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CHAPTER 1

INTRODUCTION

1.1 EXTRAGALACTIC ASTRONOMY

Since the formulation of the earliest cosmological models, observations of distant stars and galaxies have served a crucial role in constraining these models or bringing new, unknown issues to light. Galaxies are tracers of the overall matter distribution in the Universe, and as such can be used to obtain crucial information regarding the content of the Universe. Surrounded by reservoirs of gas and dark matter, and by orbiting satellite galaxies, they effectively serve as ``signposts'' which mark high-density regions of space. They are formed by - and sensitive to - a rich variety of physical processes, and thus serve as laboratories where these processes can be studied in detail.

In the early days of modern astronomy, as the structure of the Milky Way was being mapped out, thousands of faint, nebulous objects were discovered (e.g., Messier 1781; Herschel 1786). These mysterious clouds - now known to be distant galaxies - were not resolvable into individual stars, and it took a long time for the nature of these objects to become clear. Important clues regarding their properties were found in the 19th century, as new, larger telescopes became available (e.g., the 72-inch "Leviathan" built by the Earl of Rosse in 1845). A large fraction of nebulae were observed to have flat, disk-like morphologies, often with bright spiral arms, while many others were relatively featureless blobs. This morphological division marks the beginning of the study of galaxy structure.

Early classifications of galaxies based on their morphologies were greatly expanded once telescopes became powerful enough to resolve smaller structures. Furthermore, spectroscopic observations showed that galaxies not only looked different, but contained different stellar populations as well (e.g., Slipher 1918). Over the next years it became clear that many galaxy properties, such as total brightness, central concentration, or color, were connected in some way (e.g., Hubble 1926). In fact, the structure of galaxies holds key information regarding their assembly history and their interactions with other galaxies, and is closely tied to the properties of the underlying dark matter distribution. Galaxy structure therefore provides an extremely rich source of information with which to inform and challenge physical theory.

1.2 THE UNIVERSE AT Z = 0

Studies of the properties of individual galaxies and of the galaxy population as a whole can provide an effective tool to understand the contents and behaviour of the Universe. Correlations between different galaxy properties are used extensively in order to uncover the underlying physics. One of the most fundamental is the correlation between galaxy morphology and age, which results in a sequence of galaxy types that ranges from strongly starforming spiral galaxies to passive elliptical galaxies. This correlation implies that the processes which transform galaxies from disks to spheroids (such as galaxy mergers) may also trigger quenching mechanisms that cause a shutdown in star formation. It provides a fundamental connection between the stellar populations within galaxies and their overall structure.

Structural scaling relations have been known to exist for many decades: the properties of bulge-dominated galaxies are related through the fundamental plane, which connects galaxy size, average surface brightness, and central velocity dispersion, and can be interpreted as an expression of dynamic equilibrium (e.g., Faber & Jackson 1976; Djorgovski & Davis 1987). Similarly, disk-dominated galaxies follow the Tully-Fisher relation (Tully & Fisher, 1977), which relates galaxy luminosity and rotation velocity. These and other relations can be used to gain valuable information about the interplay of different physical processes and their relative importance. However, until fairly recently progress was significantly impeded by a lack of large samples of galaxies with well-understood statistical properties.

An important change in this situation came a decade ago as a consequence of the Sloan Digital Sky Survey (SDSS; York et al. 2000). This survey provided imaging in five filters over more than 8000 square degrees of the sky, as well as spectra of more than two million galaxies. The spectra enabled accurate redshift measurements and the determination of stellar population parameters (e.g., Kauffmann et al. 2003; Brinchmann et al. 2004), while the multi-band imaging was useful for measurements of properties such as galaxy sizes, bulge fractions, and color gradients (e.g., Shen et al. 2003; Blanton et al. 2005). This rich source of data has allowed astronomers to study galaxy properties in a systematic and statistically sound way, unearthing correlations and pinpointing important physical processes (e.g., Kauffmann et al. 2003; Balogh et al. 2004; Baldry et al. 2004). The importance of SDSS for extragalactic studies is evident given the fact that SDSS-derived quantities are still used as benchmarks today.

However, the findings that have resulted from SDSS and other large-scale low-redshift surveys are based on observations that cover a very limited range in time. Measurements of the nearby universe provide an important baseline, and can be used to partially reconstruct a historical timeline. But our understanding of the history of the universe will remain incomplete without actual observations at high-redshift. In particular, the era around z ~ 2, when most of the stellar matter in the universe was formed (Madau et al., 1996), can provide a wealth of useful information.

1.3 MOVING TO HIGH REDSHIFT

In order to form an accurate picture of the evolution of the universe, it is essential to have observations which sample a range of cosmic epochs. Unfortunately, accurately determining galaxy properties at high redshift is difficult, as measurements become subject to a number of important observational and theoretical uncertainties. Three issues which are particularly problematic for structure measurements are outlined below.

Firstly, galaxies become very faint as their distance increases. In order to get high signal-to-noise, exposure times need to be very long. As a result of this, spectroscopy of high-redshift galaxies is prohibitively time-consuming for all but the brightest galaxies. The most important consequence of this lack of spectroscopy is that it becomes very difficult to accurately determine the distances of galaxies. High-redshift surveys must depend instead on multi-band photometry in order to obtain approximate spectral energy distributions (SEDs). The resulting photometric redshifts are subject to much larger uncertainties than spectroscopic redshifts.

The lack of high-redshift spectra also prevents the determination of dynamic masses from observed velocity dispersions. Instead, stellar mass estimates are made, based on fits of stellar population models to the observed SED. This involves many assumptions regarding, e.g., the initial mass function, the distribution of dust in galaxies, and the star formation histories of galaxies. Typical systematic errors of photometrically derived stellar masses are estimated to be as large as a factor 6 (Conroy et al., 2009).

Thus, at high redshift two centrally important quantities - the distance to a galaxy and its total mass - can only be measured with large and difficult to quantify uncertainties. Comparison studies between stellar masses determined from SED fitting and dynamical masses from velocity dispersions indicate that, on average, SED-determined masses seem to agree fairly well with dynamical masses (e.g., Taylor et al. 2010; van de Sande et al. 2011; Martinez-Manso et al. 2011). However, these analyses are subject to other, equally problematic effects, such as uncertainties regarding the initial mass function of galaxies.

A second important problem for observations of high-redshift galaxies is the fact that their light is strongly redshifted. The emission from galaxies is a strong function of wavelength: young stars emit strongly at bluer wavelengths, while old stars (which represent the majority of mass in most galaxies) dominate the redder parts of the spectrum. This introduces problems when comparing the properties of galaxies at different redshifts, as care must be taken to always observe at the same rest-frame wavelength. Furthermore, for studies of galaxy structure it is particularly important to observe galaxies at very red wavelengths, in order to trace the mass distribution. Due to the relative inefficiency of infrared detectors (compared to optical CCDs) it is very difficult to do this effectively.

Finally, as one moves to higher redshift, galaxies of a given physical size subtend smaller angles on the sky. Atmospheric seeing becomes critically important as galaxy sizes become comparable to the size of the atmospheric point-spread function (PSF). Space-based telescopes such as HST partially alleviate this problem. However, even using these state-of-the-art facilities measurements at $z > 1$ are not straightforward. A physical distance of 1 kpc at these redshifts is comparable to the PSF full-width at half-maximum (FWHM) of the HST ACS camera, and detectors at redder wavelengths typically perform more poorly.

High-redshift observations come nowhere near $z = 0$ observations in terms of resolvable detail, and determinations of some of the most important galaxy properties suffer from large systematic uncertainties. This situation is inconvenient in many respects, but a positive side effect is that these limitations have forced high-redshift astronomers to reconsider common low-redshift approaches and to find novel ways to probe galaxy properties. One important corollary has been a stronger focus on robust observables and average properties of galaxy (sub)populations, which has led to a greater emphasis on the identification of connections between these populations.

1.4 CURRENT ISSUES

Despite observational difficulties, an enormous amount of information can be recovered from high-redshift observations by combining high-quality facilities with sophisticated analysis techniques. HST has played a major role in this respect, as it allowed astronomers to measure spatially resolved galaxy properties, and opened the door to detailed quantification of high-redshift galaxy structure.

Early studies of high-redshift galaxy structure which utilized the UV-optical ACS camera on HST revealed a universe that was significantly different from the present-day situation: galaxies were observed to be much bluer and more strongly starforming, and generally had very clumpy morphologies (e.g., Dickinson 2000; Papovich et al. 2005). These findings suggested that at $z \sim 2$ the Universe was in a turbulent phase of galaxy formation that stood in stark contrast to the ordered state of equilibrium of most galaxies today. Although at high redshift the average star formation is significantly higher, and more starforming galaxies exist, this effect was overestimated in early studies due to several causes. The first of these was selection bias; early galaxy catalogs were constructed based on selections in observed-frame optical light. At high redshift this is equivalent to a rest-frame UV selection, which will strongly bias the results towards starforming galaxies. Furthermore, since measurements of structure and morphology were often based on rest-frame ultraviolet photometry, the results mostly revealed the structure of starforming regions within galaxies, which are known to be extended and clumpy.

While it was not yet clear what the dominant morphology was of galaxies at $z \sim 2$, it had become clear that the universe already contained very old galaxies at this time. In fact, quiescent galaxies make up almost half the galaxy population at high stellar masses (e.g., Franx et al. 2003; Daddi et al. 2005; Kriek et al. 2006). Stellar population fits to the SEDs of these galaxies indicate that they contain very old (~ 1 Gyr) stellar populations. This finding came as a surprise, as it implied that the first galaxies must have formed on very short timescales and at extremely early redshifts. How early the first galaxies assembled remains an unanswered question, as old galaxies continue to be found at higher redshifts (e.g., Eyles et al. 2005; Mobasher et al. 2005; Wiklind et al. 2008; Richard et al. 2011).

Further research into these very old systems has revealed that they have properties which are very different from similarly old galaxies at z=0. The most apparent of these are their drastically smaller sizes and higher implied velocity dispersions: typical sizes are of the order of 1 kpc, a factor 4 smaller than similar-mass galaxies at low redshift (e.g., Daddi et al. 2005; van Dokkum et al. 2008). Only a very small number of possible counterparts to these objects have been found at low redshift (e.g., Taylor et al. 2010; Cassata et al. 2011; Poggianti et al. 2013), raising the question of how galaxies with no significant star formation could evolve so strongly between $z = 2$ and $z = 0$. Over the past years the subject of galaxy size growth (as well as evolution in related quantities such as velocity dispersion, concentration, and surface density) has received a lot of attention; it is one of the main themes of this thesis.

Although much attention has been given to the structural evolution of passive galaxies, the population of starforming galaxies undergoes similarly rapid changes. Measurements of the cosmic star formation rate density indicate that the amount of star formation in the Universe increases from $z = 0$ to $z \sim 2$, after which it plateaus or rises slightly (e.g., Noeske et al. 2007; González et al. 2010; Bouwens et al. 2012; Stark et al. 2013). As a result of this both starforming and quiescent galaxies at high redshift have bluer colors than their low-redshift counterparts. Furthermore, star forming galaxies evolve in size (and surface density) at a rate similar to passive galaxies (Williams et al., 2010), and through a variety of processes can build up massive central bulges (e.g., Bell et al. 2012). All these changes in the average properties of the galaxy population are closely tied to one another and to the evolving properties of the universe (such as the average matter density or the cold gas fraction in halos). In order to use such measurements to constrain theoretical models of galaxy formation it is therefore of great importance to obtain accurate and robust results at all redshifts.

1.5 THIS THESIS

This thesis addresses several of these issues, focusing on how to measure galaxy mass distributions, what such measurements can reveal about the structure and morphology of high-redshift galaxies, and how their properties evolve with time. The results presented in this thesis are primarily based on data from HST, both at optical wavelengths (using ACS) and at near-infrared wavelengths (using WFC3). The installation of WFC3 in 2009 has been a strong driver of progress over the past few years, as it represents a significant jump in the efficiency of HST in the near-infrared. Both the sensitivity and resolution are comparable to ACS, resulting in consistently high-quality photometry over a wide wavelength range (300 - 1800 nm). Since the installation of WFC3 several significant legacy surveys have been carried out, most notably the HUDF09 (Bouwens et al. 2010; Oesch et al. 2010) and CANDELS (Grogin et al. 2011; Koekemoer et al. 2011). These two surveys provide extremely deep data over a small area (HUDF09) as well as shallower data over a larger portion of the sky (CANDELS). Combined with deep K-band selected galaxy catalogs, this data enables detailed analysis of large numbers of galaxies.

In **Chapter 2** we utilize the extreme depth of the HUDF09 to address important questions regarding galaxy size measurements at high redshift. We focus on one particular extremely compact massive quiescent galaxy. Using sophisticated techniques we measure this galaxy's radial surface brightness profile and investigate the likelihood of measurement biases being the cause of small measured galaxy sizes.

In **Chapter 3** we extend our structural measurements to the overall galaxy population, analyzing the structure of the most massive galaxies in the HUDF09. Galaxies at low redshift follow a relation between morphology and star formation activity (i.e., the Hubble sequence). Using a combination of optical and NIR data we assess whether this relation between structure and stellar populations already existed at $z \sim 2$, and what this implies for galaxy formation mechanisms.

In **Chapter 4** we revisit the population of high-redshift quiescent galaxies. We take advantage of the large area of CANDELS to measure the structure of a larger sample of galaxies. The high-resolution capabilities of HST enable a very precise analysis of these galaxies' structure. We closely analyze the light distributions of these galaxies and the properties of similar galaxies at different redshifts, in order to address the validity of different evolutionary scenarios.

Measurements of galaxy structure are by necessity based on the light distribution within these galaxies. However, galaxies contain gradients of stellar populations, with corresponding gradients in stellar mass-to-light ratios. This suggests that properties derived from light distributions may not accurately reflect the properties of the underlying mass distribution. If this effect is redshift-dependent it could drastically affect conclusions regarding the mass assembly of galaxies. In **Chapter 5** we address this issue by measuring the stellar mass surface density profiles of a large sample of galaxies over a range of redshifts.

Finally, galaxy growth trends are placed in a theoretical context in **Chapter 6**, by comparing them to predictions from analytical models. These models contain simple prescriptions for the growth of stellar disks and bulges. By comparing several different models we attempt to robustly unearth the dominant underlying physical mechanisms.

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