Chapter 1

Introduction

The Universe is a fascinating place, and our perception of it has changed over the centuries. Until no more than 25 human generations ago, the geo-centric world model, in which the Earth occupies the centre of the Universe, was our fiducial prescription of the cosmos. Since then, revolutionary insights have led to a very different picture, especially during the 20th century. The Universe is vastly larger than previously thought, us humans do not seem to occupy a special place in it, nor are we made of the most common form of matter. Careful astronomical observations have been key in shaping our understanding of the cosmos. This thesis presents measurements on the stellar component in the most massive structures formed in the Universe, with the potential to test and further expand current physical models and thus our understanding of the cosmos. First, in this introduction, we summarise the sequence of scientific discoveries that led to the standard model of cosmology, and lay out open questions we are currently facing in the field of extragalactic astronomy.

1.1 The standard cosmological model

Determining the age, composition, and evolution of the Universe as a whole have been central goals in the study of cosmology. These questions have fascinated human minds for centuries, and in the 16th century the revolutionary Helio-centric model was formulated by (among others) Nicolaus Copernicus and Galileo Galilei. In this model, the planets were described to orbit a stationary Sun in the centre of the Solar system, and this led to an easier and more elegant mathematical description of the movement of the other planets. We now know that the Sun has properties similar to other stars in the firmament, although their distances to us are very different. Attempts to describe the position of the sun within this vastness of stars led to a model called the Kapteyn Universe, in which our galaxy, the Milky Way, is an island Universe of about 40,000 light years in size (Kapteyn 1922). Whereas astronomers in the 1920s agreed that the Sun does not occupy the centre of the Milky Way, the question whether the nebulae are of galactic nature was a topic of debate. Observations by Edwin Hubble (Hubble 1926) have finally shown that most nebulae are galaxies beyond the Milky Way which move away from us, and this settled the debate. The velocities (or redshift) of these galaxies were found to be proportional to their distances (Hubble & Humason 1931). This result came as a big surprise, since it implies that the Universe is not static but expanding over time.

Galaxies are not distributed randomly in space, but are clustered on a range of scales such as galaxy groups, or even larger agglomerations called clusters. When Fritz Zwicky studied the movement of galaxies in the Coma cluster, he found that their relative velocities are significantly higher than what was expected from the matter observed in this cluster (Zwicky 1933). This was the first indication of a matter component we now call "dark matter", a type of matter that does not emit light but does interact through gravity. Measurements of the rotation velocity of stars in spiral galaxies by Rubin & Ford (1970) also showed that most of the gravitational matter in galaxies could not be observed, providing another sign of dark matter. Modern estimates suggest that all the elements covered by the periodic system that we were taught at school constitute less than 20% of the total matter content of the Universe (Bennett et al. 2013), and that the rest is in an unknown form of dark matter.

The discovery that the Universe on large scales is expanding motivated the Big Bang model, a picture in which the Universe originated from a singularity in space and time and has been expanding since. Whereas a logical thought is that the expansion speed is decreasing due to gravity, a study of distant supernovae in the late 1990s led to a surprising insight. The expansion of the Universe seems to be accelerating (Riess et al. 1998; Perlmutter et al. 1999), leading to the exotic term of dark energy. This form of energy describes the vacuum energy density of space, and was first hypothesized by Albert Einstein who expressed it as the cosmological constant Λ. Altogether, no cosmological probe has been as constraining of our view of the cosmos as the observations of the Cosmic Microwave Background (CMB) (Gamow 1948; Hu & White 1996; Bennett et al. 2013). The CMB is the afterglow of the Big Bang revealing small ($dT/T \approx 10^{-5}$) temperature differences of the $\sim 380\,000$ year old Universe.

The Big Bang model, which has been tightly constrained by combining all cosmological probes, makes concrete predictions and thus far this model has passed every observational test. However, given that dark matter and dark energy make up the dominant energy content of the Universe in this model, substantial mysteries remain regarding the nature of these components. As long as their existence is only inferred indirectly, alternative cosmological theories remain to be considered.

1.2 Structure formation in the Universe

According to the cosmological standard model, just after the Big Bang, which happened about 13.8 Gyr ago, the matter in the Universe was remarkably homogeneously distributed. Due to the force of gravity, small initial perturbations in the primordial density field have been responsible for the rich diversity of structures we observe today. Whereas the protons and electrons in the young Universe were supported by thermal photons, the dark matter was able to collapse earlier, and this accelerated the formation of structures. Given the presumed collisionless nature of dark matter, the structure formation process can now be studied using large N-body simulations (e.g. Springel et al. 2005).

Although these simulations do not include baryonic physics, they make predictions on the matter distribution that have successfully passed some basic observational tests. For example, the 2-degree-Field Galaxy Redshift Survey (Colless et al. 2001) has shown a web-like structure in the distribution of galaxies that is similar to the distribution of dark matter haloes in N-body simulations. Also, just like in the mathematical model introduced by Press & Schechter (1974), the simulations suggest that small gravitationally bound structures form first, which subsequently merge to form galaxies, and larger ensembles such as groups and clusters of galaxies. This leads to a halo mass function that is dominated by low-mass haloes (e.g. Tinker et al. 2008). The luminosity distribution of galaxies (Schechter 1976) has a similar shape, although baryonic physics play a dominant role in determining the exact shape of the luminosity (or stellar mass) distribution. The radial density profile of dark matter haloes is found to be described by NFW profiles (Navarro et al. 1997), similar to what the distribution of galaxies in groups and clusters is observed to be (Lin et al. 2004; Muzzin et al. 2007; Budzynski et al. 2012). Although these simulations give results that qualitatively agree with the observations, an important goal in extragalactic astronomy today is to provide a complete understanding how baryonic structures form in this dark-matter dominated Universe.

1.3 The challenge of stellar masses

Although the majority of the baryonic mass in the Universe is in the form of gas, the presence of stars plays an important role in the overall cycle of baryons. Through stellar winds and supernova explosions, the gaseous medium is enriched by elements heavier than hydrogen and helium. These heavy elements have been important in the formation of the rocky planets in our solar system, and eventually provided the ingredients for life on Earth. To be able to constrain the build-up of the stellar component in the Universe, stellar mass measurements need to be quantified.

In the Milky Way, observations of binary stars have been used to measure the masses of stars with different spectral types. Simple scaling relations between the mass, temperature, luminosity, and lifetimes of stars have been obtained. For stars around a solar mass, the luminosity scales with mass roughly as $L \propto M^4$. In typical stellar populations, low-mass stars are substantially more abundant than high-mass stars. Whereas the total mass of a stellar population is thus dominated by the low-mass stars, the total energy output is dominated by high-mass stars. To relate the luminosity of a stellar population to its total stellar mass, we need to know its mass distribution (the Mass Function, MF). However, especially for distant galaxies the MF is not directly observable, and thus unknown to us.

Given that the lifetimes of high-mass stars are relatively short ($T \propto M^{-3}$), the MF of a stellar population evolves with age. If we consider a stellar population just after it formed (i.e. at zero-age), we refer to the MF as the Initial MF (IMF). A critical assumption in typical studies that involve stellar mass measurements is that the IMF has a universal shape (however see Bastian et al. (2010) for a review). Salpeter (1955) estimated that the IMF can be approximated by a power-law $\frac{dN}{dM} \propto M^{-\alpha}$, where α is typically ~ 2.35. Recent studies (Miller & Scalo 1979; Kroupa 2001; Chabrier 2003) have suggested refinements of this simple power-law, leading to different relations between the luminosity and stellar mass of a zero-age stellar population. As of today, the shape of the IMF at low masses is the main systematic uncertainty on stellar mass estimates of galaxies.

Since high-mass stars are very luminous in the ultraviolet, the spectral energy distribution (SED) of a stellar population becomes redder as these stars cease to exist. The age of a stellar population can be estimated by considering its full SED, and once the age is known we can estimate the current MF from the assumed IMF. The mass-to-light ratio (M/L) of a galaxy is estimated from the MF, and thus a stellar mass can be estimated for a given luminosity.

A further complication for stellar mass estimates is that the SED of a galaxy is typically not well-described by a single-age stellar population. The stars may have formed following a general Star Formation History (SFH), leading to a more complicated MF. Also, the presence of dust can redden the SED, mimicking the effect of a higher age (e.g. Worthey 1994). Given that the SED of a galaxy is observed, the SFH and dust-attenuation of a galaxy can be estimated using a typical SED-fitting program such as FAST (Kriek et al. 2009).

1.4 The world of galaxies

By measuring properties of galaxies such as their stellar masses, colours and morphologies, they can roughly be divided in two distinct types, labelled early-types and late-types for historical reasons. Late-type (a.k.a. star-forming) galaxies generally have a central concentration of old stars, and an extended disk in which stars are forming. Early-type (a.k.a. quiescent) galaxies are redder since they feature no (or very little) on-going star formation, and generally have ellipsoidal shapes compared to the spiral nature of late-type galaxies. Due to the advance of modern telescopes and instruments, galaxy studies have been expanded over the last decades, and measurements of the Luminosity Function (LF) and Stellar Mass Function (SMF) (e.g. Bell et al. 2003; Pérez-González et al. 2008; Ilbert et al. 2010) have been used as key observables of a population of galaxies. The LF and SMF describe the number density of galaxies as a function of their estimated luminosity and stellar masses, respectively, and are generally parameterized using the Schechter function (Schechter 1976).

By comparing the halo mass function with the SMF, we have learned that dark matter haloes of different masses have different stellar mass fractions (e.g. Behroozi et al. 2013). The inefficiency of low-mass haloes in forming stars is possibly due to supernova feedback (Efstathiou 2000; Dalla Vecchia & Schaye 2008), stellar winds, and the presence of a photo-ionizing background (Benson et al. 2002). In high-mass haloes, AGN feedback is expected to play a role in regulating the formation of stars (Schawinski et al. 2007; Fabian 2012).

Separating the SMF between late-type and early-type galaxies, observations have shown that the most massive galaxies are generally early-type. It is also shown that their abundance rises towards the present day compared to late-type galaxies. Contrary to what their names may suggest, late-type galaxies are thus regarded as the progenitors of early-type galaxies. Recent studies (Muzzin et al. 2013) have measured and compared the universal SMF of the two galaxy types up to $z \sim 4$, and such measurements are fundamental observables for constraining the star-formation efficiency as a function of halo mass and redshift in physical models (e.g. Schaye et al. 2010; Henriques et al. 2012; Weinmann et al. 2012; Cen 2014). A relatively simple approach to this is the abundance matching technique (e.g. Behroozi et al. 2010; Moster et al. 2010; Behroozi et al. 2013; Moster et al. 2013), in which observables such as the SMF and cosmic star formation history are directly combined with merger trees from dark matter simulations to provide constraints on the processes that build up the stellar mass in the central galaxies of dark matter haloes.

1.5 Galaxies in high-density environments

It has been known for a long time now that the properties of galaxies do not only depend on the mass of the halo in which they live, but also correlate with the density of their environment (e.g. Dressler 1980). Galaxies in crowded regions generally show a higher quiescent fraction than galaxies in sparse environments. Several physical mechanisms have been proposed to explain these differences, but a consensus is still missing. The Sloan Digital Sky Survey (SDSS) has allowed substantial progress to be made in quantifying the relationship between galaxy environment and Star Formation Rate (SFR), morphology, stellar mass, and metallicity in the local Universe (e.g. Kauffmann et al. 2004; Baldry et al. 2006; Peng et al. 2010). However, surveys that have provided insight into the far-away Universe (e.g. COSMOS; Scoville et al. 2007) typically lack the volume to study the most extreme over-densities (i.e. galaxy clusters) at these redshifts since they observe relatively small areas on the sky.

Clusters of galaxies are the most massive gravitationally bound structures in the Universe, which typically contain ~ 1000 galaxies and have a total mass of $\gtrsim 10^{14}\,\mathrm{M}_{\odot}$. Given their extreme over-densities at any epoch, we expect environmental effects on the evolution of galaxies to be most prominent in these systems. To separate these environmental effects from general redshift evolution, galaxy clusters also have to be studied at higher redshifts. In surveys that cover a large field-of-view, these systems can be detected by their hot X-ray emitting gas (e.g. Rosat), Sunyaev-Zel'dovich decrement (e.g. SPT, Planck), or galaxy over-density (e.g. SpARCS), and are then specifically targeted for follow-up observations.

Number density measurements of massive haloes as a function of redshift are also used to constrain cosmological parameters, as these haloes are a sensitive probe of the growth of structures. The two applications of cosmology and galaxy evolution are intimately related, since the presence of baryons can have a measurable effect on the shape of the matter power spectrum and the cluster mass function, and therefore on the determined cosmological parameters (e.g. van Daalen et al. 2011; Cusworth et al. 2013). In order to interpret abundance measurements of clusters in a cosmological context, a comparison with fitting functions obtained from simulations is required (e.g. Tinker et al. 2008). So far, these simulations are based on N-body codes, and thus do not include baryonic physics. In an era in which we aim to do precision cosmology, the influence of baryons can no longer be ignored in simulations and their assembly needs to be better constrained by observations.

1.6 This Thesis

In this thesis, we study the distribution of galaxies in galaxy clusters over cosmic time. Both the SMF and the spatial distribution of galaxies provide insights in the connection between dark matter and the stellar component, and the transformation of galaxies in high-density environments.

1.6.1 Galaxy clusters at $z \sim 1$

In order to assess the time evolution of galaxies in high-density environments, we study 10 clusters observed in the distant Universe in **Chapters 2-4**, when the Universe was about half its current age. This cluster sample is drawn from the Gemini Cluster Astrophysics Spectroscopic Survey (GCLASS), which consists of 10 of the richest clusters in the redshift range $0.86 < z < 1.34$ selected from the 42 square degree SpARCS survey (Muzzin et al. 2009; Wilson et al. 2009; Demarco et al. 2010).

In **Chapter 2**, we present the galaxy SMF of the GCLASS clusters, and compare it directly to the SMF of field galaxies in the same redshift range to study the effect of environment on this fundamental observable at $z \sim 1$. Interestingly, when we distinguish photometrically between star-forming and quiescent galaxies, we find that the best-fitting Schechter parameters α and M^* are similar within the uncertainties for these galaxy types within the different environments. However, there is a significant difference in the shape and normalisation of the total SMF between the clusters and the field sample. This difference in the total SMF is primarily a reflection of the increased fraction of quiescent galaxies in high-density environments. At $z \sim 1$ the clusters are already completely dominated by quiescent galaxies. We employ and evaluate a quenching model based on Peng et al. (2010), which separates the quenching of galaxies by two distinct tracks dubbed mass-quenching and environmental quenching, and find that this model gives a reasonable description of the data.

The quenching model predicts the presence of galaxies that have recently been abruptly quenched. In **Chapter 3**, we follow this prediction by studying the transformation of galaxies at $z \sim 1$ in the GCLASS clusters. Using the deep spectroscopic data available for GCLASS, we identify a population of post-starburst galaxies with no on-going star-formation, but with spectra still indicative of young stellar populations. The fact that this type of galaxy is more abundant in the clusters than in the field (Muzzin et al. 2012) suggests that the responsible process depends on environment. We find that the post-starburst galaxies have a distinctive distribution in projected velocity vs. position phase space, possibly related to quenching processes that are dependent on environment. Using several zoom simulations of clusters, we find that this coherent distribution of post-starburst galaxies can be reasonably well reproduced using a simple quenching scenario. The phase-space distribution of these galaxies can be reproduced if satellite quenching occurs on a rapid timescale ($0.1 \lesssim T_q \lesssim 0.5$ Gyr) after they make their first passage of R $\sim 0.5R_{200}$, where R_{200} is defined as the radius at which the mean interior density is 200 times the critical density of the Universe.

In order to further constrain the relation between the assembly of stellar mass and dark matter in these systems, other observables can be exploited. In **Chapter 4**, we compare the halo masses of the GCLASS systems to the stellar mass measurements of the central galaxies, and to stellar mass measurement of the entire population of cluster galaxies. When we study the distribution of stellar mass in the ensemble GCLASS cluster, we find that it is well described by a projected NFW profile, but with a relatively high concentration parameter of $c \sim 7$. This result is intriguing because it shows that the stellar mass is significantly more concentrated than the dark matter in N-body simulations in this mass and redshift regime. This is significantly different from the picture at lower redshift, when compared to studies in the literature. However, differences with analyses and data sets in the literature are a major concern and limitation.

1.6.2 Galaxy clusters in the local Universe

By extending the study described above towards lower redshift, we make the comparison across cosmic time more consistent and put the GCLASS measurements into context. **Chapter 5** describes a measurement of the stellar mass distribution in 10 clusters in the redshift range $0.07 < z < 0.26$, drawn from the Multi-Epoch Nearby Cluster Survey (MENeaCS) and the Canadian Cluster Comparison Project (CCCP). The systems have dynamical masses of $M_{200,c} \simeq 10^{15}\,\mathrm{M}_{\odot}$, which roughly matches the expected descendent population of the GCLASS sample. We find that the stellar mass distribution is well described by an NFW profile with concentration $c \sim 2$. The stellar mass distribution thus evolves significantly since $z \sim 1$, and this trend is opposite to what is seen in the evolution of the dark matter concentration in simulations. We consider different evolutionary scenarios and conclude that the build-up of stellar mass in the intracluster light and the central galaxy, combined with outside growth onto the clusters, could explain the observed evolution.

1.6.3 Probing the early phases of star-formation

Even in galaxy clusters at $z \sim 1$, the galaxy population is entirely dominated by quiescent galaxies. In **Chapter 6**, we turn our attention towards an epoch in which the star-forming fraction of galaxies was considerably higher. We use the *ugriz* data set of the CFHT Legacy Survey Deep, which spans a 4 square degree survey area, to measure the UV galaxy LF at $3 < z < 5$. The Lyman-Break Galaxies (LBGs) that we consider are star-forming galaxies that have many applications. They are identified relatively easily at this redshift range, by using multi-band optical photometry to probe the wavelength-position of the Lyman limit. Our study in **Chapter 6** is based on 100,000 LBGs, and given the large survey area compared to previous studies, this renders the systematic uncertainty on the LF caused by cosmic variance insignificant. Furthermore, we are able to measure the LF down to such bright (and therefore rare) galaxies that the intervening matter density distribution significantly alters the (Schechter) shape of the LF. With the knowledge of the intrinsic shape of the LF in hand, these LBGs can be used as sources in weak lensing magnification studies (e.g. Hildebrandt et al. 2013; Ford et al. 2013). Although the LBGs are too small to be spatially resolved in this data set, a magnification study only requires measurements of their fluxes. Since this relaxes the observational requirements substantially, it is a promising method for measuring the total masses of galaxy clusters at redshifts $z \gtrsim 1$, as shown by Hildebrandt et al. (2011) for the SpARCS cluster sample.

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