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Structure and substructure in the stellar halo of the Milky Way

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Chapter 1

Introduction

1.1 A Universe of galaxies

Galaxies are the fundamental blocks of the Universe's large scale structure. Galaxies are gravitationally bound entities that reside at the centre of dark matter (sub)haloes, and contain sufficient baryonic matter to trigger star formation, localized chemical and nuclear reactions that produce electromagnetic radiation. Galaxies consist of gas, dust, icy molecules, stars, planets and dark matter in varying proportions. Gas, dust and ice molecules together with planets' interiors, surfaces and atmospheres are involved in chemical reactions, and the basic elements of the Periodic Table —ranging from hydrogen to iron—are involved in the nuclear reactions that take place in the stellar interiors. Because of the different energies at which these processes take place, they show their signatures in electromagnetic radiation over a wide range of wavelengths.

Galaxies come in a wide range of sizes, masses, and shapes, which are a reflection of their evolutionary stage and past history, and they can be classified in the Hubble diagram (see Figure 1.1). Irregular galaxies host stars that follow complex orbits without a well defined rotation centre, and may be abundant in gas and dust (with the exception of dwarf irregulars). Spiral galaxies are also gas-rich star-forming systems but, unlike irregular galaxies, they are rotation supported, resulting in a well-defined set of structural components: an inner bulge, a disk with spiral arms, an ellipsoidal halo and, sometimes, a central bar. It is believed that the presence or absence of a bar is dependent on the mass available in the galaxy —especially the central mass of the galaxy— and on the gas+stars to dark matter mass ratio, as well as on its interaction history. These two types of galaxies contain clouds of cold gas dense enough to undergo gravitational collapses and keep producing stars. By contrast, elliptical galaxies are no star-forming and ellipsoidal, with their stars having metastable orbits around a well defined centre. Elliptical galaxies, however, have also by and large exhausted or heated their cold molecular gas, and cannot form any new generation of stars. For this reason their

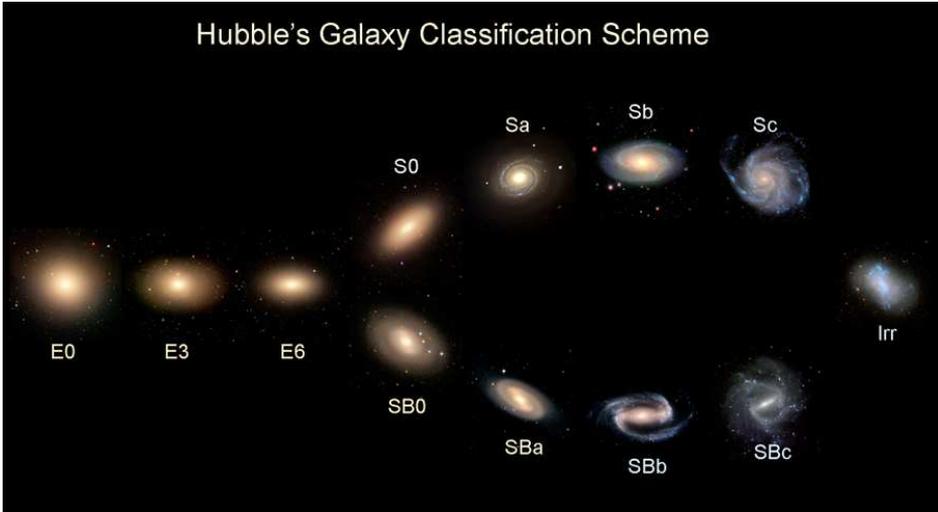


Figure 1.1: Hubble's classification diagram, as built by the Galaxy Zoo project. E indicate elliptical galaxies, S and SB indicate spiral and spiral-barred galaxies respectively, and Irr indicates the irregular type.

spectra are dominated by old low-mass stars. These two characteristics (stellar orbits and cold gas content) thus lead to morphological differences between types of galaxies and a fundamental difference in their stellar population make-up, which is reflected in their spectral energy distributions (SED).

Galaxies cover a large range of total luminosities, from $10^3 L_{\odot}$ to $10^{12} L_{\odot}$, giving rise to a relative classification of galaxies into (ultra-)faint, intermediate, bright or ultra-luminous galaxies. They can also have a variety of masses, from $10^5 M_{\odot}$ to $< 10^{13} M_{\odot}$ in total mass, leading to a classification into dwarf, medium and giant galaxies. Irregular and spiral galaxies are typically associated with the intermediate and smaller mass ranges, whereas elliptical galaxies are associated with all mass ranges. The current theory for galaxy formation links this observed distribution to their assembly history and evolution through the process of gravitational accretion (Cole et al. 1994), as we will see in the following section.

1.1.1 Galaxy formation and evolution

It is well known that a closed, isolated, isotropic and perfectly uniform system can be considered in equilibrium, and therefore will not undergo any evolution in the absence of external forces. To the best of our knowledge, the Universe is a closed, isolated and isotropic system, but it is not and was not a perfectly uniform system at the Epoch of Recombination and photon decoupling, as the Cosmic Microwave Background shows. This lack of uniformity is the reason why we observe a dynamic and evolving Universe, instead of a simple homogeneously

expanding Universe. However any theory of galaxy formation needs to explain how these inhomogeneities originated and how they evolved into an increasingly clustered and inhomogeneous state.

The theory of the Big Bang states that the Universe was born from a singularity in a very high density state that underwent a brief exponential expansion early on (the Inflation). It has continued to expand and cool since. The current paradigm for the early Universe is that primordial quantum fluctuations were amplified by the Inflation and left tiny density variations spread throughout the Universe, which grew through gravitational instability. These density variations were the seeds for current galaxies. As a small overdensity starts to gravitationally attract matter, the more matter it accretes, becoming an increasingly strong gravitational well. Eventually these density seeds accreted enough gas to form clouds that could (gravitationally) collapse and produce the first stars and galaxies. These protogalaxies in turn merged with each other into increasingly massive galaxies. This merging growth mechanism—known as the hierarchical formation scenario—comprises, together with the Big Bang theory, gravity and the early Universe observations, the current paradigm for galaxy formation (White & Rees 1978).

Gravitational interactions between galaxies can involve processes of four types. They can lead to mass growth or mass loss, as well as morphological and dynamical changes. These possible processes are high-speed encounters, galaxy mergers, tidal stripping and dynamical friction. Simply put, high-speed encounters are those in which the difference in velocity between the two galaxies is enough in comparison to their gravitational pull to prevent them from slowing down and becoming orbitally bound objects (i.e., their interaction is limited to one event), and they are characterized by high-speed processes that perturb the galaxies. Often this type of interactions require numerical simulations in order to be understood, but, in the simpler case in which the internal velocity dispersion of the perturbed galaxies is much smaller than the encounter velocity, the interaction can be approximated as a tidal shock, which causes cooling and expansion of the system, and potential mass loss.

Galaxy mergers are the direct result of a close encounter in which two systems have a sufficiently low orbital energy to make them slow down and mix with each other, eventually losing all morphological signs of one or both of the progenitors and becoming one integrated system. "Any bound orbit will eventually lead to a merger because the tidal interaction between two galaxies always transfers orbital energy into internal energy", but "if the angular momentum is high and if the orbital energy is not low enough, the merger will not happen in a Hubble time¹" (Mo et al. 2010). Additionally, mergers can also happen between initially unbound galaxies, provided that the tidal interactions of the encounter drain sufficient orbital energy from the system. Merging events can be roughly separated into two types based on their progenitors mass ratio: major or minor. Major mergers are those involving two galaxies of similar masses (with a mass ratio lower than a factor of 4), whereas minor mergers are those involving two galaxies of quite

different masses. Major mergers cause the violent relaxation of the resulting remnant, and often lead to the quick consumption or expulsion of the cold gas. This eventually turns the resulting system into a galaxy populated by old stars with a red dominated spectrum. Minor mergers involve phase mixing and Landau damping, and often result in a system that resembles (morphologically speaking) the most massive progenitor.

Tidal stripping entails the removal of material from the outer regions of a collisionless system as a result of tidal forces. This process is typical in orbitally bound systems (metastable) or in systems that are on the way to becoming orbitally bound or fully accreted (unstable). The key element of this process is that the tidal forces, in combination with the rotation centrifugal forces of the system, exceed the binding forces for some of the material in the satellite body—the material situated further than a critical distance from the centre of the satellite, a distance called the tidal radius. As a result of tidal stripping, tidal streams and tails form out of the stripped material, leading and trailing the satellite approximately along its orbit. Tidal tails can also be observed not only in satellite galaxies or globular clusters (Mateo et al. (1996), Odenkirchen et al. (2001)) but also in the merging of (disk) galaxies (Toomre & Toomre 1972).

Finally, dynamical friction is the process by which a galaxy moving in a much less dense environment experiences a drag as it transfers energy and momentum to the particles in the environment. This causes orbits to decay with time, bringing the galaxy experiencing the friction towards the centre of the host’s potential well. Since the drag force is proportional to the square of the mass of the galaxy, there is a mass segregation in the orbital decay, bringing more massive galaxies deeper into the gravitational well, and leaving them more susceptible to mergers or tidal stripping.

There is abundant observational evidence for all these processes in the local Universe: stripped gas and stellar streams around galaxies (Figure 1.2), galaxy collisions (Figure 1.3) or even ram pressure stripping in galaxies falling through a galaxy cluster (Figure 1.4). However there is also ample evidence of these processes having occurred earlier in the Universe’s history. Medium and high-redshift research shows statistical evidence for the merger, mass growth and type-evolution of galaxies (from star-forming to quiescent), as summarized in Figure 1.5 (Muzzin et al. 2013). This figure illustrates how the number density of quiescent galaxies has been increasing over time for all mass ranges, and that the high-mass cut-off has grown with time (indicating mergers). Simultaneously, the number density of high mass star-forming galaxies has been virtually constant, while low-mass star-forming galaxies outnumber the quiescent ones (indicating mergers and an eventual quenching of star-forming galaxies). This, in combination with the typical spectral energy distribution (SED) of quiescent and star-forming galaxies, supports the hierarchical formation scenario and the morphological and mass

¹The Hubble time is an estimate for the age of the Universe, based on the approximation that the Universe has always been expanding at the same rate it does today.



Figure 1.2: Faint stellar tidal streams around the edge-on galaxy NGC 5907. Image credit: R. J. Gabany in collaboration with Martínez-Delgado et al. (2010a).

evolution of galaxies.

Numerical cosmological simulations have provided a context for these observations, and have shown that the underlying mechanisms for hierarchical formation (the primordial small density variations, in combination with cold dark matter and gravity) can actually reproduce the observed history and match (most of) the current observations. Once the simulations complete the (currently ongoing) transition from dark matter-only to ones that include hydrodynamics (gas) and stellar processes like feedback, stellar winds, or central AGNs, and overcome current resolution limitations, these comparisons can grow further in sophistication. Together with improvements in the observed census of the properties of galaxies, such research will further refine our understanding of the processes that drive galaxy formation.

1.1.2 A unique test case: the Milky Way

The Milky Way—a medium-sized, modestly star-forming spiral galaxy—poses a unique case study of galactic structure, evolution and minor merging in the Local Universe. As observers located within the Milky Way, we have a 360 deg view of the Galaxy, in contrast with the one-directional view (either face-on or edge-on) we have of any other galaxy. Additionally, as opposed to what happens with most other galaxies except those in our closest vicinity, in the Milky Way we have access to spatially resolved stellar populations and spatially resolved kinematics. This means that the disk, bulge, spiral arms and halo can be studied not just as bulk components with major features, but as resolved stellar systems. Finally

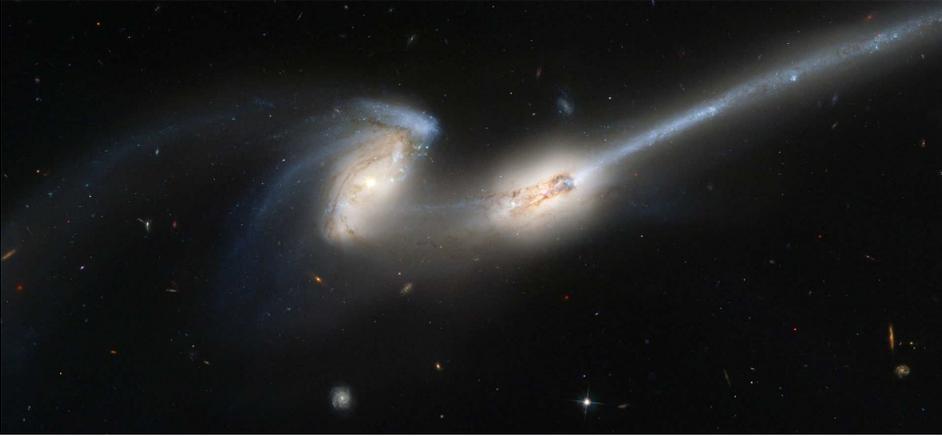


Figure 1.3: The Mice galaxies (NGC 4676) in the process of merging. Tidal tails can be observed. Image credit: NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M.Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA – APOD 2004-06-12.

our proximity allows us to probe intrinsically fainter stars and therefore study obscured or distant regions. Similarly it gives us the possibility to build a very accurate census of satellite galaxies, potentially complete at the ultra-faint end save the zone of avoidance determined by the Galactic disk.

The study of the Milky Way through detailed analysis of its resolved stellar populations is known as "Galactic Archaeology".

1.2 Stellar tracers for Galactic structure

As stars orbit their host galaxy, they suffer the perturbative influence of molecular clouds, star clusters, dark matter, spiral arms or nearby massive objects, even if overall the gravitational potential is close to a steady state. Spiral galaxies consist of a central stellar bulge, a stellar thin disk and (potentially) a thick disk, and a stellar halo. The stars in the disk are affected by transient spiral density waves that accelerate and decelerate them in their orbits, but on the whole stellar disks can be considered to be in a quasi-steady state. This may not be true for the stars in the halo, however: at large radii dynamical times are long, and hence perturbations and accretions due to minor mergers and subhaloes persist over many Gyr. Studying the distribution, kinematics, chemical composition and age of stars in the intermediate and outer halo can therefore provide significant understanding on the structure, evolution and accretion history of the Galaxy. This task can be carried out using photometric data, spectroscopic data or simulations. Particularly, when using only photometric techniques, combining measurements of different types of stars at distinct evolutionary stages, with diverse ages and

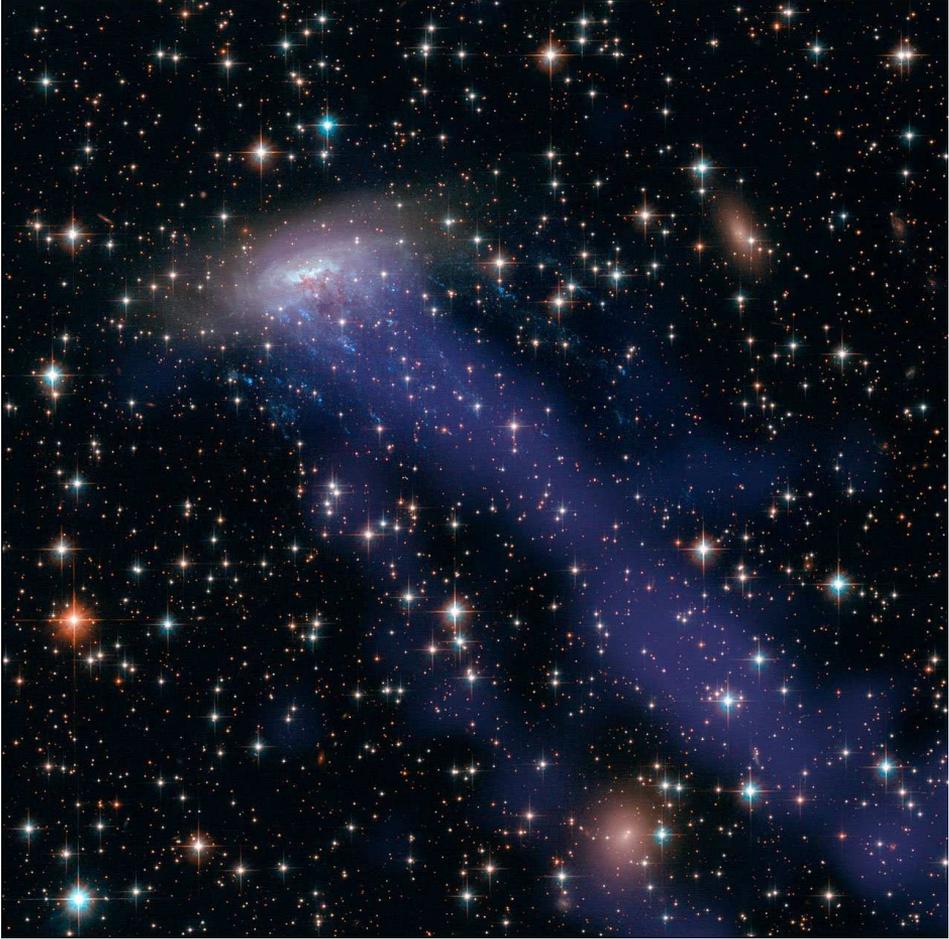


Figure 1.4: A gas stream in X-rays (Chandra X-Ray Observatory), ram pressure stripped from galaxy ESO 137-001 as it falls through the galaxy cluster Abell 3627 (Hubble Space Telescope). Credit: NASA, ESA, CXC.

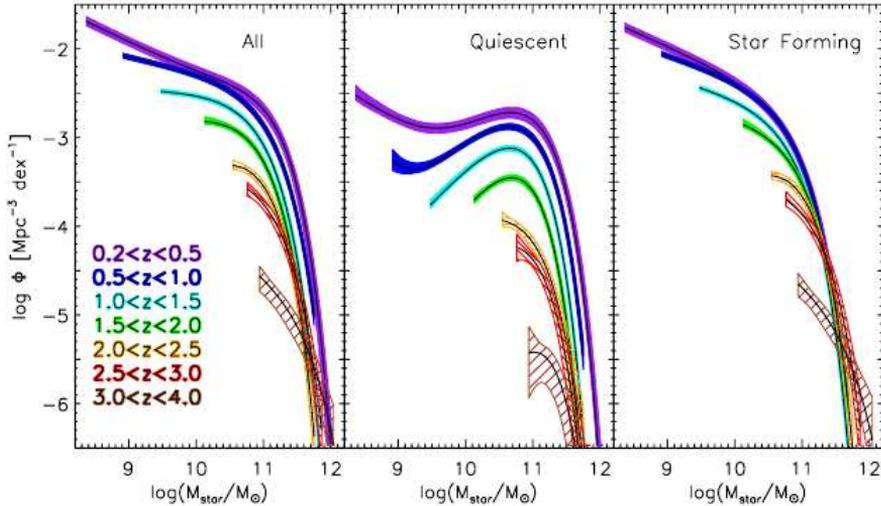


Figure 1.5: Galaxy number density distribution along different stellar masses for different redshifts. The different panels represent the general distribution (left), the quiescent population (centre) and the star forming population (right). Credit: Muzzin et al. (2013).

metallicities and located in different regions can help build a full picture of the present-day Galaxy as well as its formation and accretion history.

1.2.1 The H-R diagram

One of the fundamental photometric tools for resolved galactic Astrophysics or resolved stellar populations is the Hertzsprung–Russell diagram (H-R diagram).

The strength of the H-R diagram (left panel on Figure 1.6) lies in its descriptive and classifying power, applicable both to fundamental and observable properties of stars. The H-R diagram locates stars in a 2-dimensional parameter space of surface temperature and intrinsic brightness, in which stars nicely separate into several evolutionary stage loci. From an observational point of view, the H-R diagram is constructed from the spectral type or photometric colour of the stars and their absolute magnitude, which requires to have an estimate for each star’s distance.

Stars in the H-R diagram can be grouped along isochrones (right panel on Figure 1.6). These, as their name indicates, are the loci for stars of equal age (and equal composition) but different mass in the H-R diagram. Isochrones characterize stars that have been born from the same parent cloud and are particularly useful to trace groups of stars that have similar age and are located at similar distances.

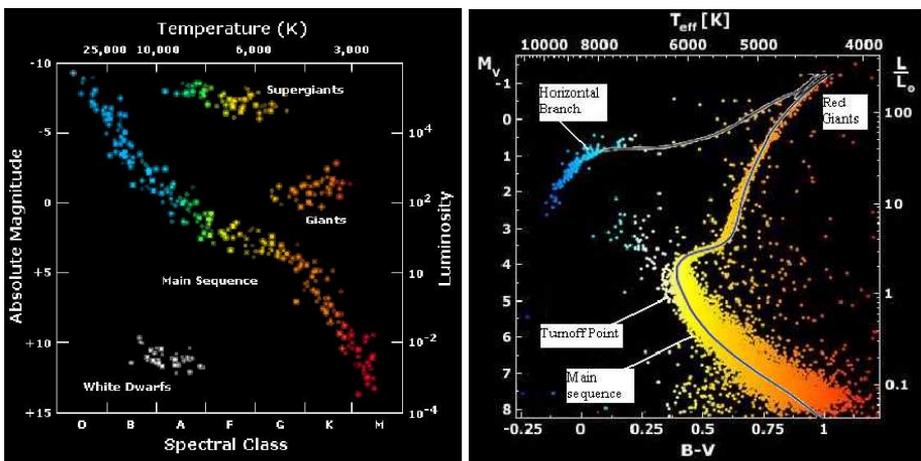


Figure 1.6: Left: the Hertzsprung–Russell diagram of stars. The y-axes represent absolute magnitude (left) and luminosity (right) and the x-axes represent effective temperature (top) and spectral class (bottom). Right: The colour magnitude diagram for globular cluster M55; a theoretical isochrone for M55 is shown (black line). The y-axes represent absolute magnitude (left) and luminosity (right), whereas the x-axes represent effective temperature (top) and colour (bottom). Credits: Cristopher Schneider (left), and B.J. Mochejska and J. Kaluzny (right).

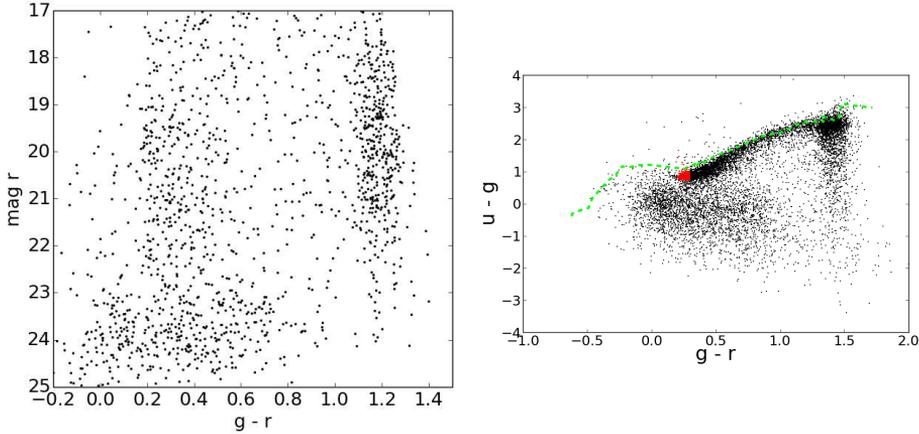


Figure 1.7: Left: Colour magnitude diagram (CMD) in the direction of galaxy cluster Abell 990; stars at different evolutionary stages are not distinctly grouped mainly because of the distance effect on apparent magnitudes. Right: Colour colour diagram for a set of CFHT-INT fields (chapter 3). The green dashed line indicates the theoretical location of the main sequence stars; the black dots indicate the observed colours for point-like sources.

1.2.2 Observational characteristics of stellar populations

In practice, the observational equivalent of an H-R diagram is constructed from the apparent magnitude and a photometric colour (the ratio of the flux of a star measured through two filters), and is called a colour magnitude diagram (CMD). In such a diagram, the different evolutionary stages can mix severely along the y-axis when there is a distribution of distances along the line of sight. Similarly, varying metallicities and ages bring small variations in temperature for stars with the same mass and evolutionary stage, moderately broadening in colour the stellar loci and evolutionary tracks. These effects make it impossible to directly recognize types of stars (see Figure 1.7, left panel) unless an overdense stellar population with a well defined distance is present in the observed field. Conversely, because photometric colours are distance-independent, it is possible to some extent to recover the information contained within the H-R diagram by constructing an observation colour-colour diagram (Figure 1.7, right panel). This type of diagram can be successful in recovering a main sequence locus, for instance; but, on the other hand and depending on the set of filters, might be unsuccessful in fully separating the main sequence from the supergiants at the red end (Covey et al. 2007).

Stellar populations encode part of the formation history of any galaxy, since they contain sibling stars formed at the same time from the same parent cloud. If stars from a given stellar population are still confined to a small region (in

young open clusters that have not had time to dissolve yet or in the halo, where dynamic time scales are longer), a clear overdensity can be identified in the form of an isochrone in a CMD, and a statistical approach can be used to accurately characterize its age and metallicity by fitting theoretical isochrones. Hence determining the birth-epoch of the stars and their contribution to the Galaxy's structure.

The particular relevance of theoretical isochrones for Galactic Archaeology lies not only in their power to characterize the age and the metallicity of a given stellar population, but also on the possibility of estimating its distance to us provided that the other two parameters (metallicity and age) are known. The metallicity of a star can be accurately measured through spectroscopy, and its age can be derived with reasonable accuracy assuming a distance or a mass is known. However, with just photometric data these parameters can only be estimated provided that very accurate colours are known. In such a case the star can also be classified according to its spectral type and evolutionary stage.

Thorough models of stellar interiors and stellar atmospheres have been developed in the last decades to derive expected absolute magnitudes for specific evolutionary stages and build robust sets of theoretical isochrones (Girardi et al. (2010); Marigo et al. (2008); Dotter et al. (2008a), for instance). However, on top of observational uncertainties and despite the very precise theoretical isochrones, some intrinsic challenges remain since an age-metallicity degeneracy in absolute magnitude and colour is present for some evolutionary stages. The reason for this is, on the one hand, that an increasing metal content always cools the temperature of stellar atmospheres and decreases their luminosity because of the associated photon absorption. This moves the stars redwards and faintwards in the H-R diagram. On the other hand, the age of stars also affects their effective temperature, with different evolutionary stages being more sensitive to age than others (some examples are provided in section 1.2.3).

1.2.3 Stellar evolution stages suitable for Galactic studies

Especially relevant to Galactic Archaeology are those stars that, because of a small scatter in their intrinsic brightness, a bright evolutionary stage or a high number density, can be used as distance tracers, age tracers or spatial density tracers (respectively). A brief description and characterization of those types now follows.

Main sequence stars are by far the most abundant type of stars, because all stars must undergo this phase at the beginning of their lives and the less massive stars can spend many Gigayears in this stage. However, precisely these most abundant low-mass main sequence stars are intrinsically faint, and main sequence stars cover a continuous range of absolute magnitudes. Both facts make them poor distance and spatial density tracers. However, there is one exception, that of the so called main sequence turnoff point (MSTO), which—for a given population of stars with the same age—represents the mass or spectral type for which stars are currently abandoning the core hydrogen-burning phase. Provided that an estimate

for the distance to the stellar population exists (from Cepheid or RR Lyrae stars, from horizontal branch stars or from the tip of the red giant branch stars), a fit to the MSTO can be used to determine the age and metallicity of the population. On the other hand, if the age and metallicity of a stellar population are known from spectroscopic works, a theoretical isochrone can be used, in combination with the distance modulus, to estimate the distance.

The red giant branch (RGB) stars are low-to-intermediate mass stars ($0.3 - 8M_{\odot}$) that have finished fusing hydrogen into helium in their cores but are still fusing it in a shell surrounding the helium core. They are intrinsically bright and relatively numerous, which makes them good spatial density tracers. Furthermore the tip of the branch (TRGB) has an intrinsic absolute magnitude ($M_I = -4.0 \pm 0.05$, Madore & Freedman (1993), Frayn & Gilmore (2003)), which also makes them accurate distance tracers when a single population can be identified in the CMD.

The red clump (RC) is an overdensity in the H-R diagram consisting of cold (either metal-rich or young) horizontal branch stars, and therefore already fusing helium into carbon in their cores. The RC has an intrinsic absolute magnitude thought to be independent of age and metallicity ($M_r = 0.6$, Bellazzini et al. (2006c)), a very narrow colour range (a very specific temperature, Correnti et al. (2010)), it is easily identified in the CMD and it indicates an intermediate age population.

The blue horizontal branch (BHB) stars are also helium-burning stars, located blueward of the RRLyrae stars. They are the least massive and oldest among the horizontal branch stars, and very metal poor. They are intrinsically bright and blue and therefore one of the most practical distance tracers in the halo, provided that the BHB tail is avoided. They have a specific colour-colour range (Deason et al. 2011) and also a specific absolute magnitude ($M_g = 0.5 \pm 0.1$), which makes them accurate distance tracers. Nonetheless, RR Lyrae stars, which are pulsating HB stars in the instability strip, are optimal distance indicators owing to the relation between their pulsating period and their absolute magnitude.

Substantial and continued efforts by the astronomical community have yielded accurate photometric selection criteria for these types of stars and reduced contamination by stellar types with similar colours. This conveniently allows for practical multi-band analytic star selection and direct distance photometric parallax calculations of BHB, RC, TRGB and MSTO stars.

1.3 The Milky Way

As briefly stated above, the Milky Way is a disk spiral galaxy, moderately star-forming and medium sized. It is one of two dominant galaxies in the so called Local Group halo, together with the Andromeda Galaxy. Both galaxies are heading towards each other and will collide in approximately 4 Gyr, eventually producing a merger remnant.

The dynamic constraints from satellite galaxies and globular clusters indicate

that the dark matter content of the Galaxy (that of the dark matter halo) is $1 - 3 \cdot 10^{12} M_{\odot}$ (Battaglia et al. 2006), whereas the baryonic mass is estimated to be less than $\sim 10^{11} M_{\odot}$. About 75% of the baryonic mass is located in the disk, and most of the remaining baryonic mass resides in the bulge. On the other hand, the dark matter mass contained within 50 kpc (the distance to the Large Magellanic Cloud) is only about one quarter of the estimated total (Sakamoto et al. 2003).

1.3.1 The structure of the Milky Way

The central 3 kpc of the Milky Way are dominated by a bulge, with a peanut shape and matching kinematics, indicating the presence of a bar. The bulge is mainly composed of an old population of stars, with a small range of ages but a large dispersion in metallicity and a metallicity gradient along the minor axis of the bulge (Zoccali et al. 2008). This suggests that the Milky Way's bulge is a mixture between a classical bulge (originated early in the history of the Galaxy) and a pseudo-bulge originated from a buckled disc, but the time of this buckling and therefore the age of the bulge as a structure is yet unclear.

The disk hosts most of the cold gas and dust of the Galaxy, and therefore most of the star formation. It is often described as a combination of two subcomponents: a thin disk with a vertical scale height ~ 300 pc and extending not further out than $R_{GC} \leq 15$ kpc, and a thick disk with scale height ~ 900 pc and only old stars. Additionally, the disk is warped in its outer regions. The actual origin of the thick disk is still unclear. Possible explanations are thin disk heating, early low-inclination satellite accretions and an early turbulent gas disk that gives rise to star formation and eventually settles into a thin disk. Moreover, the presence of the accretion substructure denominated the Monoceros ring confuses the proper delimitation of the thick disk. One of the main challenges for the future consists of finding a proper and robust definition for these two components, be it kinematical, chemical, structural or, preferably, dynamical.

The stellar halo is a spheroidal component that spans all radii from the central parts of the bulge out to probably 100 kpc. It contains globular clusters and stellar debris, as well as some of the satellite galaxies. The stellar debris can take the form of shells and clouds (when the material has long ago departed from the progenitor and it is populating the apogalacticon in wide, heating-up orbits) or the form of streams (elongated strips of stars in relatively round orbits or still close to the progenitor or the perigalacticon). Additionally, there are also ancient debris, but these are only recognizable in the phase space since by now they have already spatially mixed up (phase wrapped) with the rest of the halo. The ESA satellite Gaia, currently in operation, is expected to help unravel the halo phase space with unprecedented accuracy and reach the old heated debris contained within the disk and the inner halo. Current calculations indicate that only 60% of the halo's total luminosity density can be explained by a smooth ancient spheroidal component (Bell et al. 2008); the other 40% most likely has been accreted.

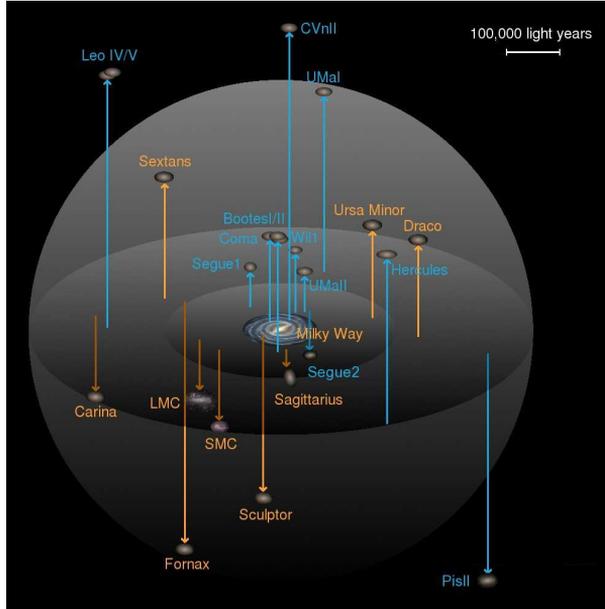


Figure 1.8: Satellite galaxies circa the Milky Way (incomplete list). Credit: J. T. A. de Jong, after J. Bullock.

1.3.2 The satellites of the Milky Way

The halo is dim and not very densely populated by stars, but interesting accretion phenomena take place in it. As soon as accurate extragalactic distance indicators became available, two prominent Southern sky objects, the Small and the Large Magellanic Clouds, were quickly identified as satellite galaxies orbiting the Milky Way. Later on, with the advent of radio observations, their tidal interaction with the Milky Way was discovered in the form of a gas bridge. However, only in 1996 the first evidence was gathered for a current disruption and cannibalizing event in the Milky Way: the Sagittarius dwarf galaxy (discovered in 1994) is being torn apart and assimilated by the Milky Way, in a stripping process that wraps two tails at least 180 deg around the Milky Way. Since then, with the advent of deep large-area surveys, many more satellite galaxies have been discovered within ~ 400 kpc of the Galactic centre, as well as several narrow and wide streams. The census of satellite galaxies (over 30, with 8 to 9 new additions just in 2015 and only 8 additions between the '30s and the '90s) and the census of stellar debris (inaugurated in 1996 and populated since 2006) have genuinely exploded in the last decade. It seems that, for now, the next discovery or improvement in the characterization is always one photometric tracer, one surface magnitude or one magnitude deeper away than allowed by the current telescopes.

In the years between the classification of the Magellanic Clouds as satellite

galaxies and the discovery of such a rich population of satellite dwarf galaxies, many Globular clusters—clustered groups of old stars and metallicities different from that of the field halo stars—have been discovered and added to the list of halo objects. They are systems with only one or two stellar populations and no detected dark matter content. Some of them are considered to be native to the Milky Way, while others are currently catalogued as natives of dwarf galaxy haloes accreted into the Milky Way’s halo. The connection between globular clusters and the lowest-mass dwarf galaxies, their role in the galaxy formation scenario, and their differences with the field stars of the halo are yet to be fully understood and placed within a single picture of the formation and evolution of the halo.

1.3.3 Stars in the halo

Halo stars are typically found at very large heliocentric distances, making them hard to detect. However, their distances and their presence in lines of sight away from the disk makes them much easier to identify, both spatially and on CMDs. With CCD astronomy and the state-of-the-art 4 – 8 meter telescopes, we have reached enough sensitivity to finally survey the halo in a systematic and statistically significant way, both photometrically and spectroscopically.

The halo is mainly populated by old, metal-poor stars. The main reason for this is that it is not an actively star-forming region in any galaxy. Cold molecular clouds are absent from our halo, since this type of gas easily sinks towards the disk, and only there acquires high enough densities to undergo a star-forming Jean’s instability collapse. Therefore the halo is formed by old stars from early generations, whose parental clouds were barely enriched with outflowing metals from previous generations.

Since halo stars are old stars, all of its most massive stars (O, B and A spectral types) have by now finished their lives, and only the least massive of them can be observed as white dwarves. Typical halo main sequence turnoff point stars are of spectral type F, with early F and late A stars having already evolved into red giants and horizontal branch giants. As stated earlier, the brightness of red giants and horizontal branch stars makes them good distant halo tracers. And both the main sequence turnoff point and the white dwarf sequence are particularly interesting to photometrically determine the age of a given equidistant halo population. However the white dwarf sequence is even more costly to observe than the main sequence due to its intrinsic faintness. Therefore, the use of red giants and horizontal branch giants has been wide-spread and main sequence turnoff point stars have been exploited to some extent, but the use of the white dwarf sequence has been limited to specific targets (like globular clusters) or extremely deep Hubble Space Telescope archival data (Hansen et al. 2002, 2013).

The stars in the halo have specific chemical abundances that separate them from the disk stars and from the old bulge population. Similarly, specific chemical abundances can be used to separate average halo field stars from accreted stars born in satellite galaxies or globular clusters with a different metal enrichment history. The current and recent spectroscopic surveys are only the first wave

leading towards a full taxonomy of the stellar halo and a complete picture of its formation history.

Overall the hierarchical formation scenario offers a framework to interpret the minor merger history of the Milky Way, and it means that we can dynamically, spatially and chemically distinguish two broad groups of stars in the halo: those belonging to the smooth field component and those accreted, which can be dynamically cold or already spatially-mixed.

1.4 This thesis

In this thesis we target the stellar halo of the Milky Way with the aim of understanding its structure, stellar populations and current accretion history. In chapters 2 and 3 we address the structural properties of the smooth component of the stellar halo. In particular we select near main sequence turnoff point stars and use them to build stellar density profiles along several lines of sight. We fit stellar halo models to these density profiles, derive the structural parameters for the best fits and determine the most plausible model. In chapter 4 we develop an algorithm to recover halo overdensities in the form of main sequence signatures from Colour Magnitude Diagrams where a foreground and background statistical subtraction to enhance the signal is not possible because of the absence of nearby control fields. We apply this method to several fields and successfully measure distances to the Orphan stream, the Palomar 5 stream and the Sagittarius stream, while finding potentially new weak overdensities. In chapter 5 we apply this method to the search for streams and underlying adjacent stellar populations around globular clusters. And, finally, in chapter 6 we explore the KiDS data release 1 and 2 footprints in search for halo substructure and overdensities. We trace the Sagittarius stream in the southern sky using main sequence turnoff point stars, and we also identify the Virgo Overdensity, the Eastern Band Structure, the Sagittarius stream and a Palomar 5 tail in the northern hemisphere. We search for potentially new overdensities such as cold streams, satellite galaxies or globular clusters but find none in the area so far probed. We conclude by reporting the future expectations for up-coming KiDS data releases.