-atlas

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Figure 4.2: Finding chart of the CFHT MegaCam footprint overlaid on an SDSS image. The relevant galaxies and the two bright foreground stars are labeled in white and red respectively.
Figure 4.3: Foreground extinction in g–band across the NGC1052 MegaCam field derived from the Schlegel et al. (1998) map and calibrated with coefficients from Schlafly & Finkbeiner (2011). The white rectangles show the footprint of the MegaCam pointing, with the main galaxies of interest marked. Extinction is very low towards this sightline.
Table 4.1: CFHT MegaCam observations of the NGC 1052 Group.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Exposures</th>
<th>Total exposure time</th>
<th>Seeing</th>
<th>Dates observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>23 × 990s</td>
<td>22770s</td>
<td>0.92&quot;</td>
<td>2020-08/2020-09</td>
</tr>
<tr>
<td>g</td>
<td>5 × 335s</td>
<td>1675s</td>
<td>0.73&quot;</td>
<td>2020-08</td>
</tr>
<tr>
<td>i</td>
<td>5 × 455s</td>
<td>2275s</td>
<td>0.78&quot;</td>
<td>2020-08</td>
</tr>
</tbody>
</table>

NGC 1052. An important goal is to place the enigmatic NGC 1052–DFs and their puzzling GC populations in the context of the NGC 1052 halo.

The peculiar ultra diffuse galaxies lacking dark matter NGC1052–DF2 and –DF4 are also captured by the survey. Given the large contiguous area covered for NGC 1052, the GC populations of the diffuse galaxies can be directly compared against the new GC candidates in their vicinity regarding the GC density, GC colour and luminosity.

Figure 4.3 shows the foreground extinction towards the NGC 1052 Group. The field does not suffer from highly variable extinction. The $E(B-V)$ values range from 0.02 to 0.03 mag, reaching maximum extinctions of 0.13, 0.1, and 0.05 for $u-$, $g-$ and $i-$bands respectively. These values are derived by Schlegel et al. (1998) and calibrated by Schlafly & Finkbeiner (2011) for the CFHT filters.

The observations were designed to reach the turnover magnitude of the GC luminosity function (GCLF). Using the well–studied population of Centaurus A as a reference, this suggested reaching to $M_u = -5.3$, $M_g = -6.9$ and $M_i = -7.8$ (Taylor et al., 2017). For the distance of NGC 1052 $D = 19.2$ Mpc this meant apparent magnitudes of 26.3, 24.7 and 23.8 for $u-$, $g-$ and $i-$bands respectively.

Even though the MegaCam CCDs have relatively small gaps between them, they still constitute significant missing area if uniform coverage of the field is required. To fill some of the gaps and avoid hot pixels, small central coordinate “dithers” were executed in between exposures. Diagonal steps of 20′ between exposures were chosen. This covers the bad pixels but does not fill any of the major chip gaps. In choosing the dithers, I had to consider the fact that there are 2 very bright foreground stars ($g$ = 8.1 and 9.1 mag) in the FOV and it was essential to keep those stars in the CCD gaps to ensure that they did not contaminate too much of the CCD area (see Fig. 4.2). Due to the increased effective seeing and significantly lower sensitivity in u, most of the allocated time was used for observations in u-band.

The observations were obtained in the second semester of 2020 (2020B) and were
fully completed. Table 4.1 shows the details of the observations. The data are of generally excellent quality in all bands. Some of the $u$–band exposures were taken in slightly worse seeing than requested but we decided to include these anyway as they increased the signal–to–noise ratio in the final stacks. False–colour images of the ultra–diffuse galaxies NGC 1052–DF2 and –DF4 shown in Figure 4.4 show the visual quality and depth of the image stacks.

### 4.3 Data Processing and Photometry

The CFHT images were pre–processed with the native pipeline Elixir, where initial reduction steps such as bias, dark, and flat–fielding were done (Magnier & Cuillandre, 2004). The images were then stacked and sources detected by Mike Irwin using the Cambridge Astronomical Survey Unit (CASU) pipeline as described in Irwin & Lewis (2001). This pipeline was used for much of the PAAndAS analysis (e.g., Ibata et al., 2014) and has been established to produce excellent quality results on CFHT/MegaCam data. After the processing, all detected and measured sources were combined from all three bands and put in a catalogue. There are $\sim227000$ detected sources, of which $\sim91000$ were measured in all three bands. The magnitude uncertainties of the detected sources vary depending on the band, shown in Figure 4.5. The uncertainties in the $i$–band are...
Figure 4.5: Magnitude errors of all objects detected in the observed CFHT field. Errors are colour-coded for each separate photometric band. The black dashed line denotes the threshold at which the catalogue objects were culled by $g$– and $u$–band error.

The catalogue provides a classification of each source, uniquely determined for each band. As described by Ségal et al. (2007), the classification mechanism relies on the curve-of-growth analysis. That is, for every detected object a circular aperture is applied with increasing radius, thus forming an intrinsic curve-of-growth. Then, the curve-of-growth of each detected object is compared against a well-defined curve-of-growth expected for a stellar source. Note that the stellar locus is directly measured from the point spread function at separate radii through integration. This model is independent of the magnitude given sufficient good quality images, i.e. they are properly linearised and no saturated images are included in the set. From comparison of the curve-of-growth of each detected object against the stellar locus, a morphological classification is obtained and quantified by the numerical sigma deviation.

The most relevant classifications in the catalogue are $-1$ and $-2$ which signify that a source is within that 1 or 2 sigma of the stellar locus respectively, i.e. it is classified as a star ($-1$) or nearly a star ($-2$). In this chapter, I will refer to these sources as “point-like” or “stellar”. Figure 4.6 shows the distribution of stellar sources across the FOV. The known galaxies which belong to the NGC 1052 group
Figure 4.6: Spatial map of the objects classed as stellar in the g–band only with a g_0 < 24 mag cut. The known galaxies which belong to the NGC 1052 group are tagged. The green circles show the 3 R_{eff} sizes of galaxies.
Figure 4.7: Spatial map of objects classed as extended in all bands with a $g_0 < 24$ mag cut. The size of the points is kept the same as in Fig. 4.6 to convey the relative amounts of objects. The green circles show the $3 R_{\text{eff}}$ sizes of galaxies. The sources shown in this map were culled with parameters described later in Section 4.4.2 with an additional magnitude cull ($g < 24$ mag) to better show the underlying structure. The subsequent maps shown in this chapter will also have the magnitude cull applied. Sources in this map include foreground stars, unresolved background galaxies and GCs at the distance of the NGC 1052 Group. The fact that concentrations of point sources are seen around NGC 1052 and NGC 1042 already indicates that I am successfully detecting this population.

Figure 4.7 shows the distribution of extended sources across the field, i.e. sources flagged as $+1$ in catalogue which lie within 1 sigma of the galaxy locus, and
hence likely to be a background galaxy. The size of the points is kept the same as in Figure 4.6 to illustrate that these sources dominate the catalogue. The distribution is mostly uniform, although there are some overdensities. These mostly coincide with bright galaxies and result from the fact that the algorithm has failed in these regions due to high crowding. Other overdensities are due to background galaxy clusters.

The reliability of the classifications in the photometric catalogue is crucial, as these will form a primary means along with colours to select GC candidates. Figures 4.6 and 4.7 demonstrate that the classification across the field look very reliable.

### 4.4 Globular Cluster Search

#### 4.4.1 Recovery of Known Globular Clusters

The search strategy used in this work for discovering new GC candidates exploits knowledge of the currently known population of spectroscopically-confirmed GCs in NGC 1052 and its satellites. Therefore, the first step is to cross-correlate the known GCs with sources in the photometric catalogue. The spectroscopically-confirmed sample for NGC 1052 is primarily taken from Forbes et al. (2019) and
Figure 4.9: Projected distance from the galaxy’s centre versus the magnitude for the recovered NGC 1052 GCs. The colours show the stellarity classification in \( g \)-band.

Figure 4.10: Fraction of recovered GCs classified as stellar as a function of projected distance from the centre of NGC 1052. The bar at 35 kpc drops to 66% due to only a single source misclassified (see Fig. 4.9).
augmented by detections around DF2 and DF4 from Shen et al. (2021a). In total, this amounts to 100 GCs with radial velocity confirmation. The coordinates of the GC labelled DF2_GC80 are taken from Emsellem et al. (2019) as the Shen et al. (2021a) publication has an error, with DF2_GC80 and DF2_GC101 coordinates appearing identical. The locations of the known GCs are matched with the coordinates of all sources in the CFHT catalogue. Any source within 1″ of a GC is classed as a detection. If I run the cross-match algorithm on my catalog with no prior culling, I can match all 100 GCs to objects in the catalogue within a distance of 0.8″ or lower. One source (N1052_GC40) had two matched sources within 1″, but one of them was easily dismissed after checking that it was detected in u-band only.

However, the classifications of the recovered spectroscopically-confirmed GCs were not consistently stellar. The right panel of Figure 4.8 shows that while more than half (51 out of 100) GCs were classified as stellar in all three bands, 13 GCs were not classified as stellar in any of the three bands. Most of the misclassified sources were categorised as extended (+1 in the catalogue). Regardless of classification, I find that all of the recovered GCs have magnitude errors less than 0.25 mag in all bands and are therefore reliable detections. The only exception is DF4_GC97 which does not have a u-band detection due to its low luminosity \( M_V = -6.7 \) (Shen et al., 2021a) and therefore cannot be used in the subsequent analysis. A recent publication by van Dokkum et al. (2022) shows that DF2_GC80 projects in front of a blue galaxy, and that DF4_GC926 projects in front of a bright galaxy merger. Both of these GCs appear as extended in all bands in the CFHT catalogue, but I decided keep them as they have accurate photometry. Overall, I use 99 out of 100 recovered GCs.

Considering only the NGC1052 spectroscopic sample of Forbes et al. (2019), I investigate the correlation between the morphological classification and other properties of the GCs. Figure 4.9 shows that GC luminosity did not appear to affect the classification as similar numbers of bright and faint GCs were misclassified. On the other hand, the projected distance from the galaxy centre clearly influences the success in correctly classifying GCs as point sources. Figure 4.10 shows that most of the misclassified sources lie at small projected radii where the sources are detected on top of the bright galaxy background and the crowding is high. As a result, the sources may appear extended to the classification algorithm.
4.4.2 Initial Culling

Based on the properties of recovered GCs, I do some initial culling of the catalogue to remove sources that are unlikely to be GCs, i.e. contamination. The highest photometric error of a recovered GC is 0.24, 0.15 and 0.15 mag for $u$, $g$, $i$-bands respectively. This motivates a cut in photometric error of 0.2 mag ($S/N \sim 5$). I apply this cut to both the $u$ and $g$-bands, but not to the $i$-band. The $i$-band has the lowest S/N of all filters and applying this error cut here would cause the removal of many sources. The classification of stellarity can vary between the filters – different bands classify different GCs as stellar, as shown in the triple Venn diagram in the left panel of Figure 4.8. While the $u$-band images classify the most of the real GCs as stellar (81) compared to $g$- and $i$- (66), the seeing is worse in $u$-band, so the classification is less meaningful. The $g$-band data has the best seeing and so I use it as the sole basis of morphological culling.

To summarise, the culling steps taken are as follows. I remove objects that:

- Have errors higher than 0.2 mag in $u$- and $g$-band.
- Are not recognized as stellar, i.e. not $-1$, $-2$ in $g$-band catalogue.
- Are spectroscopically-confirmed GCs.

The three–filter coverage allows me to construct various CMDs of sources – $((u - g)_0, g_0)$ and $((g - i)_0, i_0)$. The left panel of Figure 4.11 shows the $((u - g)_0, g_0)$ CMD. Three distinct columns of bright sources can be seen. The middle sequence is Milky Way halo stars and the Sagittarius stream can be seen as the turnoff at the faint end. The recovered GCs are shown as red points and lie just redward of this. The reddest sequence on the right is also of foreground origin from the Milky Way. Unlike the middle column, this column contains low-mass Milky Way disc stars. The bluest sequence at $(u - g)_0 \sim 0$ is most likely a combination of faint white dwarfs and quasars.

The right panel of Figure 4.11 shows the $((g - i)_0, i_0)$ CMD and it can be seen that it broadly displays similar features, namely the two bright sequences due to the Milky Way disc and halo stars. The signature of the Sagittarius stream is particularly obvious in this CMD, exhibiting a turnoff at $i_0 \sim 22$ and $(g - i)_0 \sim 0.5$ mag.
Finally, a colour–colour diagram of the field can be constructed by combining the two colours, shown in the left panel of Figure 4.12. This exhibits a clear stellar locus. The recovered spectroscopically–confirmed GCs follow the stellar locus, but are slightly offset from it. At a given \((u - g)_0\) colour the GCs are slightly redder in \((g - i)_0\) than the foreground stars. The spectroscopically–confirmed GCs span a broad range of colours but are concentrated to blue colours as expected. This narrow confinement of known GCs in colour–colour space will form the basis for my GC search. For comparison, a colour–colour diagram of extended sources is shown in the right panel of Figure 4.12. This shows a completely different behaviour and the recovered GCs overlaid no longer mimic the underlying population, thus emphasizing the importance of morphological culling of the catalogue.

4.4.3 Devising the GC Search Strategy

With a culled and well–understood stellar catalogue in hand, the final stage of the GC selection is to derive a polygon in colour–colour space that isolates most of spectroscopically–confirmed GCs. Figure 4.13 shows that the recovered GCs occupy a \(0.5 < (u - g)_0 < 2.5\), \(0.5 < (g - i)_0 < 1.5\) region in the colour–colour diagram. The confirmed GC populations of low surface brightness

Figure 4.11: CMDs of point–like sources from the culled catalogue (black points). The recovered GCs from Forbes et al. (2019) and Shen et al. (2021a) are overlaid as red points. The bright vertical sequences are Milky Way foreground stars. The sharp diagonal cutoff on the faint end of the CMD is due to the error cut \(g_{err} < 0.2\) mag. Left: \(u/g\)–band CMD. Right: \(g/i\)–band CMD.
galaxies NGC 1052–DF2 and DF4 exhibit a considerably smaller scatter in the colour–colour diagram than those of NGC 1052 which they lie blueward of, making it more straightforward to isolate them with a rectangular polygon (Román et al., 2021). Regardless, the selection polygon shown in Fig. 4.13 is guided by the NGC 1052 GCs only, though most of the DF2 and DF4 GCs are encompassed by it. It is worth remembering that my colour selection technique requires significant $u$–band emission from BHB stars. For GCs lacking such populations, my selection technique will not be effective.

Although the colour selection polygon is designed to isolate GCs, it will also include foreground stars and blue background unresolved galaxies. As a result, in subsequent analyses an additional correction will be required to remove contaminating sources. The resultant GC candidates were matched against the Shen et al. (2021a) list of confirmed contaminants around NGC 1052–DF2 and –DF4. They identified contaminants to be those with radial velocities inconsistent with NGC 1052 Group membership. Only one contaminant was matched and removed from my catalogue. Overall, my GC detection technique identified 643 new GC candidates in the NGC 1052 Group.
Figure 4.13: Colour–colour diagram of spectroscopically–confirmed NGC 1052 GCs (red), NGC 1052–DF2 and –DF4 GCs (blue), and point–like sources from the culled CFHT catalogue (black). The polygon used to select the new candidate GCs around NGC 1052 is shown in lime.
Figure 4.14: Spatial map of the new GC candidates around NGC 1052 (green). For reference, spectroscopically-confirmed GCs are overlaid (orange). The black points are stellar objects that were not classified as GCs. The red circles show the $3 R_{\text{eff}}$ sizes of galaxies.
Figure 4.15: Left: Kernel density smoothed map of the NGC 1052 GC candidates. A clear bridge between NGC 1052 and NGC 1047 can be seen. A slight protrusion towards the NGC 1042 is also visible. Right: A cropped version of a figure taken from Müller et al. (2019). A stacked luminance image taken with the Jeanne Rich telescope uncovers tidal features around NGC 1052, strikingly similar to the protrusions in the kernel density smoothed map.

4.5 Results

4.5.1 Spatial Map

With a sample of GC candidates in hand, I can now explore their properties, beginning with the spatial distribution. Figure 4.14 shows spatial map of GC candidates with a clear concentration in and around NGC 1052, with some also clustered in other neighbouring galaxies. Another galaxy with a substantial amount of GC candidates in its vicinity is NGC 1047. In fact, it appears even by eye that there may be an “arm” of GC candidates linking NGC 1052 and NGC 1047.

To explore the large scale distribution of GC candidates, I use a kernel smoothing technique based on Koposov et al. (2008)\footnote{https://datalab.noirlab.edu/docs/manual/UsingAstroDataLab/ScienceExamples/DiscoverFaintMilkyWayDwarfGalaxies/DiscoverFaintMilkyWayDwarfGalaxies.html}. Kernel density smoothing has been successfully used to discover ultra–faint dwarfs through resolved stellar populations (e.g., Martin et al., 2015), therefore it is suitable for uncovering the substructures traced by the GC candidates. The technique is as follows – the 2D spatial distribution of sources is binned and convolved with two Gaussians.
of two different kernel widths. Then, the difference is taken between the two convolutions. This way, any features with sizes outside the range spanned by the chosen kernel widths are diminished. The resultant 2D histogram then shows the enhanced features that remain after the subtraction.

Through trial and error, I find that a kernel pair of widths 3 and 25 arcmin in size enhance the substructures best. At a distance of 19.2 Mpc, this corresponds to \( \sim 16 \) and \( \sim 134 \) kpc. I show the convolved spatial distribution of GC candidates in the left panel of Figure 4.15. To better guide the eye, I embedded a 0.1 sigma contour on the distribution by convolving it with a 3 arcmin Gaussian kernel. It appears that there are several striking features visible around the NGC 1052. Firstly, there is indeed a bridging structure linking NGC 1052 and NGC 1047. Moreover, there is an obvious protrusion towards NGC 1042 in the Southwest and a small circular “droplet” feature pointing South. NGC 1042 does not appear to show any irregularities in its GC candidate population. Remarkably, these tidal features are also visible in the very deep diffuse light image, shown in the right panel of Figure 4.15 presented by Müller et al. (2019). This suggests that the GCs are tracing faint tidal features in this system, similar to what has been seen in some other galaxies (e.g., Lim et al., 2017; Mackey et al., 2019a).

4.5.2 Radial Profiles

The spatial distribution of GC candidates of NGC 1052 can be analysed in a similar manner as RGB stellar population in M81 (see Chapter 2) through constructing radial number density profiles. I create a set of four profiles which extend along the major and minor axes of NGC 1052, as well as an azimuthally averaged profile. Figure 4.16 shows the four directions colour-coded on the spatial map. Combined, these profiles yield information about the mean behaviour as well as any large scale asymmetries in the halo. For this analysis, I assume that the halo of NGC 1052 is spherical.

Several challenges are presented in attempting to construct the radial density profiles of GC candidates. Firstly, the large chip gaps that were not filled by drizzling \(( \eta \pm 0.28 \) in the \( y \)-axis) incur a non-negligible loss of area and hence possibly GC candidates. This is accounted for by calculating the fraction of the area of each circular wedge that coincides with either of the chip gaps. These calculations are performed through a simple Monte-Carlo method for calculating areas of non-regular polygons. Each chip gap is modeled as a rectangle that I fill
Figure 4.16: Spatial map of point-like sources (black) across the field. GC candidates are overlaid and colour-coded by the quadrant in which they lie. The red circles enclose the control field used for determining the background level. The excluded Northwestern quadrant of the control field is marked.
Figure 4.17: Radial number density profiles of GC candidates along the major and minor axes of NGC 1052. The blue line shows the azimuthally averaged profile. The profiles level off at a constant value of $\log_{10}(N_{GC}) = -0.95 \text{ arcmin}^{-2}$ (black horizontal line) until reaching the edge of the footprint, where edge effects cause them to plummet. The central 20 kpc is omitted due to the difficulty of identifying GCs near the centre of NGC 1052. The uncertainties are only shown on the azimuthal profile to minimize clutter.

Figure 4.18: Background–subtracted radial number density profiles of GC candidates along the major and minor axes of NGC 1052. The blue line shows the azimuthally averaged profile and the dashed black line is a power–law to this. The $\log_{10}(N_{GC}) = -0.95 \text{ arcmin}^{-2}$ line (black) at which the profile leveled off before background subtraction is added for reference here. There are clear quadrant–to–quadrant variations visible. The uncertainties are only shown on the azimuthal profile to minimize clutter.
with \( N = 10000 \) points at random. The number of points that are captured by the circular wedge used to estimate the radial profile reflect the fraction of the chip gap covered, which is the area that is subtracted when calculating the GC candidate density.

Figure 4.17 shows the resultant GC candidate number density represented in logarithmic form. The central 20 kpc is omitted due to the difficulty of identifying GCs near the centre of NGC 1052. The errors come from Poisson counts, i.e. \( N \pm \sqrt{N} \). The profile also includes spectroscopically-confirmed NGC 1052 GCs from Forbes et al. (2019). Note that the distances here are shown as projected circular radii, which is appropriate for a spherical halo. The profiles along all four annular wedges decline sharply until \( \sim 60 \) kpc, at which point they all flatten off and decline more slowly until the edge of the field is reached at \( \sim 160 \) kpc. This is because the catalogue of GC candidates is expected to contain a uniform background of false-positives, regardless of the culling and classifications of sources in the catalogue. These sources will either be foreground stars or background unresolved galaxies that will have the right colour to fall within the polygon selection box. To account for this, a control field is needed in which I expect close to zero true-positive GC candidate sources. Since the profiles flatten beyond \( \sim 60 \) kpc, I conservatively take a circular annulus between 110 and 160 kpc to be the control field. While there may still be some true GCs in this region, the amount should be very small. As the Northwestern area of the pointing contains a few galaxies, namely NGC 1035, NGC 1052–DF4 and –DF5, I exclude this quadrant for the control field annulus entirely. The control field used is shown in Figure 4.16. The mean contaminant density is found to be 0.1 \( N_{\text{contaminants}} \) arcmin\(^{-2} \). This value is subtracted from the profiles in Figure 4.17 to correct for the contaminant counts.

Figure 4.18 shows the results of performing the background subtraction from the radial density profiles and correcting for the missing area due to chip gaps. The resultant radial profiles show clear quadrant-to-quadrant variations. For example, the Southwest profile is consistently higher than all the others out to 90 kpc while the Southeast profile shows a deficit of sources inside 50 kpc. Nevertheless, all of the profiles show a steady decline, consistent with the behaviour of the azimuthal profile. The uncertainties for the latter profile come from combination of Poisson uncertainties for both the GC candidates and estimated contamination.

To characterise the azimuthal profile, I fit a power-law:
\[ \Sigma(r) = cr^\gamma \]  

(4.1)

where \( c \) is a constant and \( \gamma \) is the power–law index. The dashed black line in Fig. 4.18 shows the fit. The fit describes the azimuthal profile reasonably well, with the power law estimated to be \( \gamma = -2.24 \pm 0.21 \).

With the GC number density profile constructed for the NGC 1052 halo, the GC populations of NGC 1052–DF2 and –DF4 can be compared to the expected halo populations at the appropriate galactocentric radii. While the recently estimated TRGB distances of NGC 1052–DF2 and –DF4 in the literature are 22.1 ± 1.2 kpc and 20.0 ± 1.6 respectively [Shen et al., 2021b; Danieli et al., 2020], I will assume that they are at the same distance as NGC 1052 for this comparison. The effective radii of these galaxies are 21.3 and 16.8 arcsec [Román et al., 2021]. A circle of \( 10 \text{R}_{\text{eff}} \) encompasses all known GC populations for each galaxy, including 6 new GC candidates in each case. By taking the density of known and candidate GCs and subtracting the background in the same way as for the halo GCs, I find that NGC 1052–DF2 and –DF4 have a local GC density of \( \log_{10}(N_{\text{GC}}) = -0.40 \) and \( -0.32 \text{arcmin}^{-2} \). At the same projected distances in the halo (73 and 152 kpc), the fitted power law yields \( \log_{10}(N_{\text{GC}}) = -1.26 \) and \( -1.98 \log_{10} \text{GCs arcmin}^{-2} \). This means that there are \( \sim 7 \) and \( \sim 45 \) times more GCs in the vicinity of the DFs to the expected NGC 1052 halo population.

### 4.5.3 Luminosity Functions

To further analyse the NGC 1052 GC population, I examine luminosity functions (LFs). The luminosity function is constructed by binning the magnitudes of the GC candidates into a histogram. As there were three photometric filters used, three unique luminosity functions can be constructed.

For the subsequent analysis, I define the stellar halo sample of NGC 1052 as those GCs projected at distances of 20 < \( r < 100 \) kpc from the centre of the galaxy. The NGC 1052 halo sample consists of new candidates in this work and the spectroscopically–confirmed GCs from the Forbes et al. (2019) sample, of which 7 are in my defined halo range. I do not add the known NGC 1052–DF2 and –DF4 GCs from Shen et al. (2021a) to this sample.

The control field used for background subtraction is the same as before – an
Figure 4.19: $u$–band luminosity function (LF) of the stellar halo sample, defined as $20 < r < 100$ kpc. The contaminant–subtracted candidate GCs augmented with spectroscopically–confirmed halo GCs are shown as orange bars, whilst all spectroscopically–confirmed NGC1052 GCs from Forbes et al. (2019) are shown as black solid lines. The contaminants drawn from the control field are shown as dashed–cyan lines. The halo GCLF is fit with a Gaussian (black curve).

Figure 4.20: $g$–band LF of the stellar halo. Lines and colours are the same as in Figure 4.19.
annulus covering a radial range of 110 kpc to 160 kpc, excluding the Northwestern quadrant. To avoid negative values in histograms, the background is subtracted in a randomised way as described by Lim et al. (2017). First, the number of contaminants N is scaled by the ratio of the area of the stellar halo region and the control field annulus. Then, a contaminant is randomly drawn from the control field population N times this ratio, with the candidate GC with the closest magnitude removed from the GC candidate halo population each time. This way, the same number of GCs is removed as if subtracting by an area–scaled histogram of contaminants, but there are no negative histogram bins resulting from oversubtraction. I show the LFs in Figures 4.19, 4.20, 4.21 for $u-$, $g-$ and $i-$ bands, respectively. The LFs are binned in 0.27 magnitude bins in order to have adequate statistical strength and resolution of the curve. The randomly drawn contaminant population is shown in cyan and the spectroscopically–confirmed sample of NGC 1052 GCs is shown in black. It is clearly seen that the spectroscopically–confirmed sample is biased to brighter magnitudes than the bulk halo population that I have uncovered here. Note that most of these objects lie < 20 kpc of NGC 1052.

GCLFs are generally modelled with a Gaussian. The most remarkable thing about them is the fact that they all share nearly the same turnover magnitude regardless of the galaxy (Rejkuba, 2012). This has been tested and proven for elliptical galaxies as well (e.g., Jordán et al. 2006, 2007). Therefore, I proceed to
Table 4.2: Gaussian fits on the NGC 1052 GC stellar halo GC luminosity functions.

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\mu$ (mag)</th>
<th>$\sigma$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>24.83 ± 0.06</td>
<td>0.53 ± 0.06</td>
</tr>
<tr>
<td>$g$</td>
<td>23.61 ± 0.07</td>
<td>0.55 ± 0.08</td>
</tr>
<tr>
<td>$i$</td>
<td>22.78 ± 0.05</td>
<td>0.60 ± 0.05</td>
</tr>
</tbody>
</table>

Table 4.3: Parameters of the NGC 1052–DF2 and –DF4 GC luminosity functions.

<table>
<thead>
<tr>
<th>Filter</th>
<th>$m_{\text{peak}}$ (mag)</th>
<th>Peak difference (mag)</th>
<th>Distance ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>24.1 ± 0.15</td>
<td>0.73 ± 0.16</td>
<td>1.40 ± 0.1</td>
</tr>
<tr>
<td>$g$</td>
<td>22.7 ± 0.15</td>
<td>0.91 ± 0.17</td>
<td>1.52 ± 0.12</td>
</tr>
<tr>
<td>$i$</td>
<td>22.0 ± 0.15</td>
<td>0.78 ± 0.16</td>
<td>1.43 ± 0.11</td>
</tr>
</tbody>
</table>

fit a Gaussian to the GCLFs constructed in this work so that they can be readily compared to other samples. I fit a function of form:

$$N_{\text{GC}}(x) = Be^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (4.2)$$

where $\mu$ is the Gaussian peak, $\sigma$ is the width of the Gaussian and $B$ is the normalisation. All three parameters of the function are freely varied to find the best–fitting parameter set using the PYTHON package SciPy (Virtanen et al., 2020).

The fitted parameters for different bands are given in Table 4.2.

The GC populations of the ultra diffuse galaxies NGC 1052–DF2 and –DF4 were also examined in the form of luminosity functions. To retain the possibility of direct comparison against the LFs presented for NGC1052, I examine the GC populations in apparent magnitudes, i.e. no assumption of their line–of–sight distances. I combine the LFs of DF2 and DF4 into one for better statistics and also augment them with new candidates found within 10 $R_{\text{eff}}$. 12 GC candidates were found within 10 $R_{\text{eff}}$ of the galaxies – 6 for DF2, and 6 for DF4. One of the GC candidates around DF2 is clearly too bright ($i_0 = 16.4$ mag), and the expected control field GC count scaled by the circular area of radius 10 $R_{\text{eff}}$ for both galaxies combined is 5 GCs, thus leaving 6 potentially legitimate candidates, most of which cover the faint side of the known GCs in the LF.

The LFs are shown in Figures 4.22, 4.23 and 4.24. The area–scaled contaminant population is shown as cyan bars, but the candidate+spectroscopically–confirmed population is not background–subtracted so as to retain all GC candidates.
Figure 4.22: $u$–band LFs of NGC 1052–DF2 and –DF4 GC populations added together. The candidate GCs augmented with spectroscopically—confirmed halo GCs are shown as orange bars, whilst the spectroscopically—confirmed NGC 1052 GCs from Shen et al. (2021a) are shown as black solid lines. The area–scaled population of contaminants is shown as cyan lines. The GC candidate sample was not contaminant–corrected. The Gaussian fit for the NGC 1052 GCLF scaled down by a factor of 3 is overlaid.
Figure 4.23: $g$–band LFs of NGC1052–DF2 and –DF4 GC populations added together. Lines and colours are the same as in Fig. 4.22.

Figure 4.24: $i$–band LFs of NGC1052–DF2 and –DF4 GC populations added together. Lines and colours are the same as in Fig. 4.22.
Figure 4.25: \((u - g)_0\) colour function (CF) of the stellar halo sample, defined as \(20 < r < 100\) kpc. The contaminant–subtracted candidate GCs augmented with spectroscopically–confirmed halo GCs are shown as orange bars, whilst all the spectroscopically–confirmed NGC 1052 GCs from the Forbes et al. (2019) are shown as black bars. The contaminants are shown as dashed–cyan lines. The candidate GC CFs are fit with a two–Gaussian model, with contributing individual Gaussians shown as dashed lines.

shown in the LFs. The Gaussians fitted for the NGC 1052 halo GC population are overlaid on the LFs as blue dashed lines. I compare the peak bins of the NGC 1052–DF2 and –DF4 GC candidate+spectroscopically–confirmed GC sample \(m_{\text{peak}}\) against the Gaussian peak of the NGC 1052 halo GCs in Table 4.3. This offset in magnitude may reflect intrinsic differences in the GCLFs of the DFs and NGC 1052 or it may reflect a distance effect. Indeed, the almost universal peak of GCLF (Rejkuba 2012) means that it can be used as a crude distance indicator. Assuming the latter, the ratio of line–of–sight distance ratio is calculated instead of the difference in distances in order to stay agnostic about the true line–of–sight distance measurements of both the NGC 1052 galaxy and the DFs.

4.6 Colour and Colour Functions

The luminosity functions rely on measurements from a single filter, whereas colour functions (CFs) rely on two. This gives insight into the constituent populations
Figure 4.26: $(g - i)_0$ colour function (CF) of the stellar halo sample, defined as $20 < r < 100$ kpc. Lines and colours are the same as in Figure 4.25.

Figure 4.27: $(u - i)_0$ colour function (CF) of the stellar halo sample, defined as $20 < r < 100$ kpc. Lines and colours are the same as in Figure 4.25.
of the GCs, and even on their origin. In particular, it has been argued by e.g. Forbes et al. (1997) that GCs formed in–situ are generally redder than an accreted population. Going radially outwards, it is expected that the accreted component (blue GCs) of the stellar halo will dominate over the in–situ (red GCs). The extinction–corrected three–filter observations provide three unique colour distributions: $(u - g)_0$, $(g - i)_0$ and $(u - i)_0$.

The CFs presented in this work are generated in a similar way to the LFs in the previous section. The CFs are shown in Figures 4.25, 4.26 and 4.27. The colours of GCs are sampled in 0.1 mag wide bins. The background is subtracted in the same way as before by randomly drawing sources from the control field. The CFs all show a dominant peak at blue colours and a long tail to the red.

To test whether my distributions is bimodal, I use the Gaussian Mixture Modelling (GMM) technique to fit two Gaussians simultaneously. This was done using the PYTHON package scikit-learn (Pedregosa et al., 2011). Naturally, the CF may not be bimodal in every case. The GMM algorithm allows testing fits for any number of Gaussians including just one.

Following Lim et al. (2017), I use a metric described by Muratov & Gnedin (2010). Here, the separation of two populations in the estimated 2–Gaussian fit can be quantified through the characteristic separation defined as the $D$–value:

$$D = \frac{|\mu_1 - \mu_2|}{[\sigma_1^2 + \sigma_2^2]/2]^{1/2}}$$

(4.3)

where $\mu_1$, $\mu_2$ are the peaks of the Gaussians and $\sigma_1$, $\sigma_2$ are the widths. This value quantifies the significance of separation between the peaks relative to their widths. When fitting data with a bimodal distribution, two Gaussians are preferred over one if the separation of the peaks is $D > 2$. The uncertainty on the separation is calculated through re–running the same method $N = 1000$ times, drawing a new contaminant population from the distribution each time as suggested by Lim et al. (2017). The uncertainty is then the standard deviation of the estimated separations ($D$–values). The two–Gaussian fit parameters are given in Table 4.4. The $D$–value is less than 2 in all cases. Overall, the highest significance of bimodality was found in the $(u - i)_0$ colour sample.

I also examine the the overall colour trend of the GC candidate population...
Table 4.4: GMM two–Gaussian fit parameters on the NGC 1052 stellar halo GC colour functions.

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\mu_{\text{blue}}$ (mag)</th>
<th>$\mu_{\text{red}}$ (mag)</th>
<th>$D$ (mag)</th>
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<tr>
<td>$u-g$</td>
<td>1.05</td>
<td>1.2</td>
<td>1.48 ± 0.1</td>
</tr>
<tr>
<td>$g-i$</td>
<td>0.78</td>
<td>0.89</td>
<td>1.9 ± 0.14</td>
</tr>
<tr>
<td>$u-i$</td>
<td>1.84</td>
<td>2.11</td>
<td>1.94 ± 0.02</td>
</tr>
</tbody>
</table>

Figure 4.28: Radial $(u - g)_0$ colour variation of background–subtracted GC candidates (red). The candidates were binned in 20 kpc thick annuli from 20 to 120 kpc and expressed as mean colour, with the uncertainty being the standard deviation. The dotted line indicates a linear fit. For reference, individual colours of spectroscopically–confirmed GCs are added (black points).
Figure 4.29: Radial \((g - i)_0\) colour variation. Symbols and lines as in Fig. 4.28.

Figure 4.30: Radial \((u - i)_0\) colour variation. Symbols and lines as in Fig. 4.28.
including the spectroscopically-confirmed GCs from Forbes et al. (2019). In a similar manner as Forbes et al. (2001), I bin the GC candidates into 25 kpc size bins from 20 kpc to 120 kpc. Each bin has sources removed according to the control field populations in the same way as CFs above. The radial colour trends are shown in Figures 4.28, 4.29 and 4.30. The error on the mean colour at a given radius is the standard deviation of the measured colours in that bin. The radial colour measurements were fit with a linear fit. Formally, the \((u-g)_0\) and \((u-i)_0\) exhibit negative radial gradients, \(-0.0019 \pm 0.0008\) and \(-0.0007 \pm 0.0009\) mag kpc\(^{-1}\) respectively. On the other hand, \((g-i)_0\) shows a positive radial gradient, \(0.0007 \pm 0.0005\) mag kpc\(^{-1}\). Overall, the estimated radial gradients are negligible in all cases over the radial range fit here.

### 4.7 Discussion

#### 4.7.1 GC Candidate Numbers

Forbes et al. (2001) found 359 GC candidates, 74 of which were spectroscopically-confirmed in their follow-up paper Forbes et al. (2019). This translates to a \(\sim 21\%\) success rate. These observations were done using the Keck 8m telescope in \(BV\)–\(I\)–bands and with 0.8″ seeing. They had significantly less exposure time (2400, 1200 and 300s respectively) than data in this work, especially in the longest wavelength filter. Moreover, the observations covered only the inner regions of NGC 1052 (6 \(\times\) 9′), which is significantly more crowded than the outer regions. Bearing in mind that this project focuses on the less crowded outer regions using filters spanning a broader wavelength than the ones used in the aforementioned survey, their 21% success rate on true-positive GC candidates is a likely lower bound for the 643 GC candidates found in this survey. This means that my work has uncovered at least \(\sim 135 \times 643\) new GCs in NGC 1052, more than tripling the size of its GC system.

Barely any new GC candidates were found in the vicinity (10 \(R_{\text{eff}}\)) of the dark matter-deficient dwarf galaxies – 6 GCs for DF2, and 6 GCs for DF4. One of the GC candidates for DF2 is clearly too bright (\(i_0 = 16.4\) mag) and is therefore disregarded. The area-scaled control field GC count is 5 within both of these regions combined, leaving \(\sim 6\) potentially legitimate candidates. Almost all GC candidates occupy the faint side of the GCLF.
Another important caveat is the coverage of other galaxies that belong to the NGC 1052 Group. It is expected that the GC candidates found within $\sim 3R_{\text{eff}}$ of these galaxies are likely to belong to their respective galaxies. However, a fraction of these GC candidates may only appear in such arrangement due to projection along the line–of–sight, and may actually belong to the NGC 1052 stellar halo instead. Only radial velocity information will be able to distinguish between these situations. Moreover, the larger galaxies of the group may have significant amounts of false–negative extended GC candidates which were misclassified as extended due to local crowding of sources.

4.7.2 Stellar and GC Streams

As uncovered by the surface density map of GC candidates, there are significant asymmetries in their distribution around NGC 1052. There is a clear bridge of GC candidates linking NGC 1052 and NGC 1047 together. Whilst tentative, a preferential direction of GCs in the Forbes et al. (2019) sample towards NGC 1047 can also be seen. The asymmetric distribution of GCs in the halo of NGC 1052 and the association of GCs with tidal streams is similar to what has been observed in M31 (e.g., Mackey et al. 2019a) and other galaxies (e.g., Foster et al. 2014; Lim et al. 2017). This clearly demonstrates how accretions and mergers build up not only the stellar halos of galaxies, but also their GC systems.

There is also a significant enhancement in GCs towards NGC 1042 visible in my map. These coincide with the tidal tail and loop features that lie to the southwest of NGC 1052 which were uncovered through low surface brightness diffuse light imaging by Müller et al. (2019). The features have been argued to have no connection with NGC 1042, which also lies in this direction, as there are no significant distortions in its outer isophotal profile nor are there any features in its vicinity. This suggests it has either entered the NGC 1052 Group domain relatively recently, or it is a foreground galaxy that has no physical connection to the group whatsoever. The authors claim that while the line–of–sight velocity is consistent with the rest of the NGC 1052 group (Adelman-McCarthy & et al. 2009), there are redshift–independent Tully–Fisher relation distance measurements which support the hypothesis that NGC 1042 is in the foreground. These measurements show that NGC 1042 is at $D \sim 13$ Mpc (Theureau et al. 2007).

There are a 8 GC candidates found in this work that are within $3R_{\text{eff}}$ of NGC 1042.
The radial velocities measured during the process of spectroscopically confirming these GC candidates may shed more light on this issue of discrepant distances of NGC 1042.

### 4.7.3 Radial Profiles

Forbes et al. (2001) found that the GC number density profile followed a power law of slope $\gamma = -2.08$ radially outwards from NGC 1052. My measured power law is $-2.24 \pm 0.21$ over a much larger radial baseline. While it is steeper, this measurement is within $1\sigma$. The azimuthally-averaged radial number density profile does not have any significant breaks in its density at least up to 120 kpc in projected radius. These results are rather similar to those of the M31 halo system, which has also been characterised as a power–law function of index $-2.37 \pm 0.17$ over the range $25 – 150$ kpc (Mackey et al., 2019a).

The GC populations of NGC 1052 satellites NGC 1052–DF2 and –DF4 were compared against the power law model of the GC candidates at their respective radii. They exhibit clear overdensities compared to the underlying halo. The DF2 and DF4 GC populations within 10 $R_{\text{eff}}$ of their centres are 7 and 45 times larger than expected for the NGC 1052 halo population, therefore the hypothesis that the DF2 and DF4 GCs are simply NGC 1052 halo GCs is unlikely. The NGC 1052 halo GC distribution was also compared against that of the DFs by Shen et al. (2021a) using the power law estimated by Forbes et al. (2001). As expected, they arrived at the same conclusion.

### 4.7.4 Luminosity Functions

The luminosity functions fitted with a Gaussian provide a means to directly compare the NGC 1052 GC population to other galaxies. For example, Taylor et al. (2017) has measured the peaks of GCLFs in absolute magnitudes for the Centaurus A galaxy GC population as $\mu_u = -5.34 \pm 0.04$, $\mu_g = -6.86 \pm 0.04$ and $\mu_i = -7.83 \pm 0.04$ mag. While it is not a highly reliable technique to estimate the line–of–sight distance to a galaxy (Rejkuba, 2012), the GCLF peak can be used to give an approximate estimate of distance. I transform my measured GCLF peaks to absolute magnitudes for the NGC 1052 stellar halo GC population by subtracting the distance modulus $(m – M)_0 = 31.42$ mag, Tully et al. (2016). My
measured peak magnitudes are then $\mu_u = -6.89 \pm 0.06$, $\mu_g = -7.81 \pm 0.07$ and $\mu_i = -8.64 \pm 0.05$ mag. The absolute magnitudes differ from those measured by Taylor et al. (2017) by 0.8 to 1.24 mag, far above 1$\sigma$. The puzzling discrepancy may be due to two reasons: either the NGC 1052 stellar halo GC population is intrinsically brighter than that for typical galaxies, or the estimated line–of–sight distance is not correct. Indeed, assuming that the GC population of NGC 1052 has the same peak GCLF values as Centaurus A, the NGC 1052 line–of–sight distance is estimated to be in the range of 10.8–13.2 Mpc depending on filter rather than 19.2 Mpc. This could have a number of profound consequences for understanding the NGC 1052 Group and will be studied more carefully in future work.

Assuming that the most populated bins of the NGC 1052–DF2 and –DF4 GCLFs represent their peaks and that their GC populations are typical, the DFs are 1.4–1.5 times closer than NGC 1052, although this is based on small number statistics. Shen et al. (2021a) proposed a bimodal GC luminosity function model for the DFs, suggesting that there should be a second population of GCs in the fainter regime. Unfortunately, the CFHT survey analysed in this chapter did not successfully reach magnitudes deeper than the faintest known GC in the DFs, so I could not test this. Therefore, it is unclear whether the expected rise of GC numbers going fainter towards the “true” universal GCLF peak ($M_V \sim -9$) predicted by van Dokkum et al. (2019b) is plausible.

### 4.7.5 Colour Functions

A significant NGC 1052 colour bimodality was detected in the NGC 1052 GC candidate populations by Forbes et al. (2001) using $(B-I)_0$ colour. However, none of my CFs exhibit a significant bimodality. The largest peak difference of the bimodal Gaussian model I fit is measured in $(u-i)_0$, where $\Delta(u-i)_0 \sim 0.27$, lower than $\Delta(B-V)_0 \sim 0.4 \pm 0.1$ estimated by Forbes et al. (2001). It may be that the GC population at small projected radii ($r < 20$ kpc) is indeed bimodal, while the stellar halo ($20 < r < 100$ kpc) population is not, or that the significant crowding in the inner regions combined with the low $i$–band completeness conspired to create an artificial bimodality in Forbes et al. (2001).

Both the Milky Way and M31 spectroscopically–confirmed GC populations do not express bimodality in $(V-I)_0$ colour. Huxor et al. (2014) estimated the median colour $(V-I)$ of the confirmed M31 GCs to be $(V-I)_0 = 0.95$ mag, which is
almost the same as the median colour measured for the Milky Way, \((V-I) = 0.93\) mag \(\text{[Harris 1996]}\). However, the existence of a bimodal GC colour distribution does not directly imply the same behaviour of the metallicity distribution due to non-linear relations between colours and metallicities of GCs \(\text{[e.g., Blakeslee et al. 2010, Usher et al. 2012]}\). The non-linearity works vice-versa: for example, while the Milky Way GC population does not exhibit a colour bimodality in \(V\)-band, there is a clear bimodality in the metallicity \(\text{[Cezario et al. 2013]}\). On the other hand, there is little to no evidence of a bimodality in metallicities M31 GC population \(\text{[Caldwell et al. 2011]}\). All in all, this shows that any colour-backed inferences of metal content and its distribution in NGC 1052 GCs without spectroscopic confirmation and analysis should be approached with caution.

### 4.7.6 Colour Gradients

Considering the whole GC candidate population in the stellar halo \((20 < r < 120\) kpc), I found no statistically significant radial colour gradient in any of the colour pairs: \(-0.0019 \pm 0.0008\), \(-0.0007 \pm 0.0009\), and \(0.0007 \pm 0.0005\) mag kpc\(^{-1}\) for \((u-g)\), \((u-i)\) and \((g-i)\) respectively. \(\text{[Forbes et al. 2001]}\) found no gradient considering the inner <20 kpc blue and red subpopulations separately in \(B-I\) colour, although the mean colour did exhibit a negative colour gradient when these populations were considered together. They claimed that the gradient is likely to have been caused by radial changes in the relative mix of the blue/red subpopulations of GCs rather than the mean colour of the whole GC population. Unfortunately, there are not enough GCs in the NGC 1052 halo to examine if there is a GC colour bimodality as a function of radius.

A similar flat trend in colour is observed in M31 halo GCs \(\text{[Huxor et al. 2014]}\). The mean colour measured radially declines at a rate of \(-0.0007 \pm 0.0004\) mag kpc\(^{-1}\). This is consistent with the lack of a metallicity gradient via spectroscopy, as found by \(\text{[Fan et al. 2011]}\) and \(\text{[Colucci et al. 2012]}\).

The work in this chapter has examined the NGC 1052 GC sample via a large sample of new detections in the outer halo. These show how examining inner populations alone as in \(\text{[Forbes et al. 2019]}\) can give a biased view of the properties and that wide area coverage is needed for a complete picture. We intend to pursue spectroscopic following of the brightest NGC 1052 GC halo candidates in the near future.
Chapter 5

Conclusions

5.1 Summary of Work Presented

In this thesis I have presented results from analysing Local Volume galaxies in the low surface brightness regime, in particular the resolved stellar populations in a stellar halo (M81), tidal tails (F8D1) and globular clusters in a stellar halo (NGC 1052). The galaxies were studied using deep wide-field ground-based data taken with Subaru Hyper Suprime-Cam and CFHT MegaCam, including some ancillary analysis done with data from pencil-beam HST images.

In Chapter 2 I analyse the stellar halo of M81 through combining diffuse light and resolved stellar population methods using data from Subaru/HSC and CFHT/MegaCam. M81 is a challenging case for stellar halo analysis due to the large and variable cirrus in this part of the sky as well as the fact that it is currently undergoing strong tidal interactions with two galaxies, but its proximity ($D = 3.6$ Mpc) means that it is the next frontier in understanding the formation of stellar halos. I find that the stellar halo contains a large percentage of total light and mass ($8 \pm 2.5\%$), suggesting an active accretion history. My measured radial stellar density profile of the stellar halo is fit with a power-law ($\gamma = -1.6 \pm 0.1$) which is shallower than other recent measurements Smercina et al. (e.g. $\gamma = -2.59$ 2020).

Analysis of metal content along the principal axes uncovered tentative evidence that the stellar halo of M81 is not chemically axisymmetric. In addition, the measured metallicities are more metal-poor than previously thought. For
example, I measured the mean metallicity of the Eastern minor axis of M81 as $[M/H] = -1.46 \pm 0.11$ dex, whereas Smercina et al. (2020) measured $[M/H] = -1.2$ dex. However, due to significant contamination from the nearby galaxies M82 and NGC 3077 the results are not completely certain and will require more reliable and in–depth approaches in the future to fully understand the stellar halo of M81.

In Chapter 3, I use data from Subaru/HSC and CFHT/MegaCam to revisit the properties of F8D1, a peculiar dwarf satellite companion of M81. I have mapped the distribution of individual RGB stars on the Northeast side of F8D1. I have found evidence for a giant tidal tail emanating from this system. This feature can be traced for over 1 degree on the sky, corresponding to ≥ 60kpc at the distance of the galaxy. I have mapped the distribution of stars along and across the stream, finding evidence for an S–shaped structure that is characteristic of tidal stripping. Using the TRGB distance estimation method, I confirm that F8D1 lies on the far side of the M81 Group at $D = 3.67$ Mpc $\pm 0.06$ Mpc while the nearby dwarf spiral NGC 2976 is on the near side at $D = 3.50$ Mpc $\pm 0.04$ Mpc. Considering this along with the available mass estimates, I argue that the most likely cause of F8D1’s tidal disruption is the central galaxy M81.

I have also improved the photometric and structural characterisation of the main body of F8D1 and placed its tidal stream in context. I find the effective radius to be in the range of 1.7 – 1.9 kpc, with a trend towards larger values for redder filters. When combined with the central surface brightnesses of $\mu(0) \sim 24.7 – 25.7$ mag arcsec$^{-2}$, it is clear that F8D1 is a bona–fide example of an UDG and in fact the closest currently known example of this galaxy type. I update the main body luminosity of F8D1 to be $2.58 – 3.34 \times 10^7$ L$_\odot$, depending on whether the directly measured flux inside of 3.6 arcmin or the extrapolated total magnitude is used. Assuming a comparable stream on the other side of F8D1 beyond the extent of our current imagery, I deduce that 30–36% of F8D1’s light is contained in the extratidal features. These results show evidence that strong tidal stripping is a way to form UDGs.

In Chapter 4, I present a GC candidate search in the NGC 1052 Group using deep $ugri$–band data from the CFHT/MegaCam. I use morphology, colour and photometric selections based on spectroscopically–confirmed GCs in the inner regions of the halo. I find 643 GC halo candidates in the catalogue of sources. The radial number density profile of halo GC candidates follows a steady power law of $\gamma = -2.24 \pm 0.21$, measured in the range of 20–120 kpc around NGC 1052.
I also study the luminosity colour functions of the halo GCs, correcting for contaminants. I find these can be described by Gaussians and proceed to measure their parameters. A surprising result is that the LF of NGC 1052 halo GCs peaks a magnitude brighter than expected if the galaxy lies at a distance of $D = 19.2$ Mpc. This suggests that either the distance to this system has previously been overestimated or that the GC system is anomalous compared to others. Moreover, there is no strong evidence for bimodality in the colour distribution, although there is a slight negative colour gradient with galactocentric radius.

The dark matter–deficient galaxies NGC 1052–DF2 and –DF4 have 11 new GC candidates in total within $10 R_{\text{eff}}$ in this survey. I measure the GC density within $10 R_{\text{eff}}$ of the DFs and find that it is 7 and 45 times higher than NGC 1052 halo GC density at the respective projected radii. Therefore, it seems that there are genuine overdensities of GCs in the vicinity of these systems.

Finally, all three chapters are indirectly focused on one major goal – understanding the mechanism behind galaxy formation. These results will contribute towards future galaxy models, simulations of galaxies. In particular, they demonstrate the importance of deep wide–field imaging for gaining insight into the role of accretion.

5.2 Future Work – M81

The work contained in this thesis has addressed many issues but also leads to many new directions for follow–up work. As mentioned in Chapter 2, an issue with the analysis of the M81 halo in this thesis is the available extent along the Northern and Western axes, which is limited by the currently analysed area of the M81 Group survey catalogue. Three additional fields west of M81 were not contained in the catalogue I used as they were observed much later.

In the near future, a full reprocessing of all seven fields of the M81 HSC survey will be done with the latest version of the HSC pipeline, allowing contiguous study of RGB stars over 12 deg$^2$. The full area analysis will allow the halo of M81 to be traced in all directions, including well beyond the M82 tidal debris (see Fig. 2.3). The larger area covered will allow an even better analysis of the M81 halo and a more detailed inspection of the metallicity profiles.

In addition, we have also recently acquired deep $u$–band data from CFHT/Mega-
Cam for the inner 9 deg$^2$ of the HSC survey footprint. This will allow a search for GCs to be carried out, similar to the analysis described in Chapter 4 of this thesis. It will be possible to search for and study GCs in the stellar halo of M81 and around its dwarf satellite galaxies, including F8D1.

5.3 Future Work – F8D1

The work in Chapter 3 relied on the assumption that there is a symmetric stream on the unobserved side of F8D1 for some of the results such as the amount of stellar mass lost to the stream. I wrote a successful proposal to observe the Southwest side of F8D1 with HSC and these data have been obtained in April and May 2023. These data will be reduced and analysed in the coming months. This will allow a better estimation of luminosity in the stream, and the shape and orientation of the stream may provide further insight into whether M81 is the cause of F8D1’s disruption.

5.4 Future Work – NGC 1052

For the NGC 1052 analysis, the way forward is to propose follow-up observations via spectroscopy to confirm the GC candidates presented in Chapter 4. A suitable instrument for this would be the WEAVE spectrograph on the William Herschel Telescope in La Palma (Roque de los Muchachos Observatory). This instrument can deploy up to 1000 individual fibres covering a circular 2 degree diameter field, making this an ideal option to cover the 1 deg $\times$ 1 deg CFHT field in one go (Dalton et al., 2014). Each fibre has a diameter coverage of 1.3 arcsec, thus providing an excellent resolution and separation of individual GC candidates. The latitude of the telescope is 28.76$^\circ$ which is perfect to study the system, as the declination of the NGC 1052 system is $\sim -8^\circ$.

In addition, a more sophisticated method to uncover GC candidates than what was done in Chapter 4 is through the use of a probabilistic approach. The stellar locus is always populated by foreground populations to some degree, especially if the system of interest is at a low galactic latitude. While NGC 1052 should not suffer from significant foreground contamination due to its galactic latitude (b $\sim -58$), the Sagittarius stream in the observed field may pose a higher risk of
false-positive GC candidates. There are effective techniques used to minimise the foreground contamination, such as manually removing contaminant sources using a reference field (e.g., Piatti 2022). Despite that, methods involving removal of sources would inadvertently remove a fraction of real GC candidates. Therefore, a probabilistic approach is required instead to allow for more freedom of fine-tuning the scope of selection.

Taylor et al. (2017) describes a probabilistic GC search method that they used for Centaurus A. Firstly, the foreground sources are drawn from the Besançon model of foreground stars (Robin et al., 2003). When the expected number for a population of foreground stars is reached, GCs are simulated in a similar approach. With the foreground stars and GC populations constructed, each object is assigned a probability given by the fraction of the constructed GC population against both GC and foreground star populations captured in the colour–colour space vicinity of that object in the catalogue. The “vicinity” is defined as a square based on the object’s estimated errors in colour.

However, due to time constraints and a low necessity given the high NGC 1052 galactic latitude, the probabilistic GC candidate method was not used for this project but may be used in the future.

### 5.5 Future Prospects

Knowledge of stellar halos in the Local Volume is expected to greatly improve in the next decade. With state–of–the–art space telescope missions such as Euclid Wide Survey (Euclid Collaboration et al., 2022), the Legacy Survey of Space and Time with the Vera C. Rubin Observatory (Ivezić et al., 2019) and the High Latitude Survey of the Nancy Grace Roman Space Telescope (Akeson et al., 2019), precision wide–field studies will be improved for individual giant branch stars to 5–10 Mpc distances. These surveys will yield rich information on the statistical properties of galaxy outskirts within ~ 5 Mpc (e.g., Pearson et al., 2019). The Nancy Grace Roman space telescope will have a 100 times larger field of view than the HST with similar sensitivity and resolution, requiring far less pointings to perform a wide field deep survey.

The Vera C. Rubin Observatory (LSST) has the potential to yield major breakthroughs in research of stellar halos. Its survey of the whole southern sky
done every three days may provide us with many new discoveries. More ultra faint satellite galaxies are expected to be found in the vicinity of the Local Group and beyond (Simon et al., 2019). Its prototype survey — the HSC–SSP — has already found two candidates in the Milky Way group (Homma et al., 2016), Fukushima et al. (2018). However, all photometric dwarf galaxy discoveries will require follow-up spectroscopy measurements. According to Najita et al. (2016), mass measurements of the discovered satellites around the Milky Way will require more than a year of time allocations if current 8–10 m telescopes are used. In contrast, the ELT is expected to perform the spectroscopic observations up to 10 times faster, with the ability accurately measure velocity dispersions for up to 80 percent of galaxies discovered by Rubin (Drlica-Wagner et al., 2019).

The remnants of tidal interactions are expected to be detected at far greater distances with Rubin than any other survey before. It is expected that when the 10-year depth is reached (30 – 31 mag arcsec$^{-2}$), about 80 percent of light from the tidal features in the vicinity of the Milky Way will be captured. Should the program fall short and reach a shallower limit of (29.5 mag arcsec$^{-2}$), 60 percent of flux will still be recovered. Assuming perfect optimisation of the LSSTpipe, the survey may also detect flux of tidal features around MW-mass galaxies at distances up to (z << 2) (e.g. Martin et al., 2022b). In addition, Rubin will be essential in resolved dwarf galaxy searches, reaching up to 2 magnitudes below the TRGB within 5 Mpc (Mutlu-Pakdil et al., 2021). Naturally, the diffuse light of tidal features will be greatly complemented by resolved stars tracing the structure within the Local Volume and beyond.
Appendix A

Elliptical Functions

The ellipse functions provided in Python libraries were lacking in functionality and speed. To save time on running code, I made an Ellipse package that uses mathematical properties of an ellipse to improve the efficiency in making radial profiles of galaxies. For example, to check if an arbitrary point \((x, y)\) is inside an ellipse with a specified centre \((x_0, y_0)\), position angle \((\theta_p)\) and axial ratio \((a/b)\), the position of the point must first be corrected for the ellipse centre and position angle:

\[
\begin{pmatrix}
  x_p \\
  y_p
\end{pmatrix} = \begin{pmatrix}
  \cos \theta_p & -\sin \theta_p \\
  \sin \theta_p & \cos \theta_p
\end{pmatrix} \begin{pmatrix}
  x - x_0 \\
  y - y_0
\end{pmatrix}
\]

(A.1)

Then the condition for the point to be inside the ellipse is:

\[
\frac{x_p^2}{a^2} + \frac{y_p^2}{b^2} < 1
\]

(A.2)

This mathematical prescription for an ellipse can then be used to construct a radial profile of a galaxy by creating annuli from pairs of outer and inner ellipses. This is known as an azimuthal profile as it encompasses points at all angles around the ellipse (Fig. A.1).

If there is an angular requirement for the selection of points, e.g. points that lie between angles \(\theta_1\) and \(\theta_2\) relative to the major axis of the ellipse as specified by the position angle \(\theta_p\), then the angle of a point \(\theta\) relative to the major axis must
be derived first. The most efficient method involves performing both a scalar and a vector product of the point and the major axis. The vector representing the point is calibrated for the centre of the ellipse to be at the origin:

$$\vec{v} = \begin{pmatrix} x - x_0 \\ y - y_0 \end{pmatrix}$$ (A.3)

The vector representing the major axis which points from the origin:

$$\vec{v}_m = d \begin{pmatrix} \cos \theta_p \\ \sin \theta_p \end{pmatrix}, \text{where } d = \frac{ab}{\sqrt{a^2 + b^2}}$$ (A.4)

The angle of the scalar product describes the numerical value of the relative angle $\theta$:

$$\theta_{\text{scalar}} = \cos^{-1} \left( \frac{\vec{v} \cdot \vec{v}_m}{|\vec{v}| |\vec{v}_m|} \right)$$ (A.5)

The angle of the vector product describes the sign of the relative angle $\theta$:

$$\theta_{\text{vector}} = \sin^{-1} \left( \frac{\vec{v} \times \vec{v}_m}{|\vec{v}| |\vec{v}_m|} \right)$$ (A.6)

Combined together, we get the relative position angle from the major axis of the ellipse:

$$\theta = \theta_{\text{scalar}} * \text{sgn}(\theta_{\text{vector}})$$ (A.7)

The relative angle can then be used to determine whether a point is located inside a specific slice of the ellipse, i.e. the wedge. For example, if a radial profile along a major axis with a 40° opening is needed, then the relative angle requirement is simply $-20^\circ < \theta < 20^\circ$. Similarly, if a profile with the same opening angle is needed along the minor axis to the left of the major axis (position angle 90°), then the relative angle is in the bounds of $70^\circ < \theta < 110^\circ$. The wedge profiles are shown in Fig. A.2

Radial profiles are often quantified in units per area. The area of a wedge of an ellipse defined by relative angles $\theta_1$ and $\theta_2$ is calculated by a two-part equation.
Figure A.1: Ellipses centred at (-4,-5), position angle $-20^\circ$, axis ratio 0.5, with radii in the range of $0.1 < r < 0.5$ on mock data. The coloured dots show an example of selection for a radial azimuthal profile with annuli.
First, the representative area is calculated for both angles:

\[ A(\theta) = \theta - \tan^{-1} \frac{(a - b) \sin(2\theta)}{a + b + (b - a) \cos(2\theta)} \] (A.8)

Then the difference between the angles gives the area of the wedge:

\[ A = \frac{ab}{2} (A(\theta_2) - A(\theta_1)) \] (A.9)

If the coordinate along the ellipse at any given relative angle \( \theta \) from the major axis is required, the vector coordinate is calculated by:
\[ \vec{v}(\theta) = \begin{pmatrix} \cos \theta_p & -\sin \theta_p \\ \sin \theta_p & \cos \theta_p \end{pmatrix} \begin{pmatrix} d \sin \theta \\ d \cos \theta \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \end{pmatrix}, \text{ where } d = \frac{ab}{\sqrt{(a \sin \theta)^2 + (b \cos \theta)^2}} \]
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