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INTRODUCTION

1.1 The Birth of Extragalactic Astronomy

At the beginning of the XX century, our perception of the size and the structure of the Universe dramatically changed. If we had to set a symbolic date for that paradigm shift, we should go back to April the 26th, 1920.

On that day, two influential astronomers of the time, Harlow Shapley and Heber Curtis, debated the nature of spiral galaxies and the size of the Universe in front of a crowded auditorium at the Smithsonian Museum of Natural History, in Washington DC. Shapley argued in favor of the Milky Way, the faint stripe of stars visible in the sky during a dark clear night, as the entirety of the Universe. He believed that spiral nebulae, such as the ones classified by Messier and Herschel in the XVIII century, were part of our own galaxy. Curtis instead thought that Andromeda and the other nebulae were separate galaxies, or island universes (as Immanuel Kant had defined them one hundred years before).

Both scholars were backing their claims with different observations available at the time. However, the main support for Shapley’s theory, i.e. the observation of the rotation of the Pinwheel Galaxy (which would have implied a distance smaller than the radius of the Milky Way disk) by Adriaan van Maanen, was soon shown to be incorrect. Observations by Edwin Hubble in the next years finally settled the debate. In 1922 Edwin Hubble measured the periods of Cepheids (a type of variable stars) in the outskirts of the Andromeda Nebula. Thanks to the work of Henrietta Swan Leavitt (1912), Cepheid stars were known to have a tight relation between their luminosity and the period of their variability. Hubble’s observations showed incontrovertibly that Andromeda was in fact a separate island Universe, far outside the Milky Way.

It was again Hubble, a few years later (1927), who found a rough proportionality between the distance of galaxies and their receding velocity: since then, astronomers started to realize that the Universe was expanding. The observations by Edwin Hubble marked the start of modern observational cosmology; it is not by chance that the most ambitious space telescope orbiting the Earth is named after him.

1.2 The Striking Diversity of Galaxies

Even though the large diversity in morphology of nebulae was identified since the XVIII century, the most common classification scheme for galaxies in use today is
due, again, to Edwin Hubble (1926). Hubble noticed that galaxies could be roughly separated in two classes: elliptical galaxies, consisting of a round or flattened smooth distribution of light, and spiral galaxies, consisting of a flat disc with spiral structures extending from a central concentration of light (known as the bulge).

Hubble referred to elliptical and lenticular galaxies as "early-type", and spirals as "late-types" with no intent of this nomenclature to be an evolutionary path, contrary to popular belief (Hubble, 1927):

The nomenclature, it is emphasized, refers to position in the sequence, and temporal connotations are made at one’s peril. The entire classification is purely empirical and without prejudice to theories of evolution.

The definition morphology of galaxies have been made quantitative by Sérsic in the Sixties, who proposed to fit the surface brightness profile of a galaxy (i.e. how the intensity of light varies from the center) with a parametric function of the form:

$$
\Sigma(r) = \Sigma_e \times \exp \left( -b_n \left( \frac{r}{r_e} \right)^{1/n} - 1 \right)
$$

where \( r_e \) is the radius within which the galaxy emits half of its brightness and \( \Sigma_e \) is the surface brightness at \( r_e \). The value of \( n \) determines how concentrated the profile is, with particular cases of \( n = 1 \) corresponding to a disk-like profile, and \( n = 4 \) corresponding to a bulge-like profile.

Subsequent studies have shown that morphology of present-day galaxies is tightly correlated to other properties such as mass, color, and environment.

In general, elliptical galaxies have redder colors than spirals (Strateva et al., 2001; Blanton et al., 2003; Driver et al., 2006), reflecting the fact that the light of elliptical galaxies tends to be dominated by old stars, while spirals tend to be actively forming new stars. Higher-density environments tend to be dominated by early-type galaxies (Dressler, 1980, Blanton et al., 2005), and the most massive galaxies tend to be early-type as well (Kauffmann et al., 2003b).

In the local Universe, this dichotomy can be interpreted as being primarily an effect of mass (even though further studies such as Franx et al. 2008 hint that velocity dispersion might be a more fundamental parameter to describe this transition). Kauffmann et al. (2003b) have shown that the distinction between evolved early-type, red, quiescent objects, and late-type, blue, star-forming galaxies occurs at \( M_* = 3 \times 10^{10} M_\odot \).

A similar bimodality in colors, star-formation rates, and morphology of galaxies has been observed all the way to \( z \sim 2 \) (e.g. Labbé et al. 2005, Kriek et al. 2006, Szomoru et al. 2012). However, while in the local Universe massive (\( M_* > 10^{11} M_\odot \)) galaxies constitute a substantially uniform population of red-and-dead objects, at \( z \sim 1.5 \) a high fraction (60%, compared to 10% in SDSS) of them is found to be star-forming, blue, and disk-like (Figure 1.1, van Dokkum et al. 2011). The fraction of quiescent galaxies increases towards lower redshifts while star-forming galaxies tend to dominate the galaxy counts at progressively lower mass (Brammer et al. 2011, Muzzin et al. 2014). Understanding the origin and the evolution of the galaxy
bimodality, and the process that quenches galaxies are perhaps the most fundamental questions of extragalactic astrophysics.

Figure 1.1: The diversity of massive galaxies at $1.0 < z < 1.5$ (from van Dokkum et al. 2011), in a mass selected sample ($\log M_*/M_\odot > 11$) from the 3D-HST survey. The relation between $\text{EW(}H\alpha\text{)}$, morphology (parametrized by the Sersic index) and color of galaxies shows that the high redshift population is made up of a group of quiescent, red, elliptical galaxies with low star-formation rates, complemented by blue, spiral-like, star-forming objects.

1.3 Measuring Star Formation through cosmic time

One of the most fundamental parameter describing a galaxy is the star formation rate (SFR), defined as the solar masses formed as stars per unit time. As the youngest stellar population emit the bulk of their energy in the rest-frame ultraviolet ($\lambda < 3000$ Å), the most direct way to measure SFRs consists in integrating the light of galaxies at those wavelengths. However, since stars form within clouds of gas and dust, the light they emit is at least partially attenuated and therefore any measure of SFR from the UV might be light might be severely underestimated.

One can either correct for the dust absorption, by for instance comparing the observed UV spectrum with the theoretical slope one would expect the spectrum to have (e.g. Meurer et al. 1995, Bouwens et al. 2009), or consider the additional contribution of the light absorbed in the UV and re-emitted at longer wavelengths (Bell et al. 2005, among others). Infrared measurements are however challenging
as well, and SFRs in the infrared are often inferred from observations at a single wavelength, from which the total IR luminosity is extrapolated under assumptions on the overall IR spectral shape.

Since young massive stars produce copious amounts of ionizing photons that ionize the surrounding gas, Hydrogen recombination lines (including the Balmer lines at optical wavelengths) represent the most traditional SFR indicator (Kennicutt 1998). The relation between the ionizing photon rate and the intensity of an hydrogen recombination line is dictated by quantum mechanics (e.g. Osterbrock & Ferland, 2006). Dust absorption affects optical Balmer lines to a lesser extent that UV - light, but dust corrections are still necessary. A commonly used technique consists in estimating the dust absorption in a system by comparing the ratio of the intensities of two emission lines (generally Hα and Hβ) to that expected by quantum mechanics in the absence of dust.

More indirect SFR indicators are based on radio and X-ray emission, respectively based on the acceleration of cosmic rays in supernovae explosions and the number of high-mass X-ray binaries, both correlated with the presence of young stars. At these wavelengths however, active galactic nuclei often dominate the emission, making SFR measurements more uncertain.

A comprehensive measurement of the SFRs at large lookback times has necessarily to rely on different tracers at different redshifts. Various measurements (among others: Madau et al. 1996; Lilly et al. 1996; Bouwens et al. 2007; Karim et al. 2011; Sobral et al. 2013; Madau & Dickinson 2014) of the star formation rate density (SFRD) at different cosmic times give an indication of the star formation activity of the universe (from z=8 to 0). Even though large uncertainties in the determination of the SFRD still exist, the global picture is well established: the SFRD rises from the Big Bang to a peak at z ~ 2 (“Cosmic Noon”), and afterwards falls by a factor of approximately 10 to the current value (Figure 1.2). Measuring the time evolution of the SFRD has implications for the reionization of the Universe, the cosmic chemical evolution, the transformation of gas into stars and the buildup of stellar mass.

In order to understand the physical processes driving the evolution of the Universe, one would ideally want to go beyond the global description of the SFRD and trace galaxy evolution on a galaxy-by-galaxy base, by connecting star formation rates with other physical properties of galaxies. In that respect, with the building of large statistical samples (SDSS) it became possible to establish that, for star-forming galaxies, mass and star-formation rates are tightly correlated, with most of the objects having a linear (or slightly sublinear) relation between log $M^*/M_\odot$ - log SFR, with a relatively small scatter (0.2 dex, Brinchmann et al. 2004).

In the meanwhile, infrared telescopes (IRAS, Spitzer) had already led to the identification of a different class of star-forming galaxies, with infrared luminosities and star-formation rates 100 to 1000 times higher than those of the Milky Way (Lonsdale et al. 2006, and references therein). Those rare objects have been dubbed (U)LIRG, i.e. (Ultra)Luminous InfraRed Galaxies, and turned out to be mainly products of merging or interacting galaxies inducing huge bursts of star formation (e.g. Armus, Heckman & Miley, 1987).

Looking back in the past, ULIRG-like star-formation rates appeared to be more
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Figure 1.2: Evolution of the cosmic star formation density, from Madau & Dickinson (2014). The star formation rate of the Universe reached a peak around $z \sim 2$ and has declined by a factor of 10 since then. Determinations based on infrared measurements are shown in red, determinations based on UV measurements in blue/green/magenta.

Figure 1.3: From Whitaker et al. 2012, the SFR-mass sequence for star-forming galaxies out to $z = 2.5$. At each redshift, more massive galaxies have higher SFRs than those of lower mass galaxies, with a non-linear slope. The normalization of the sequence increases towards higher redshifts.
prevail e.g. Lilly et al. 1996, Cowie et al. 1996). However subsequent studies showed that \( z \sim 1 \) star-forming galaxies, despite the similar high star-formation rates, had nothing in common with local (U)LIRGS, while instead resembled relaxed disks, with less than 20% of them being interacting systems (Zheng et al. 2004, Bell et al. 2005). Subsequent studies showed that a relation between stellar mass and star-formation rates, similar to that seen in the local Universe, was present for galaxies at high redshift too (Noeske et al. 2007, Elbaz et al. 2011, and others).

Since star-formation is thought to be regulated by the balance between the accretion rate of cold gas onto the galaxy and some feedback process (e.g., Dutton et al. 2010; Bouche et al. 2010), the star-forming main sequence may be a natural consequence of “cold mode accretion” (e.g., Birnboim & Dekel 2003), as the SFR is approximately a steady function of time and yields a relatively tight relationship between SFR and \( M_\star \).

The normalization of the star-forming main sequence increases towards higher redshifts (Karim et al 2010, Whitaker et al. 2012, Figure 1.3), with a slope that is generally steeper than that predicted by semi-analytical models of galaxy formation (e.g. Guo et al. 2010). The fact that the main sequence shifts towards lower values as the Universe gets older reflects a gradual decline of the average star-formation in most individual galaxies, as gas gets gradually exhausted, accompanied by an increase in the fraction of quenched galaxies (e.g. Muzzin et al. 2014).

1.4 Issues at high redshifts

Despite the invaluable technological advances of instruments and telescopes in the last twenty years, starting with the building of 8-10m class telescopes and the new generation of space telescopes (such as Hubble and Spitzer), measurements of high-redshift galaxies are still extremely challenging, and our knowledge of those systems is nowhere near to that we have of local galaxies.

In the first place, galaxies become fainter as their distances increase. Spectroscopy of high-redshift galaxies is therefore prohibitively time-consuming for all but the brightest sources. The most fundamental problem related to the absence of spectroscopy is that the redshift determination is uncertain. High-redshift surveys use multiband-photometry to obtain a spectral energy distribution (SED) of galaxies, and fit those with a set of modeled SEDs in order to derive redshifts and other physical properties of galaxies. Even in extragalactic fields covered by 20-30 different photometric bands spanning from the UV to the NIR photometric redshifts are hardly more precise than \( \delta z / (1 + z) = 3\% \) once compared to spectroscopic redshifts of generally bright objects with emission lines (Skelton et al. 2014). Estimation of galaxy masses from photometry are affected by systematic uncertainties of the order of 0.3dex or more (e.g. Muzzin et al. 2009, Dahlen et al. 2013, Pacifici et al. 2014).

A second fundamental problem for observations at high redshift is that their light is strongly redshifted. Light from old stars (representing the bulk of mass in most galaxies) is redshifted into the infrared at redshifts higher than \( z \sim 0.5 \). This causes problems because of the inefficiency of infrared detectors, and the atmospheric absorption in those bands caused by water vapor. Even in the most ideal places for
infrared ground-based telescopes (dry locations at high altitude), the transparency of the Earth’s atmosphere is limited except in a few infrared wavelength windows.

Our knowledge of ages, star-formation rates, and metallicities of galaxies relies often on spectral indicators at rest-frame optical wavelengths (such as D4000, Balmer and metal lines), which are challenging and time-consuming to measure at high redshift when they shift in the infrared. For instance, a well-calibrated standard indicator of the SFR is the already mentioned Hα luminosity (Kennicutt, 1998). As a consequence of its shift into the near-IR at redshifts higher than \( z \sim 0.5 \) (8 billion years ago), studies of the evolution of star-formation rates covering a wide redshift range use diverse SFR indicators (such as UV, IR, [OII], SED fitting), relying on a set of assumptions and inter-calibrations. For each indicator, accessing fluxes correspondent to SFR \(< 10 – 20 M_\odot/yr \) becomes challenging, if not impossible, for individual sources at \( z > 0.5 \). The identification of samples of galaxies with low star formation at high redshift is therefore generally based on their rest-frame colors only, by selecting galaxies whose optical and near-IR light is dominated by an old stellar population.

An additional bias induced by ground-based spectroscopy is that samples for spectroscopy are generally optimized for observations in the atmospheric windows, and they are consist generally in blue star-forming objects selected on the basis of their rest-frame UV emission (Steidel et al. 2004, and others), while continuum observations are available for limited samples of bright objects (Bezanson et al. 2013, van de Sande et al. 2013). The absence of bias-free and mass-complete samples of measurements of physical properties of galaxies such as ages and metallicities limits our understanding of the assembly history and the evolution of galaxies.

1.5 This Thesis

This thesis addresses several of the issues described in the previous section. In particular, we take advantage of a novel set of observations taken with the Wide Field Camera 3 (WFC3) grism onboard Hubble Space Telescope (HST), in the context of the 3D-HST survey (Figure 1.4, Brammer et al. 2012), in order to investigate the evolution of star-formation rates, emission line contributions and stellar population properties of both star-forming and quiescent galaxies, in mass selected samples at \( 0.5 < z < 2 \). 3D-HST provides rest-frame optical spectra for a sample of \( \sim 10000 \) galaxies at \( 1 < z < 3.5 \), the epoch when 60% of all star formation took place, the first galaxies stopped forming stars, and the structural regularity that we see in galaxies today must have emerged. Such a wide-field near-IR spectroscopic survey would be currently infeasible from the ground, since it proves a larger cosmic volumes thanks to the broad range of redshifts covered by the WFC3 grism, and targets every object in the field of view.

In Chapter 2, we combine the first available data from the 3D-HST survey (40 % of the entire survey) with those of ground-based surveys at lower redshift in order to evaluate the evolution of EW(Hα), the equivalent width of Hα. Since EW(Hα)
Figure 1.4: The 3D-HST survey provides spectra for all galaxies in a particular field with the WFC3/IR grism. The panels on the left show 50x28 arcsec cutouts of the F140W and G141 observations within the GOODS-South field, with wavelength increasing towards the right on the grism panel. Galaxy spectra are extracted in 2D and 1D (bottom right) and used in combination with the full SED of the objects (top center) in order to determine a redshift measurement which is greatly improved to that from photometry alone: the top-right panel shows the probability distribution of the redshift determined from the photometry alone (grey region), and that determined with the addition of grism data (black region), compared to a spectroscopic redshift (vertical line). Image from Brammer et al. (2012).

is defined as the ratio of the Hα luminosity to the underlying stellar luminosity, it represents a measure of the current to past star formation, and it is therefore a model-independent, directly observed proxy for the specific star formation rate (sSFR=SFR/M). We find that at each redshift EW(Hα) goes down with mass, and that at fixed mass the EW(Hα) grows towards higher redshifts as $EW(H\alpha) = (1 + z)^{1.8}$. This evolution is independent of stellar mass, and it is steeper than that predicted by models of galaxy evolution. We moreover predict the evolution of EW(Hα) at higher redshift, finding that the contribution of emission lines to the total light of galaxies continues to increase at $z = 4 − 8$, with important consequences for spectroscopy and photometry of sources that will be accessed with James Webb Space Telescope.

In Chapter 3 we investigate the SFRs of galaxies selected as quiescent on the basis of their optical and near-IR spectral energy distributions, which indicate an old stellar population. Spectral energy distribution fits for optically selected quiescent galaxies indicate SFRs even lower than those expected from gas recycling, assuming that the mass loss from evolved stars refuels star formation. However, optical and near-IR SED fitting can miss star formation if it is hidden behind high dust obscuration, and its ionizing radiation is reemitted in the mid-infrared. We therefore select spectroscopically confirmed quiescent galaxies in the 3D-HST survey, and measure
their dust-obscured SFRs with stacks of mid-infrared fluxes from Spitzer-24µm, in five redshift bins centered on \( z = 0.5, 0.9, 1.2, 1.7, 2.2 \). We show that, at each redshift, SFRs of quiescent galaxies are 20-40 times lower than those of star-forming galaxies at the same redshift, indicating that quenching is very efficient even in the young Universe where typical SFRs on the main sequence reach hundreds of solar masses per year. The true SFRs of quiescent galaxies might be even lower than that, as we show that mid-infrared fluxes can be due also to processes uncorrelated with present star formation, such as dust heating by old stellar populations and circumstellar dust.

Chapter 4 focuses on the spectra of star-forming and quiescent galaxies from \( z=0.5 \) to \( z=2 \) in more detail, in order to determine their stellar ages. We stack spectra of quiescent and star-forming galaxies (selected on the basis of a rest-frame color-color technique), and fit them with commonly used stellar population synthesis models. We find that stellar population models fit the observations well at wavelengths lower than 6500Å, while they show systematic differences from the observed spectra at redder wavelengths. We show that quiescent galaxies have little emission line contribution, and those are consistent with SFR measurements from mid-infrared. The ages of quiescent galaxies implied by the models differ according to the model in use, but on average quiescent galaxies are young, i.e. younger than half of the age of the Universe at each redshift. For star-forming galaxies the inferred ages depend strongly on the assumed stellar population model and star-formation history.

In Chapter 5 we take advantage of the full 3D-HST data to analyze how the EW(H\( \alpha \)) depends on galaxy properties and in particular on the optical/near-IR spectral energy distribution shape of the galaxy, in the redshift range where H\( \alpha \) can be observed with the HST/WFC3 grism (0.7 < \( z \) < 1.5). We demonstrate that galaxies with strong and weak H\( \alpha \) are well separated in a rest-frame color-color diagram. For star-forming galaxies, we investigate how H\( \alpha \) varies as a function of the rest-frame colors of the galaxy and how it relates to the specific star formation rate, measured from the ultraviolet and mid-infrared emission. At a fixed mass, red star-forming galaxies have lower EW(H\( \alpha \)) than blue star-forming galaxies. We also show that, at fixed mass, the median specific star formation rates of galaxies decreases towards redder U-V colors, and that the dust absorption increases towards redder colors. We show that the overall variation of EW(H\( \alpha \)) as a function of color can be explained by the combined effect of lower specific star formation rate and higher dust absorption for galaxies with redder colors.

Bibliography


Hubble, E. P. 1927, The Observatory, 50, 276


