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Introduction

1.1 Cosmological context

The universe is often characterized by the following two words: *homogeneous* and *isotropic.* This means that the average density of matter is the same in all places in the universe (homogeneity), and at the same time, the universe looks the same in all directions as viewed by a particular observer (isotropic).

If the universe were infinite and unchanging, this would imply that wherever we look, we would always see the light of some star, and the entire sky would always be filled with light[1]. Instead we observe that the night sky is mostly dark. The most recent insights are that the universe has only existed for a finite time, and is furthermore undergoing accelerated expansion, so that light from distant sources hasn't had the time to reach us yet. The expansion also causes light from distant sources to become redshifted beyond the range of optical light that our eyes can see.

On small scales the universe is very inhomogeneous and non-isotropic. Matter is gravitationally bound together into stars, planets and galaxies. We are part of the Milky Way, a galaxy as massive as 100 billion times the mass of the Sun and itself part of the Local Group, together with its neighbour Andromeda and a number of smaller satellite galaxies. It is believed that the origins of these matter-dense regions of space lie in quantum fluctuations that occured during the very first moments of the universe.

The universe is estimated to have originated about 13.7 billion years ago from a hot, dense initial state, a phase we call the Big Bang. Shortly after the Big Bang (about 10^{-36} seconds) a period of inflation most likely took place (Guth 1981). This lasted for about 10^{-34} or more seconds and during this time the universe expanded at an astonishing rate, increasing its size by approximately 100 e-folding times, or a factor of $\sim 10^{43}$. The theory of inflation solves the so-called *horizon problem*: if the universe is homogeneous on large

[1]Olbers' paradox (Harrison 1987)

scales, this is likely because all regions in the observable universe have been in causal contact at one point in the past, even though we cannot now observe it in its entirety. Inflation also causes quantum fluctuations to be frozen into the density fluctuations that provide the initial conditions for the growth of structure in the universe.

After inflation, the universe cooled until particles were formed. During 377,000 years the universe was opaque to light, as photons could travel only short distances before interacting with an electron. At the end of this period, the universe had cooled enough for the recombination of electrons and protons into neutral hydrogen atoms, and shortly after that the photons were decoupled to travel freely through the universe. With our astronomical observations we can probe the distant universe back in time until this epoch, and we observe an imprint of the universe at the moment of decoupling, which is called the Cosmic Microwave Background (Alpher et al. 1948; Penzias & Wilson 1965). This is a faint signal redshifted to microwave wavelengths, due to the large expansion of the universe since that time. In it, we can see small fluctuations that are the beginnings of the structure we see in the universe today.

According to the Lambda Cold Dark Matter model, overdense regions are formed through the gravitational collapse of dark matter into dark matter haloes, and their subsequent hierarchical merging (White & Rees 1978). One of the greatest unresolved questions in physics and cosmology is: *What is the nature of dark matter?* To answer this question is far beyond the scope of this thesis, but it is worth noting that dark matter contributes 25.9% (Planck Collaboration et al. 2015) to the energy density of the universe. Baryonic matter, that stars, planets, humans and atoms consist of, makes up only 4.9% (Planck Collaboration et al. 2015). Important evidence of the existence of dark matter comes from studying the rotational velocities of galaxies. Based on visible mass, basic laws of motion suggest declining rotation curves towards larger radii. This is not observed and implies the presence of large quantities of dark matter mass (e.g. Freeman 1970; van Albada et al. 1985).

Baryonic matter, which consists mostly of neutral hydrogen gas, will collapse along with the dark matter, cool down, and flow to the centers of the haloes. Once the first galaxies are formed, they embark upon a complex journey of gas accretion, star-formation, feedback processes, and interactions with other galaxies. The details of the galaxy formation process are not yet well understood. In the local universe we find galaxies with a variety of morphologies, which are often linked to star-formation activity. Some galaxies are very massive and have all but stopped forming new stars. Therefore another key question in cosmology is: *How do galaxies form and evolve?* And related to this: *What causes galaxies to stop forming new stars?* These two questions are the focus of this thesis.

1.2 Galaxies at low redshift

A logical starting point for understanding galaxies is their morphology. It is correlated to their dynamics and other galaxy properties, such as age, mass and star-formation history. The structure of galaxies is closely tied to their assembly history and the underlying dark matter distribution. Since galaxy formation models will have to be able to reproduce the great variety of galactic shapes, it is an important gauge for determining the validity of any model.

One of the earliest classification systems was that of Hubble (1926, 1936). This is the famous tuning fork, consisting of the following classes: elliptical galaxies, lenticular galaxies, disk galaxies with spiral structure, and irregular galaxies. Ellipticals and lenticulars are historically termed early-type, and spiral galaxies late-type, because originally it was thought that galaxies evolved from elliptical shapes into the seemingly more refined spiral morphologies. Early-type galaxies are, in fact, the oldest and most evolved kind of galaxies.

Some clues as to the formation history of early-type galaxies can be found by studying their physical properties. They are predominantly the most massive galaxies in the local universe and can often be found in the centers of groups and clusters of galaxies. They have old stellar populations, with distinctly red optical colours, they have little ongoing star-formation, and they are kinematically supported by random motions. Their high stellar ages indicate they assembled the bulk of their stellar mass at high redshift: redshift $(z) > 2$.

Spiral disk galaxies have blue optical colors, from light emitted by populations of young stars. They are actively forming new stars and have large rotational velocities. It is thought that the Milky Way is a spiral galaxy, with a modest rate of star-formation. It is clear that these two types of galaxies have very distinct physical properties, which, without any foreknowledge, were captured accurately by Hubble simply by studying morphology.

A well known scaling relation for star-forming galaxies is the Tully-Fisher relation, first reported by Tully & Fisher (1977). It describes a tight correlation between rotational velocity and, historically, luminosity. Since rotational velocity can be measured accurately regardless of distance, the Tully-Fisher relation was first used as a distance indicator for galaxies. In present day research, the Tully-Fisher relation is expressed in terms of stellar mass instead of luminosity and is used for kinematical studies of galaxies. At low redshift the Tully-Fisher relation is well established, but it remains elusive for galaxies at high redshift. Determining if and by how much the Tully-Fisher relation evolves over time is key to understanding the kinematic evolution of galaxies, which is closely tied to understanding the formation of dark matter haloes and the interplay of dark matter with baryons.

Galaxies with low star-formation rates and red optical colors are often termed *quiescent*. Several definitions exist for quiescence. These amount to either a star-formation rate maximum or a colour threshold that captures a spectral feature related to the age of the galaxy. If the progenitors of early-type galaxies were spirals, it could be that the process that changed their structure is the same as that which caused a halt to star-formation. A logical way to study the transition from the star-forming phase to the quiescent phase is to look for galaxies that are in the middle of this process. To find these, larger numbers of galaxies than those available in the local universe have to be studied.

The first large multi-wavelength galaxy survey was the Sloan Digital Sky Survey (SDSS; York et al. 2000). SDSS provided imaging in over 14,000 square degrees of sky, and spectra of more than 2 million galaxies. The survey led to several breakthroughs, such as pinpointing the bimodality in colour-mass space between star-forming and quiescent galaxies (Kauffmann et al. 2003; Blanton et al. 2005), and the determination of the relation between size and stellar mass (Shen et al. 2003). Additionally, SDSS allowed for the first time to map the three dimensional large scale structure of matter in the universe.

Despite the vast amount of galaxies observed, SDSS is a low redshift survey, covering only a limited range of time. The most effective way to study the evolution of galaxies would be to capture them as they evolve, by observing them at different epochs throughout the existence of the universe. Since SDSS a number of galaxy surveys have succesfully attempted to probe further and further into the distant universe, and assemble large samples of galaxies at high redshift. A key epoch is $1 < z < 4$, when most of the star-formation took place (Madau et al. 1996), the first galaxies ceased forming stars, and the familiar elliptical and spiral morphologies first emerged.

1.3 Galaxies at high redshift

Quiescent galaxies have been confirmed to exist out to redshifts $z \sim 2.3$ (e.g., Kriek et al. 2006). A key discovery was that at high redshift, their morphology is not the same as at low redshift. Instead of having extended elliptical shapes, they are very compact (e.g., Daddi et al. 2005; Trujillo et al. 2007; van

Dokkum et al. 2008; Damjanov et al. 2009; van der Wel et al. 2014). Their average size decreases with increasing redshift, although the general correlation between size and stellar mass, with larger sizes for more massive galaxies, remains intact. The interpretation is that elliptical galaxies grow inside-out, by first forming a dense stellar core, and later accreting more mass by star-formation and mergers with other smaller galaxies.

This does not solve the riddle of why star-formation in these galaxies ceased. Stars are formed from dense, cold gas, and a number of reasons have been suggested for the quenching of star-formation in galaxies. One such reason is feedback by active galactic nuclei, as during periods of rapid accretion onto the central black hole, a great amount of energy is released into the surrounding environment of the galaxy (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998). Another example is feedback from supernovae, massive and old exploding stars that heat and dilute their surrounding gas (e.g., Mathews 1990; Ciotti et al. 1991). Less massive old stars can also influence their environment, by shedding an envelope of mass, which initially moves with the speed of its host, but interacts with surrouding gas reservoirs (e.g., Conroy et al. 2015). Finally, in time some dark matter haloes hosting galaxies become so massive that they switch from cold-mode to hot-mode accretion. This means that the cooling time of primordial gas flowing into the centers of the haloes becomes too long (e.g., Birnboim & Dekel 2003; Cattaneo et al. 2008).

A method of separating between the various proposed quenching mechanisms is charting the number density, fraction, and structural properties of quiescent galaxies to high redshift, and to link these properties to possible star-forming progenitors. Research into progenitors is now focusing on finding similarly compact star-forming galaxies, but these have proven difficult to find (e.g. Barro et al. 2014a,b; Nelson et al. 2014). Furthermore, the discovery of massive quiescent galaxies at higher and higher redshift implicates a swift formation process, with rapid star-formation at very early times. Only a subset of the star-forming population at those early epochs ($z = 4 - 10$) is known, and these tend to be UV-bright galaxies. Observations at $z > 1$ have revealed the existence of a large population of dust-obscured star-forming galaxies, with high SFRs, but similar red colours as quiescent galaxies (e.g. Reddy et al. 2005; Spitler et al. 2014). Their redness makes them difficult to find at $z > 4$ with current techniques, which means we may be missing a large fraction of the star-forming population at these redshifts. It also proves a challenge for identifying quiescent galaxies as the two kinds may easily be confused. A question that remains standing is: *When did the first galaxies become quiescent?* Pinpointing that moment in time will be essential to constrain galaxy formation scenarios and is the topic of one of the chapters of this thesis.

Apart from a large fraction of star-forming galaxies being dust-obscured, other properties of the star-forming population are different at high redshift as well. For example, their average star-formation rate is higher, and a larger fraction of their mass is in the form of gas. Their morphology is more irregular, with clumps of star-forming matter and more visible effects from disruptions by late interactions with other galaxies. Under these circumstances, it is hardly expected that the Tully-Fisher scaling relation between stellar mass and rotational velocity holds in exactly the same way as for low-redshift galaxies. If and by how much the Tully-Fisher relation evolves is another topic of this thesis.

1.4 The FourStar Galaxy Evolution Survey

The most important challenge in astronomy is to determine accurate distances. For extragalactic observations this means precisely calculating the redshift of a source – it has been realised that redshift inaccuracies are the most dominant factor inhibiting our understanding of galaxy properties such as stellar age and mass (e.g., Chen et al. 2003; Kriek et al. 2008). The best method for this is to measure the electromagnetic spectrum of a galaxy, and use features such as emission lines from atomic transitions to determine the factor by which the spectrum was shifted towards redder wavelengths. To study galaxy evolution, this method has several drawbacks. Observing large samples, i.e., thousands, of galaxies is highly inefficient and requires a previous detection to pinpoint the location of the source. Spectroscopy is also limited to bright sources or sources with strong emission lines, and these are usually star-forming galaxies with moderate dust-obscuration, which are not necessarily representative of the full galaxy population at any redshift. Spectroscopy is therefore often used in follow-up programs of imaging surveys.

Determining redshifts for galaxy surveys that rely on imaging is done by observing sources through different filters to obtain a spectral energy distribution and fitting models to these. In a sense a spectral energy distribution is a very low resolution spectrum. Therefore this process becomes more accurate if more filters are used, with measurements at different wavelengths.

Optical light, carrying information about the age of a galaxy, is shifted into the near-IR for sources at $z > 1.5$. This is problematic for groundbased observations, because the light of typical galaxies is outshone by a factor 10^5 by the Earth's atmosphere in the IR. The FourStar instrument on the 6.5m Magellan Baade Telescope at Las Campanas Observatory in Chile provides a solution for both issues. FourStar has a set of six near-IR medium-bandwidth filters that can capture light in small wavelength windows where the atmosphere is transparent. These six filters also provide an excellent sampling of spectral features typical for old galaxies, allowing a $1-2\%$-level redshift accuracy.

The technique of using medium-bandwidth filters was first employed for optical light by the COMBO17 survey (Wolf et al. 2004) and shown to be effective in the near-IR as well by the NEWFIRM Medium-Band Survey (Whitaker et al. 2011). The FourStar Galaxy Evolution Survey (ZFOURGE) takes this one step further by being unprecedented in depth, reaching K_s-band magnitudes (the reddest filter) of ~ 26 in AB units.

ZFOURGE is a 45 night legacy program, conducted between December 2010 and November 2012, covering a total of 400 square arcminutes in three pointings on the sky. The three pointings reduce the effect of field-to-field variance, which is caused by matter being unevenly distributed on relatively small cosmological scales. The pointings overlap with those of previous surveys, so that the near-IR data can be optimally augmented by earlier measurements ranging from the UV to the far-IR.

The aim of ZFOURGE is to shed light on how galaxies evolve by studying them at the crucial epoch between $z = 1.5$ and $z = 4.5$. It is excellently suited to identify quiescent galaxies out to $z \sim 4$, which may be the epoch in which they first appeared in the universe. With ZFOURGE we can also study scaling relations for these galaxies, such as the relation between size and stellar mass, which evolves in a different way for star-forming and quiescent galaxies.

A spectroscopic follow-up program, ZFIRE (Nanayakkara et al., 2016, submitted), was started in December 2013, employing the near-IR spectrograph MOSFIRE on the Keck I telescope on Mauna Kea in Hawai'i. The primary targets were star-forming cluster galaxies, discovered with ZFOURGE, at $z = 2.095$. At this redshift, little is known about the kinematic properties of star-forming galaxies. The spectra obtained with MOSFIRE cover the Hα emission line (rest-frame $\lambda = 6563$Å), at high spectral resolution. They are therefore an excellent tool to measure the rotational velocities of galaxies beyond $z > 2$ for the first time with single-slit spectra.

1.5 Outline and summary

In this thesis we discuss the properties of high redshift galaxies at two key epochs. We use ZFOURGE to find and study the earliest quiescent galaxies at $z \sim 4$, when the universe was only 1.6 billion years old. And we employ the ZFIRE spectroscopic data to measure the Tully-Fisher relation for star-forming galaxies at $2.0 < z < 2.5$, at the time when the cosmic star-formation rate was at its peak.

In **Chapter 2** we first present the data products from ZFOURGE. We use ultra-deep near-IR K_s–band ($2.16\mu m$) images to detect > 70000 galaxies. For each of these we derive fluxes in > 27 UV, optical and IR filters, and measure the photometric redshift. We perform an in-depth analysis of the photometric redshift accuracy, including a comparison with spectroscopically derived redshifts from literature and an analysis using galaxy pairs. Using the large sample of galaxies from ZFOURGE, we additionally investigate the efficacy of a two colours test, used to distinguish between quiescent and star-forming galaxies, at high redshift ($z > 2$).

In **Chapter 3** we present the discovery of massive quiesent galaxies at redshift $z \sim 4$. Using deep far-IR data from the MIPS instrument on the Spitzer Space Telescope and the PACS instrument on the Herschel Space Observatory, we verify that these galaxies indeed have strongly suppressed star-formation rates. From their high average stellar mass, we infer that they must have formed extremely rapidly, and quenching mechanisms were efficient even at high redshift. Lastly, we speculate that most of the star-formation in the progenitors of these galaxies was obscured by dust.

We continue our study of $z \sim 4$ quiescent galaxies in **Chapter 4**, where we investigate their sizes. We study near-IR images of both star-forming and quiescent galaxies at $z \sim 4$, which, because the light is redshifted, is a measurement of UV light emitted by the galaxies. We find that the quiescent galaxies are very compact, and much smaller than star-forming galaxies of similar stellar mass. Next, we compare with lower redshift results, to study the size evolution. We find that both quiescent and star-forming galaxies at $z \sim 4$ continue the trend of smaller average sizes towards higher redshift. We then look for compact star-forming galaxies in our sample, which could be the progenitors of similary compact quiescent galaxies at later times. We find only one, indicating these are very rare and possibly dust-obscured.

In **Chapter 5** we jump forward in time, to study the Tully-Fisher relation at redshift $2.0 < z < 2.5$. Here we make use of a sample of star-forming galaxies that were spectroscopically observed with ZFIRE. We derive rotational velocities by measuring the shear of the Hα emission line. We extensively analyse systematic effects and find that velocities measured with single-slit spectra can easily be underestimated. Taking this into account we derive a Tully-Fisher relation that is offset compared to low redshift results. We then attempt to unify previous measurements at various redshifts, and infer a gradual evolution with redshift, which is in agreement with theoretical predictions. Lastly, we find evidence of a general increase in random motions and speculate the evolution of the Tully-Fisher relation may in part reflect the conversion from gas to stars.

1.6 Future prospects

In this work we present the discovery of the furthest quiescent galaxies to date. These will be a valuable addition to the known population of quiescent galaxies through cosmic time, showing in the first place their early existence. Their number density, average stellar mass and average size will provide important constraints on galaxy formation models, dealing with the efficiency of star-formation, morphological evolution and testing of various quenching mechanisms. The question of how and why these galaxies have all but stopped forming new stars is still an open one, but we now know that galaxies can assemble most of their stellar mass rapidly and an efficient quenching mechanism is possible.

One caveat is that the existence of $z \sim 4$ quiescent galaxies has not yet been verified by other observations. The first logical step for future research is to use spectroscopy to confirm and measure more precisely their redshift. Facilities able to do this are MOSFIRE on Keck I and the spectrograph NIRSpec on the James Webb Space Telescope (JWST), which is scheduled for launch in 2018. JWST will also have an IR camera installed, that can probe the universe to further depths without hindrance by Earth's atmosphere. If quiescent galaxies exist even beyond $z > 4$, they may be found by JWST. JWST will also study the very first galaxies formed after the Big Bang and will possibly shed more light on the progenitors of early quiescent galaxies.

To better understand the evolution of the Tully-Fisher relation for star-forming galaxies at $z > 2$, the most important step is to acquire larger samples of spectroscopically observed galaxies and study these using consistent methodologies. The uncertainties on current observations – especially the discrepancies between results from different surveys – are too high to constrain by how much the relation actually evolves. Facilities for this are already in place, such as the single-slit spectrograph MOSFIRE on Keck I and the integral-field-unit KMOS on the VLT. JWST will also provide excellent quality data from its NIRSpec. Another important technical development is adaptive optics, which will provide the resolution needed to better study the complex dynamics and irregular shapes of star-forming galaxies at high redshift. Finally, both observations and models need to focus on a more detailed assessment of the interplay between gas, stars and dark matter.

As a final remark it is worth mentioning the Atacama Large Millimeter / sub-millimeter Array (ALMA). With ALMA we can study the dust and molecular gas properties of distant galaxies at high resolution. These kind of observations will yield insights into the gas content of galaxies and its conversion into stars, a highly relevant topic for galaxy evolution.

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