Complete Optical-to-Near Infrared Spectra of Galaxies at z $\sim$ 1

Investigating Star Formation Rate, Mass, Hα Emission, Hδ Emission, Velocity Dispersion and Spectra of Galaxies up to z $\sim$ 1

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1 Abstract

We have only known about the existence of other galaxies for less than 100 years when Hubble discovered them, and ever since his discoveries astronomers have been determined to learn about galaxies far away. Until recently though, we only had highly detailed information about our nearby neighbourhood of galaxies at low redshifts. Most of this information has been obtained with the Sloan Digital Sky Survey, but a new era in astrophysics has begun, and we are now able to detect and characterize large representative samples of galaxies further away, closer to the beginning of the Universe. And not just that, both a much larger sample but also at much higher resolution than ever before for higher redshifts. These observations provide key elements in the studies of how the Universe, the stellar populations of galaxies and our local environment evolved to be as it is today.

In this paper we combine data from two different surveys observing galaxies at redshifts up to ~ 1, namely the Lega-C and 3D-HST surveys. Back to half the age of the Universe. By combining two surveys observing at different wavelengths we are able to obtain a broader variety of key emission and absorption lines but also broader spectra for each of the observed galaxies.

The main features from the spectra that we look at is the star formation indicator Hα from the 3D-HST survey and the star formation history tracer Hδ and star formation indicator [OII] from the Lega-C survey. We study these features in UVJ-diagrams to confirm the previously discovered bimodality of quiescent and star forming galaxies.

Lastly we fit models to two stellar spectra and obtain χ^2 values between 1.06 and 2.15, suggesting that with current theoretical galaxy population synthesis models, developed on a base of the nearby Universe we can already reasonably explain the very detailed spectroscopic characteristics of galaxies. Even for galaxies at much earlier cosmic times.

2 Introduction

It was only in 1920, not even 100 years ago, the existence of other galaxies than the Milky Way was established. Before this they were classified as nebulae: fuzzy objects not containing stars, but that did not keep astronomers from studying the night sky. Soon Edwin Hubble discovered variable stars in the Andromeda 'nebula' M31 by showing that their luminosity varied like the variables in our own galaxy. With this knowledge he quickly concluded that they were so far away they must be part of a galaxy in it's own right.

By studying the galaxies he observed, he started classifying them based on their photographic appearance and arranged them in different groups, which then became known as the Hubble Sequence, the Hubble Classification Scheme or Hubble's Tuning Fork. As seen in Figure 1, Hubble put galaxies into four main categories: spirals, ellipticals, lenticulars and irregulars.

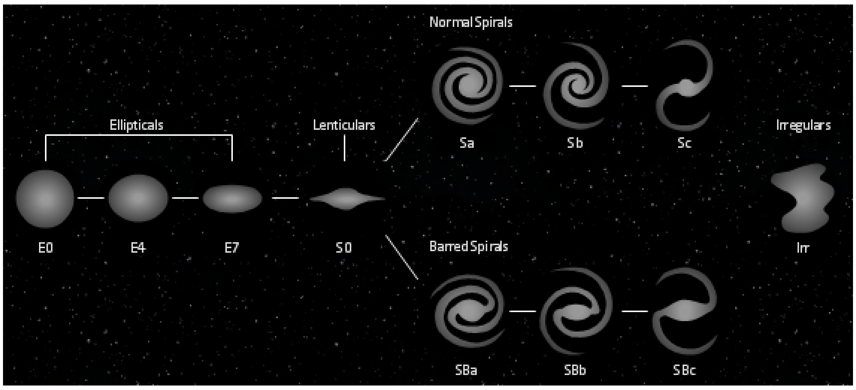

Figure 1: The Hubble "Tuning Fork" Classification Scheme. On the lefthand side are the elliptical galaxies, in the middle are the lenticular galaxies. The two arms consist of barred and un-barred spirals and to the far right are the irregulars.

For many years Hubble and other astronomers thought the Hubble sequence was an evolutionary track for galaxies and that they went from ellipticals through lenticulars and then became spirals. This theory was discarded though and today we know he was on the right track, but backwards, we now believe that they evolve from spirals through lenticulars and into ellipticals instead. Ever since Hubble discovered other galaxies and started classifying them, astronomers have wanted to study the evolution of the universe and the galaxies within and figure out why it was in fact a backwards evolutionary sequence. This has been found to be a difficult task though since surveys have to compromise between quality and quantity when looking further back than a redshift of ~ 0. Telescopes have gotten larger and more efficient and exposure time on each object on the sky longer, allowing us to obtain higher resolution and broader spectra of galaxies at higher redshifts. With the Lega-C survey obtaining high resolution spectra of many galaxies and the 3D-HST survey obtaining many spectra over a small area - both at redshift to and above 1, we open up the possibility of studying galaxy evolution, star formation and figuring out how, why and when galaxies went quiescent. Looking this far back might in the end give an insight in how our own galaxy, the Milky Way, and our neighbourhood, the Local Group, evolved into what they are today.

Another incredibly important thing Hubble discovered was the fact that other galaxies and objects are not static in space, they are moving away from us - and that with an increasing velocity. He discovered that the universe is expanding, and with this came the discovery of redshift. He found that the light from objects moving away from us was not stretched or likewise, but the whole spectrum of the object was shifted towards redder wavelengths, and that the size of the redshift was then proportional to the distance from the observer. This gives us the term 'cosmological redshift' which is redshift due to the expansion of the universe. The expansion of the Universe thereby lengthens the original wavelength, between the time of emission of the light and the time of observation of said light - it gets redshifted. Another important part of cosmological redshift is its relation to time, in other words a redshift of $z = 1$ corresponds to looking back nearly 8 billion years in time, more than half of the age of the Universe.[18]

In this paper I am going to combine data from two different surveys: Lega-C and 3D-HST, to achieve more complete info about galaxies with a redshift up to 1. This includes but is not limited to spectral features such as the Hα emission line that is known to be the most robust star formation indicator. Before looking at the actual spectra we have to make sure that the galaxies we use are representative of the population we want to study. This is done through analyzing different parameters such as stellar mass, velocity dispersion and star formation rate(SFR) to name a few. When and if we confirm that the sample is representative, we can start looking at the combined spectra for the galaxies and fit models to them. This will enable far more knowledge of galaxies at higher redshifts, their contents and the processes within them. Furthermore it will allow us to further study the evolution of galaxies and stellar populations in the earlier Universer. We can then use the spectra to improve our current models of different galaxy types by looking at where they match and do not match actual spectra and why they might be different from these.

2.1 Galaxies Today ($z = 0$)

The first substantial breakthrough in studying large samples of galaxies was the Sloan Digital Sky Survey (SDSS). The SDSS yields for the nearby universe, the most homogeneous and consistent measurements for such a wide range of different galaxy types. The SDSS has enabled the creation of the most detailed three-dimensional maps of the Universe including multi-color images of over a third of the sky and detailed spectra of over three million objects on the night sky.[24] In Figure 2 we see an incredible outcome of the SDSS, it has become possible to map out the nearby Universe and see Large Scale Structures too.

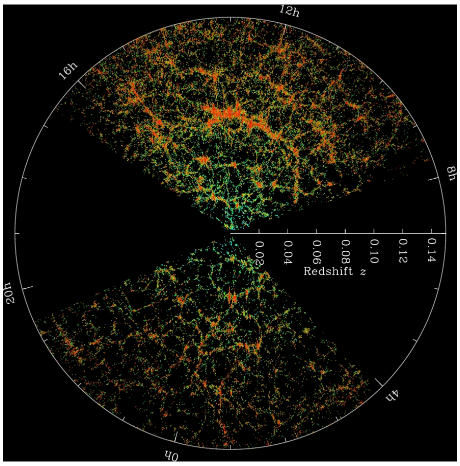

Figure 2: The SDSS map of the nearby Universe, with each dot being a galaxy. [20]

Beginning observations in the year 2000 the SDSS is an enormous multi-spectral imaging and spectroscopic survey resulting so far in 15 data releases and counting with a 16th release planned for the upcoming December. Up until 2009 the survey included both images and spectra of objects and in 2009 the imaging camera was taken out of function. SDSS uses a 2.5-m wide-angle optical telescope and has computed photometric observations of nearly a billion objects. Between the galaxies in this sample the median redshift is at $z = 0.1$.[25]

Since the beginning of the SDSS the field of studying galaxies systematically and statistically has been revolutionized by the SDSS providing accurate measurements of hundreds of parameters for hundreds of thousands of galaxies from a broad variety of environments. The SDSS contributed greatly in the discovery of a bi-modality for galaxies, clearly demonstrating a separation between the populations of star forming galaxies like our own Milky Way, and the quiescent galaxies with little to no star formation and these properties even correlate with the structure, just as in the Hubble Classification Scheme in Figure 1. Furthermore the SDSS' mapping of nearby galaxies has started studying thousands of nearby galaxies for details and clues about how and when the galaxies evolved to what they are today.[24]

With such comprehensive knowledge of nearby galaxies it has become possible to test evolutionary

Figure 3: An image of the galaxy with Object ID: 1237651225709904108 and $z = 0.114$. Image from the SDSS server.[22]

models for subjects like galaxy formation and why galaxies stop their star formation.

One of the major strengths with the SDSS is the combination of imagery and spectroscopy. Imagery is relatively cheap compared to spectroscopy and from the image of a galaxy you can get a lot of information about the colour, morphology and structure. On the other hand, the more expensive spectroscopy provides detailed astrophysical parameters from the continuum such as metallicities and star formation history and crucial properties of the ionized gas from emission lines, including for example the star formation rate. An example of a galaxy from the SDSS where both an image and a spectrum has been obtained is the galaxy in Figure 3, it is the brightest orange dot in the middle. Figure 4 shows the corresponding spectrum for the galaxy. From the image it appears to be just any old elliptical galaxy, but looking at the spectrum is has strong emission lines in [OII] and Hα which are both the best tracers of star formation, or that gas is accreting onto a supermassive black hole in the galaxy center - essentially telling us what the picture can not - it is not quiescent.

2.2 The Large Early Galaxy Astrophysics Census (Lega-C)

The primary targets for the survey were chosen to be a ~ 10000 galaxy large parent sample with a K_s-band magnitude limit of $K < 21.08$ at a redshift of 0.6 and $K < 20.36$ at a redshift of 1.0 resulting in a lower mass limit of $\sim 10^{10} M_{\odot}$. In comparison, our own Milky Way has a mass of $6 \cdot 10^{10} M_{\odot}$.[11] The targets for the masks were chosen after the brightest first resulting in a sample dominated by stellar masses of $10.5 < log\frac{M}{M_{\odot}} < 11$ and velocity dispersions of $100 < \sigma' < 200\frac{km}{s}$. This results in a total of ~ 3200 K-band selected target galaxies.
In Figure 5 the blue points show the sky coordinates of the 1988 Lega-C galaxies which where observed during the 130-night ESO survey. These 1988 galaxies are the targets for which fully reduced spectra in one dimension were obtained, along with spectroscopic redshifts, emission line fluxes, absorption line indices and (spatially integrated) observed velocity dispersion. It was conducted with the Visible Multi-Object Spectrograph(VIMOS) which operates in the visual part of the spectrum at $0.36 - 1\mu m$.[1]

Before Lega-C The Sloan Digital Sky Survey(SDSS) has been the largest and most used set of data when studying the detailed spectroscopic properties of galaxies in the nearby universe. The SDSS includes several hundred thousand spectra of low-redshift galaxies, and detailed key properties such as ages, metal content, structure, size and star formation rates, but spectroscopic surveys must usually compromise between a large sample size or a high signal-to-noise(S/N).[1]

Since the SDSS, larger surveys focusing on multi-wavelengths photometry have quickly increased our knowledge of the more distant universe. We now possess measurements of stellar mass, star formation rates and of morphology of thousands of galaxies at redshifts up to $\simeq 4$.[1] Our knowledge of the more detailed physical properties of galaxies are more limited though. The properties that are effects of continuum emission and absorption lines including ages, metallicities and kinematics still only come from small samples at $z < 1$ because samples have been optimized for

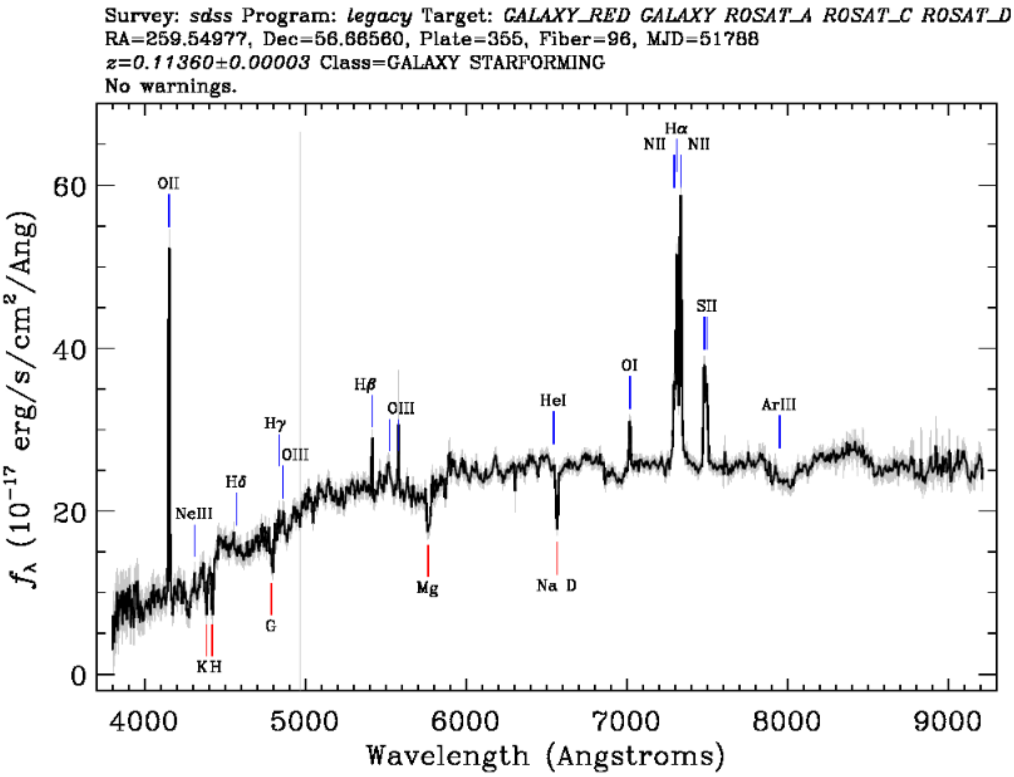

Figure 4: Spectrum for the galaxy with Object ID: 1237651225709904108 and $z = 0.114$. This particular spectrum has very strong Hα and [OII] lines, clear star formation indicators, but also has the characteristic shape of an older stellar population being more intense on average at higher wavelengths. It even has the characteristic G-band of an older galaxy. Image from the SDSS server.[22]

data quality instead of quantity.[1] Thus the most dominating galaxies and their properties have not been properly studied at $z \sim 1$ in samples large enough to be on the same significant scales as SDSS.

With the knowledge that $\sim$ 50% of stars formed since $<\sim 1$ they expect to find that the stellar population $\sim$ 8 Gyr ago must have been very different from today, though this has only been studied in very small samples. This is the strength of Lega-C, it provides an outstanding opportunity to combine the archaeological approach on the formation of galaxies with the ability to actually look this far back in time. The goal of the Lega-C survey was to provide the depth to obtain high quality spectra of a relatively large sample of galaxies further away than our own neighborhood, i.e. at $0.6 \lesssim$ z $\lesssim 1$ with a S/N $\simeq 20$ Å^{-1}. This was done from December 2014 to March 2018 by observing objects for $\sim$ 20 hours each instead of the 1 hour for usual redshift surveys and hereby providing a sample at scaling relations on a level with the SDSS.[16]

Another reason for the Lega-C survey is looking at whether the trends we see in galaxy populations today are the same as or different from other cosmic eras. In the past this has been challenging to investigate due to it being so expensive and time consuming to observe large samples of more distant galaxies. Usually surveys have been completed for specified samples, often targeting the brighter population of galaxies, giving the results a bias. Surveys like the DEEP2 spectroscopic survey[14] did a good job at looking at how trends evolved, but we still needed a large census of the distant galaxies that provided much more detailed spectroscopic information and was representative in as many areas as possible, something similar to the SDSS for nearby galaxies.

With the Lega-C data there has already been made progress. In an article Wu et al.[4] look at the $D_n4000 - EW(H\delta)$ plane in Figure 6 and show the distribution of galaxies in four different mass bins. This shows a very clear bimodality for galaxies in the higher redshift Lega-C sample,

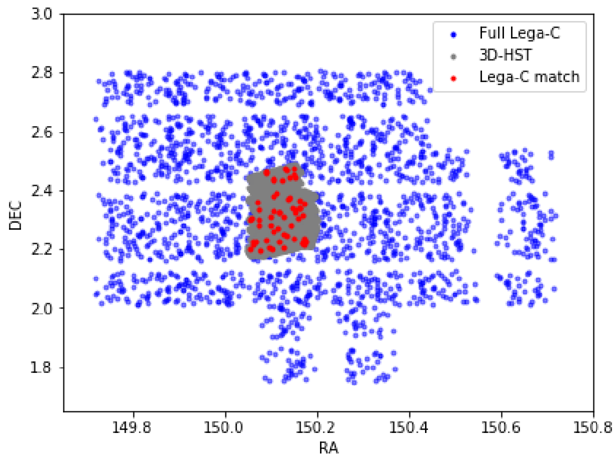

Figure 5: The position on the sky of the galaxies from the different surveys overplotted. The blue points represent the full Lega-C sample, the grey points represent the full 3D-HST sample, and the red points represent the galaxies from the Lega-C sample that have been matched with a 3D-HST galaxy.

but not for the low redshift galaxies in the SDSS sample. A high value of D_n4000 and low value of Hδ signifies an old stellar population. This means that for higher mass galaxies the stellar populations are also older. It also supports the fact that there must have been more actively star forming galaxies at higher redshift given that a high Hδ signifies star formation.

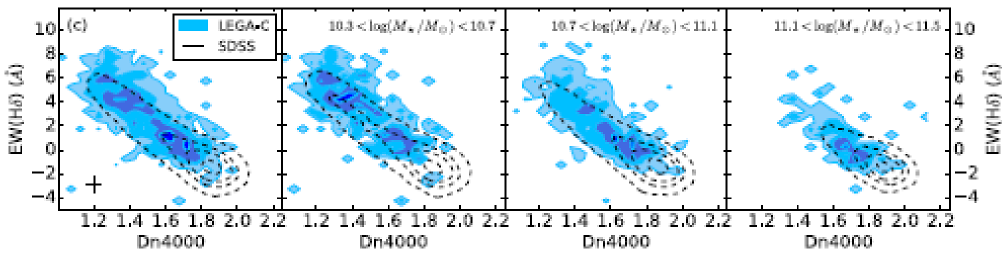

Figure 6: Distribution of completeness corrected Lega-C and SDSS samples showing how the distribution of galaxies in the $D_n4000 - EW(H\delta)$ plane changes with mass. The blue solid contours are the Lega-C sample and the black, dashed line is the SDSS sample. The Lega-C sample shows a bimodality whereas the SDSS sample does not. The age of a galaxy's stellar population increases roughly from the upper left towards the lower right in this diagram. Image from Wu et al.[4]

2.3 The 3D-HST Project

In Figure 5 the grey points show the sky coordinates of the 36611 available galaxies from the 3D-Hubble Space Telescope (3D-HST) survey. Because the telescope is space-based it gives the possibility of observing at wavelengths otherwise blocked by Earth's atmosphere. Had it been ground based observations the slitless technique would also be a bad idea because of background light, but for a telescope in space with very faint background light, it is competitive in quality and often superior to the ground-based slit spectroscopy. The Grism spectra are unique because where most spectrographs and ground-based telescopes use slits or small apertures to isolate an object to observe, the 3D-HST survey used the Wide Field Camera 3(WFC3) where spectra are obtained through slitless spectroscopy, which means that individual objects are dispersed. This is a very effective observation technique as it obtains spectra of all objects within the field of imaging simultaneously instead of only a few targets. A lot of these spectra overlap but with the SExtractor software the individual spectra were extracted and photometric redshift and Hα

emission lines among many other properties were determined by fitting the galaxy spectra.
With this slitless observation technique it was possible to measure continuum emission down to $JH_{IR} \leq 24$ for 22,548 targets and redshift and emission line strengths down to $JH_{IR} \leq 26$ for 98,663 targets. The different grisms in the telescope have different wavelength coverage with the G102 grism covering $0.8 - 1.15\mu m$ and the G141 grism covering $1.1 - 1.7\mu m$ and thereby it covers the Hα emission line wavelength that Lega-C does not.[15]

2.4 Combined

Together the two surveys provide much more info about a single galaxy than either of them can separately.
When combining the surveys it is possible to create much more complete spectra due to them observing at different, and crucially, coinciding wavelengths allowing us to compute broad spectra like those of the SDSS in Figure 4 instead of just snippets of important parts of the spectrum. With Lega-C we are able to see the part of the spectrum where a lot of emission and absorption lines appear in the spectra of both old and young galaxies. For many galaxies this includes the strong Hβ line, the SFR indicator [OII], the star formation indicator from Hδ absorption and the 4000 Å break that is very hard to obscure. The Lega-C wavelengths do not get red enough to cover another important line though, the Hα line or lack thereof. The 3D-HST survey does cover the coinciding, redder wavelengths though, which is important because Hα is considered the most robust indicator of ongoing or recent star formation. This line is for example seen clearly in the spectrum in Figure 4 telling us that though the spectrum resembles that of an older stellar population, it has had a recent star formation or that it has an active supermassive black hole in the center. Furthermore, when galaxies age they get increasingly dominated by the older, redder stars. When adding redshift to this it makes it impossible for Lega-C to observe these galaxies as they will barely emit any light in the bluer wavelength range of this survey making the 3D-HST survey crucial when observing older and further away galaxies.

Combining them also makes it possible to observe different characteristic lines namely Hδ and another SFR-indicator, [OII] from Lega-C and Hα from 3D-HST. They provide redshift obtained through two different methods, and furthermore the Lega-C survey provides stellar velocity dispersion values for the galaxies. Thus by combining these surveys we get a much more complete image and understanding of galaxies at redshifts up to 1, enabling in the future a better understanding of galaxy formation and star formation histories.

3 Theory

After discovering the Andromeda galaxy in year 1936 Hubble soon set out to find and classify many other galaxies. His classification became the "Hubble classification scheme" which has been modified and expanded a few times, but is nevertheless still used today. It features four main categories; ellipticals, spirals, lenticulars and the irregulars.

Ellipticals are mostly featureless in terms of appearance and lack cool gas for star formation resulting in these galaxies being quiescent and dominated by a population of old, redder stars. The stars within show little organized motion because they rotate in random orbits around the center resulting in the elliptical look and higher velocity dispersion. Ellipticals predominate the populations of the rich and densely populated galaxy clusters.

Spirals have a compact central bulge and fast-rotating spiral arms, hence the name, where the arms are either waves of star formation compressing the great amount of cold gas into hot and blue O and B stars or as recently discovered, possibly rigid, real structures with stars bound by their mutual gravity physically rotating together.[19] In spirals the rotation and orbits of the stars are far more organized, mostly rotating in the same plane and they therefore show smaller velocity dispersion.[6]

Lenticular galaxies are the transition class between spirals and ellipticals in that they have a compact central bulge with a large, rotating disk, though without any spiral arms. Like ellipticals, they lack extensive gas and dust and mostly reside in the densely populated clusters. But like spirals they have a thin and quickly rotating stellar disk.[6]

Irregular galaxies make up the fraction that does not fit into the other three categories, and today mainly consist of small blue galaxies without an organized spiral or other structure. Spiral galaxies usually reside in the less densely populated galaxy groups, such as the Local Group which is the small group the Milky Way belongs to.[6]

Another group of galaxies that Hubble would have deemed irregular are starburst galaxies, systems that formed many stars and exhausted their gas supply in recent past i.e. within the last $\sim$100 Myr. The spectrum for a star burst galaxy is usually bright at shorter, blue wavelengths - the stars ionize the gas surrounding them and produce strong emission lines. If the stars are surrounded by dust on the other hand, the radiation will be absorbed and re-emitted in the infra-red. This results in some powerful starbursts seen as luminous infrared galaxies. Starbursts can come about in different ways, for example gas thrown out by supernova explosions or interactions between two or more systems where they collide and the gas in the galaxy is then compressed to form stars. Starbursts are not just scaled up Star Formaion Rate(SFR) of a galaxy like the Milky Way, the gas pressure in these regions are a hundred times greater than in the Solar neighbourhood and emission lines are up to five times stronger in starbursts compared to Carbon Monoxide emission from diffuse gas.[6]

Post-starburst galaxies(PSB) are galaxies that were once producing stars at a relatively high rate but which have later slowed down the process. These galaxies are mostly elliptical and have an excess amount of A-type stars. They are believed to form the link between the red, quiescent, elliptical galaxies and the blue, star forming, spiral galaxies by possibly being the transition between the two types. The definition of a PSB is slightly ambiguous though. Some research groups demand strong Hδ absorption because it is an indicator that a galaxy has young A-type stars. Other also require that the galaxy lacks Hα emission since that would be a lack of star formation. Nonetheless most agree that the spectrum must lack [OII] emission because this also implies no ongoing star formation. Looking at Figure 7, depending on the definition they either belong in the blue cloud when only strong Hδ absorption was demanded, somewhere in between the two categories in what is called the green valley where strong Hδ absorption and a lack of [OII] emission was demanded, or as part of the red, quiescent galaxies when all three indicators were demanded to be present.[8]

With the SDSS as the primary source of data, a lot of information about our nearby neighbourhood has been made publicly accessible knowledge. A very important point was the discovery of the strong connection between the absolute magnitude and stellar and dynamical masses. One of the main points to obtain is that in most color-magnitude diagrams we observe a bi-modality with galaxies roughly splitting into red and blue sequences like in Figure 7. It is not entirely as simple as basic morphology but for the most part the blue galaxies can be classified as star forming spiral galaxies whereas the red sequence is a more nuanced combination of all different types of elliptical galaxies, early type spirals and spirals reddened by dust. A general sign to look for in red galaxies is their lack of star formation indicators, but also the fact that their colour weakly correlates with the mean stellar age and metallicity, which are both factors that rise with mass.

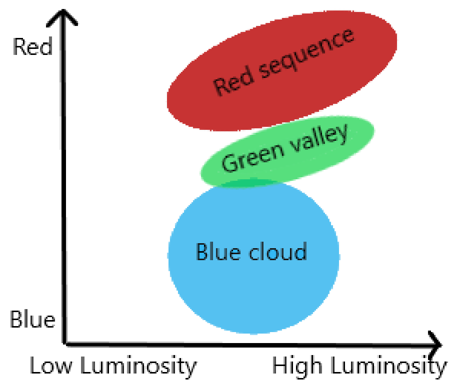

Figure 7: Colour-Magnitude diagram illustrating the distribution of Post StarBurst galaxies. Idea from AstroBites.[21]

What we currently know about the distribution of galaxies in the Universe is that about half of the galaxies reside in galaxy groups or clusters. Clusters are the quite densely populated areas filled with elliptical galaxies, dense centres and hot gas. Galaxy groups on the other hand are sparsely populated and the dilute gas in between the galaxies in groups, possibly make up 90% of the baryons in the Universe. We know that about 90% the stars in the Universe formed after z$\sim$ 2 and about 50% formed after z$\sim$ 1.[7] Therefore it also makes sense that the relative abundance of quiescent versus star forming galaxies has evolved over time. In the present day Universe massive, quiescent galaxies are dominant, whereas at higher redshifts star forming galaxies become abundant. This also tells us that the stellar population is going to be very different at higher redshifts than it is today.

When studying galaxies and their formation and history, one of the main features we want to know about is the formation of the stars within the galaxies. We look at the SFR to study how fast the stars are currently forming, and the star formation history(SFH) to figure out how quickly they have been forming up until now, for example whether there has been a recent star formation burst(SFB) or if it has been quiescent for a long time.
Hα emission and Hδ absorption are two important properties to look at in this context. Hα emission is the parameter to look at when studying the current SFR. This is because only stars with masses over $10M_{\odot}$ and ages less than 20 Myr contribute to this emission by ionizing the gas around them, which means it is an almost instantaneous glimpse of the SFR and it is essentially independent of the star formation history(SFH).[5] Therefore Hα tells about how the current ongoing star formation relates to the past star formation. This is because Hα corresponds with the specific SFR(sSFR) - low Hα means low SFR - if it has a low sSFR now, it would have spent a very long time with that SFR to form the mass of stars it currently contains.
Hδ is interesting to look at when considering the SFH because this increases rapidly within a few hundred megayears after a star formation burst, as the O- and B-stars die out and A-stars start to predominate the galaxy spectrum. Later on when the A-stars start to die off so does the Hδ absorption. This strong absorption is possibly an indicator that within the last 1 Gyr the SFR has been quickly declining and we will therefore be looking at this for the sample.[4]

Often [OII] emission lines are used to determine SFR because the radiation ionizing the Oxygen into [OII] comes from young, massive stars and though less intense than Hα they can be the strongest feature in a spectrum next to Hα. Furthermore, [OII] at rest-frame 3727 Å is often used though because Hα is redshifted into the near-infrared for galaxies above $z = 0.5$. Here there are many strong emission lines from the sky making it impossible for ground-based telescopes to observe here. [17] But with the data from both the 3D-HST survey and the Lega-C survey we are able to compare the [OII] emission lines to both Hα and Hδ, but most importantly Hα as they are both measures of SFR.

Another interesting factor for galaxies is the velocity dispersion, σ_{stars} which is how large the dispersion, from the average rotational velocity of the stars, is. The smaller it is the more uniform the rotational velocity of the stars. This results in elliptical galaxies typically having a much larger σ_{stars} than spiral galaxies. Since SF galaxies typically are spirals and so forth it also tells us that SF galaxies have lower σ_{stars} than ellipticals. For this sample the observed σ_{stars} is typically $\sim 150km\ s^{-1}$ for star forming galaxies and $\sim 200km\ s^{-1}$ for quiescent galaxies. An important relation regarding velocity dispersion has been found, namely that there is a clear correlation between the velocity dispersion and mass of a galaxy - the more massive, the higher the velocity dispersion due to fundamental gravitational physics in the balance between potential and kinetic energy of a stable gravitating system. [23]

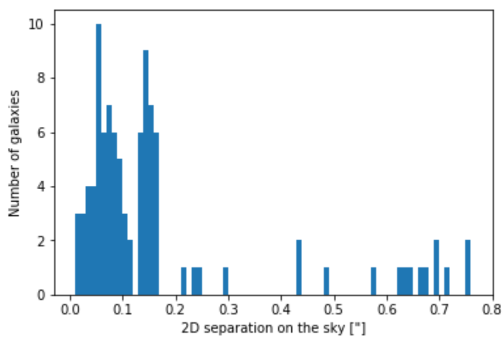

Figure 8: Histogram of 2D separation on the sky between the Lega-C coordinates and the 3D-HST coordinates for each galaxy.

4 The Sample

4.1 Sample Selection

During the process of selecting galaxies to use we had to compare the two samples. The first step was to find the galaxies from the two projects that had the same position on the sky and therefore would most likely be the same galaxy. This was done by finding their 2D-separation on the sky with the astropy coordinate matching tool.

After looking at the histogram in Figure 8 we had to choose a threshold for the separation. There appears to be a large gap between 0.3 and 0.43 arcseconds and very few galaxies to the right of this gap, and therefore we set the threshold to be 0.3". This narrowed the sample down to 85 galaxies. From the Lega-C catalog quality flags to say whether they considered the data for a galaxy reliable or not for scientific analysis, were then applied to the sample. After applying this flag it narrows the sample down to 58 galaxies.

The next step was checking whether the matched galaxies also measured the same 3D-HST and Lega-C redshift. On the left-hand graph in Figure 9 we plot the Lega-C and 3D-HST redshifts, the points are coloured for the Lega-C usefulness flag f_{use}. The points on the line are galaxies that show the same redshift for the two samples, but it is also obvious that the 3D-HST redshifts often measure much higher than the Lega-C redshifts and only once the other way around. The Lega-C redshifts are measured spectroscopically i.e. through emission lines in the spectra whereas the 3D-HST redshifts were obtained through photometry, i.e. through fits to the spectra and while this is a good method, occasionally spectra do not contain any spectral features for constraining the redshifts making them less accurate.

On the right-hand graph in Figure 9 the points are coloured by their 2D-separation on the sky and the Lega-C quality flag has been taken into account, thereby removing a few of the points above the line and additionally some of the galaxies with the highest 2D-separation. Without the f_{use} the upper limit on 2D-separation is 0.3".

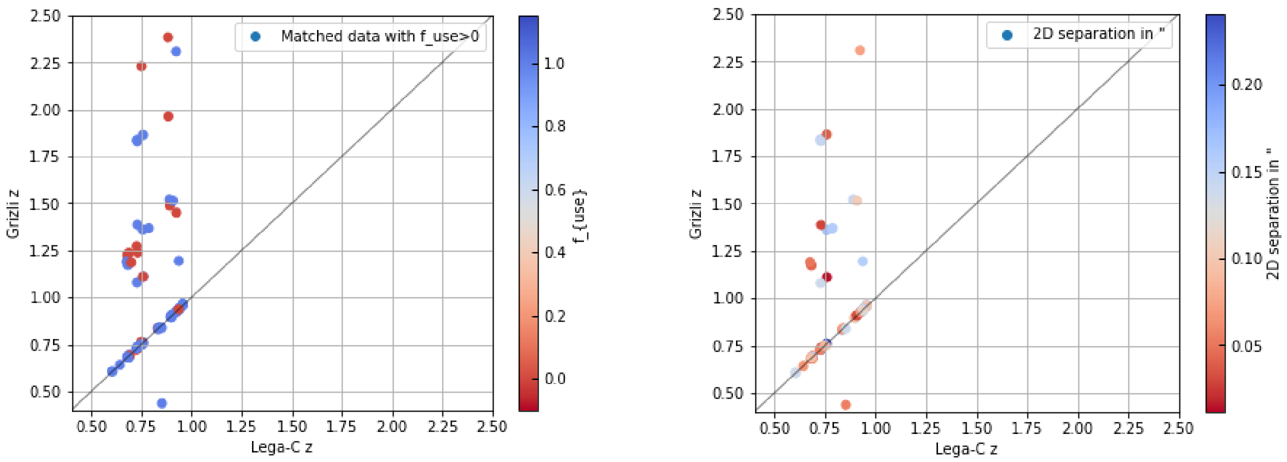

Figure 9: Lega-C and 3D-HST spectroscopic redshifts. The points on the line have the same redshift for both surveys. On the left side graph the points are coloured by the Lega-C flag f_{use} with blue corresponding to a value of 1, meaning it has been flagged useful. On the right side graph the points are coloured by their 2D separation on the sky in arcseconds and the 'use' flag has been applied to remove 'bad' data.

4.2 Is This Sample Representative?

To check whether the matched Lega-C + 3D-HST sample is representative of the Lega-C sample as a whole, we look at whether it covers the same ranges, in several parameters, as the parent samples do.

In terms of star formation rate (SFR) and stellar mass($M_\odot$) we see on the righthand graph in Figure 15 that despite the size of the sample, it covers most of this particular parameter space making it a good representation in terms of $M_\odot$ and SFR.
Looking at Figure 9 and considering the redshift range of Lega-C and 3D-HST the sample also proves representative as it covers almost the whole range from 0.55 to 1, even considering only the ones where the 3D-HST and Lega-C redshifts are the same.
In terms of locations on the sky they span over most of the 3D-HST area, though this is the limiting factor as the parent sample area is much smaller for the 3D-HST sample than for the Lega-C sample, though the empty spot in the top left corner of the 3D-HST area comes from Lega-C not having data in that area.

From the UVJ-diagrams in Figures 11 and 15 it can be seen first and foremost that the sample covers a great range of colours and from the separation defined by Muzzin et al.[2] it covers both quiescent and star forming galaxies. These figures also show a broad representation of $H\delta$ and $H\alpha$ values and a wide range of stellar velocity dispersion, though slightly dominated by higher values there.

To conclude the sample is properly representing the parent sample.

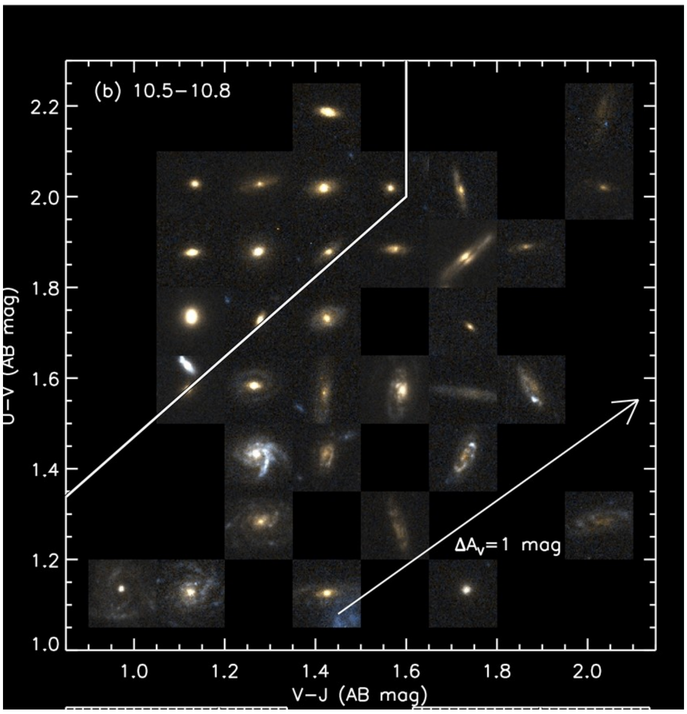

Figure 10: UVJ-diagram with images of galaxies depicting how ellipticals, edge-on spirals and face-on spirals segregate. Image from Patel 2012.[10]

5 Discussion

We will now look at the behaviours of galaxies in the context of a UVJ-diagram, that is a diagram with the V-J colour magnitudes of the galaxy on the x-axis and the U-V colour magnitudes on the y-axis. Typically in UVJ-diagrams we see a bimodal split, one track extending diagonally from blue to red V-J and then a collection of galaxies clustering at red U-V but blue V-J a bit above the track. This has been found to be a segregation between the Star Forming (SF) track and a Quiescent (Q) cluster in the top left corner. These distinctions are directly related to the "blue cloud" and "red sequence" in Figure 7. This is the strength of the UVJ-diagram, it allows us to see the clear difference between red SF and red quiescent galaxies. In general galaxies with blue U-V colors are galaxies with clear ongoing star formation, whereas red galaxies can be both quiescent galaxies with an evolved, older population or it can be dust-reddened star forming galaxies. In the UVJ-diagram though, the dust-free and quiescent galaxies are instead blue in V-J, and therefore place themselves in the upper left corner, segregating from the star forming track. From Figure 10 we are able to very clearly see where certain galaxy types reside. In the top left corner within the white line, we see the elliptical and circular, mostly featureless galaxies with no on-going star formation, furthermore most of them appear yellow or orange. In the bottom left corner, we see the face-on spiral galaxies, with clear spiral arms featuring a clear blue colour. Moving along the track to the top right corner, the galaxies become more edge-on, making the spirals appear more yellow. This happens because when seeing them edge-on, all of the light from within the galaxy has to pass through the dust inside the galaxy itself, and the total light from it is thereby reddened and moved up this track. Conventionally the U-B colour is used because it better depicts the narrow 4000 Å break characteristic of an old population, but this depends on photometric redshifts that often come with large uncertainties. The U-B is therefore not sufficiently accurate in comparison.[9]

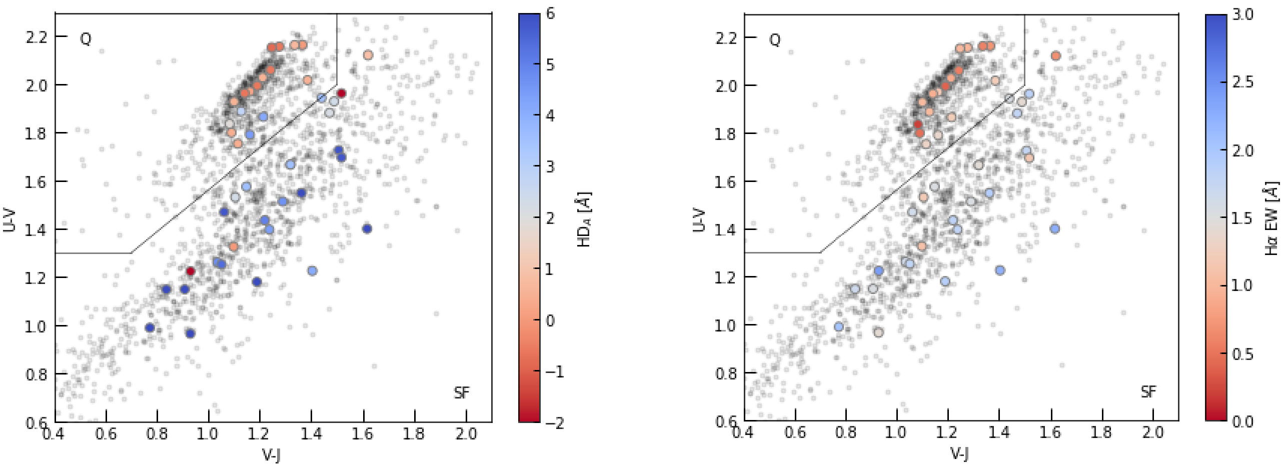

Figure 11: UVJ-diagrams with the left panel colour coded by $H\delta_A$ and $H\alpha$ in the right panel and the grey points are the full Lega-C sample. The letter Q designates Quiescent and SF designates Star Forming and the separation is given by the definition in [2].

5.1 H_α and H_δ dependency

With out detailed Lega-C + 3D-HST spectroscopic observations, we can now more precisely study the qualitative trends of the UVJ-diagram discussed above. As seen in the left panel of Figure 11 we notice a trend, the quiescent galaxies on average have much lower values of $H\delta$ than the star forming galaxies with $H\delta$ decreasing towards redder U-V and bluer V-J colours. In the right panel we see the same trend with $H\alpha$ suggesting there is a connection between Hα and Hδ lines. When we compare this to Figure 12 it makes perfect sense that they show the same trend because they are both indicators of star formation or lack thereof.
There are two very obvious 'outliers' in Figure 11. The two dark red points. The one in the lower left corner has a much lower value of Hδ than the trend would suggest and it should therefore be

examined whether the measurements for this particular galaxy is riddled with error. When looking at it's spectrum though it was found that it is an accurate measurement and not a problem with the data, making it an interesting subject for possible further research. Another point that is a bit of an outlier is the pink point at the top right corner. The reason it is so far up in the UVJ-diagram is most likely that it is very dusty which would as seen earlier make both the U-V and V-J colours redder.

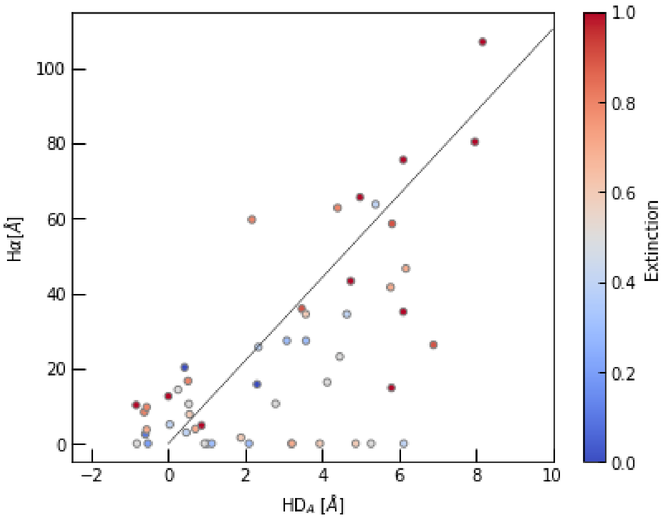

Figure 12: Hα line strength vs Hδ line strength that shows a weak linear correlation between the two. The line plotted is the relative strength of the Hα to Hβ lines, divided by the relative strength of Hβ to Hδ.

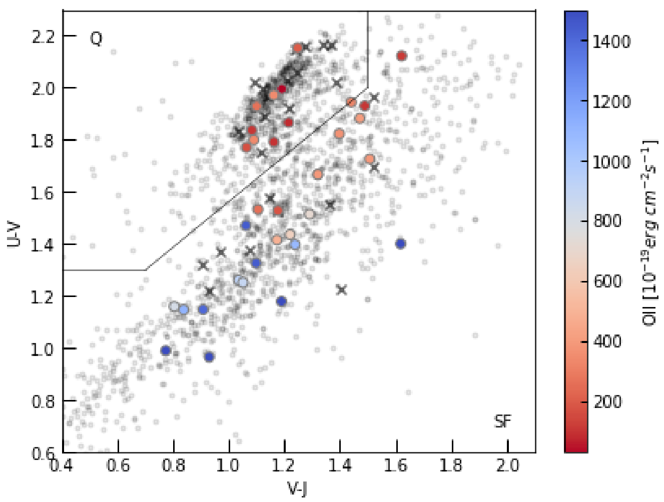

Figure 13: UVJ-diagram colour coded by [OII] line flux and the grey points are the full Lega-C sample. Black X'es are galaxies without an [OII] measurement.

In Figure 12 the line plotted is the relative strength of the Hα to Hβ lines, divided by the relative strength of Hβ to Hδ. Here we expect the points to lie above the line because the inevitable dust we observe through will redden bluer wavelengths more than red, and therefore weaken the Hδ line more than the Hα. What we see is more of an even spread on both sides of the line which could be due to large errors on the Hα values.

Comparing the right graph in Figure 11 with Figure 13 we notice the same trend for [OII] as for Hα with only low value [OII] galaxies within the quiescent region of the plot, and mostly high values of [OII] in the SF region. This corresponds well with both Hα and [OII] being indicators of star formation. There is also a somewhat intermediate region showing a transition between the two regions where the [OII] values are around 600. This could suggest that when a galaxy goes from star forming(designated by SF) to quiescent (designated by Q) organically it wanders from the bottom of the diagram and upwards while also slowly decreasing the [OII] line intensity. They could also be PSB galaxies in the phase of transitioning from SF to Q galaxies.

Looking at Figure 14 we expect the same as from Figure 12. We want the points to be above the line due to the [OII] line being at a lower wavelength than Hα and thereby more obscured by dust, and here we do observe this trend. Most of the points are above, and most of the points below have high extinction telling us that they have probably been reddened so much that it also affected Hα significantly.

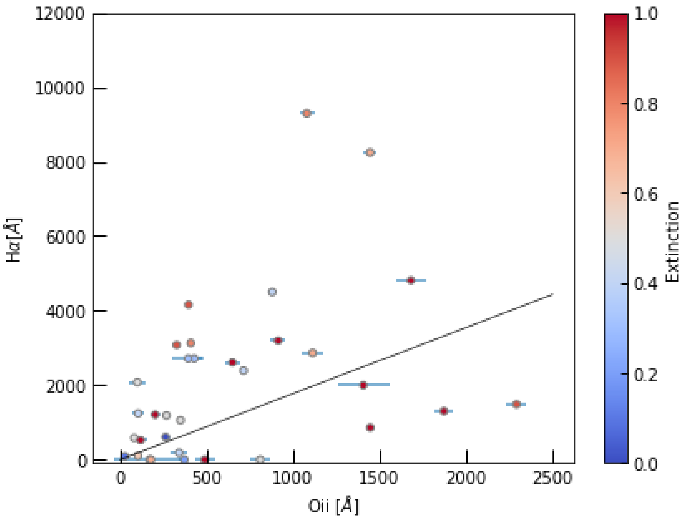

Figure 14: [OII] line strength vs. Hα line strength. The line is computed from the constant from which you can get the SFR from [OII] luminosity divided by the same constant for the Hα luminosity.

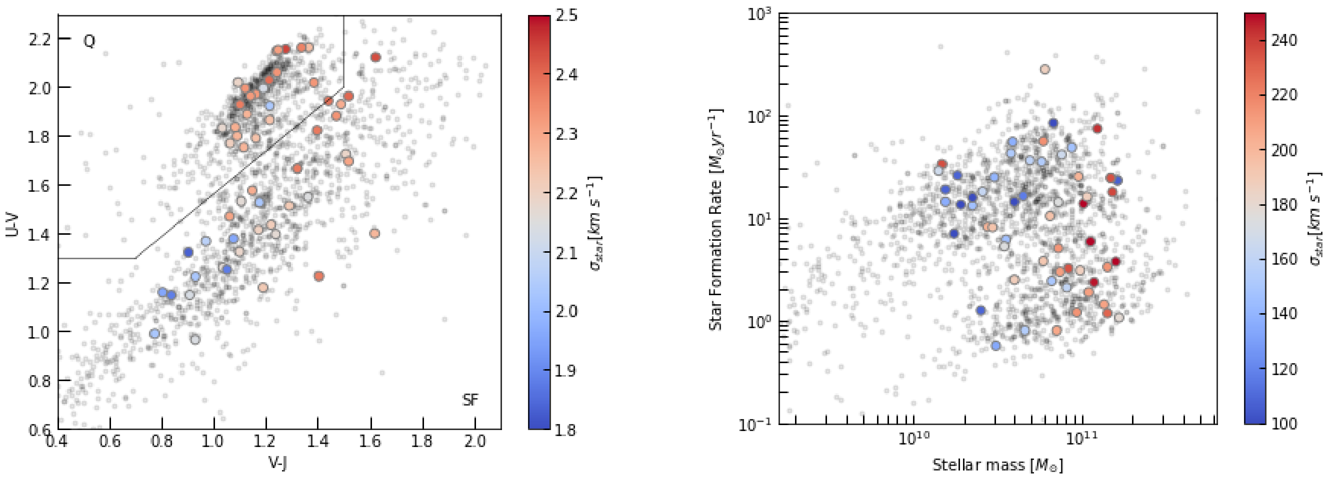

Figure 15: On the lefthand graph is a UVJ-diagram colour coded by the stellar velocity dispersion and the grey points are the full Lega-C sample sample. On the righthand graph is the stellar mass in solar masses versus star formation rate in solar masses per year, for the Lega-C galaxies. The grey points represent the full Lega-C sample and the coloured points are the galaxies matched with the 3D-HST sample and coloured by their stellar velocity dispersion.

5.2 Velocity Dispersion and Stellar Mass Dependency

On the lefthand graph in Figure 15 the trend is the opposite of $H\delta$ and $H\alpha$ with increasing σ_{stars} with redder U-V colour though it is a less obvious trend with most showing higher σ_{stars}. This agrees with the observed trend in (Straatman et al.)[1] where they find that the observed σ_{stars} increases towards redder U-V and a lower σ_{stars} for the post-starburst population. Likewise we also find the highest values to be not only for the quiescent galaxies, but also for the redder SF galaxies, and the lowest values for SF galaxies.

On the righthand graph in Figure 15 the sample is colour coded by their σ_{stars} and are plotted over the parent sample. There appears a somewhat obvious bimodality. Higher masses have higher velocity dispersion and lower SFR. We also see that for a fixed stellar mass quiescent galaxies have higher velocity dispersion.[7] In summation, older quiescent galaxies have higher velocity dispersion than younger star forming galaxies. This is the same trend that is seen in (van Der Wel et al. 2016) where they look at our parent sample.

6 Results: Complete Spectra and Models

When modelling these spectra we use population synthesis models from the Flexible Stellar Population Synthesis(FSPS) code. The models of this code essentially sum up the spectra of a distribution of stellar types and ages to create a simulation of the stellar population of the fitted galaxy. These models are in general calibrated with observations of the nearby Universe. This means that their applicability to the stellar populations of galaxies at an earlier cosmic time is not trivial, which is what we wish to investigate here.[12][13] In Figure 16 we have the grey data from the Lega-C

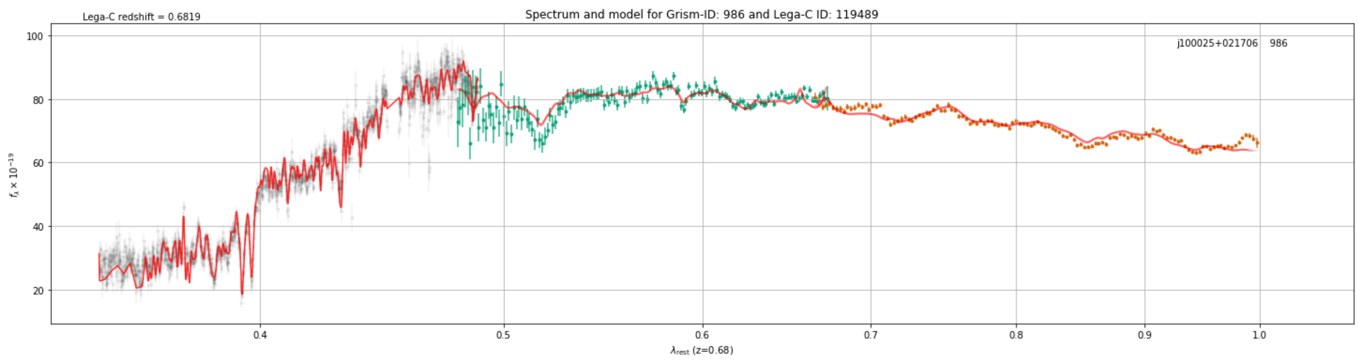

Figure 16: Full spectrum for the galaxy with 3D-HST group ID: 986. On the x-axis the unit is Angstrom and on the y-axis the unit is $\frac{erg}{cm^2 \cdot s \cdot \mathring{A}}$. The left, grey part is Lega-C data, the middle green part is data from the G102 grism and the right, orange part is data from the G141 grism. The model is fitted to the spectra over all, also using velocity dispersion and redshift from the Lega-C data.

survey, the green data from the G102 grism and the orange data from the G141 grism. This particular spectrum was chosen, because it was one of only two final candidates that had data in both Lega-C, G102 and G141, currently making it the most complete spectrum at this redshift. The other of the two had most likely been contaminated by the spectrum of a neighbouring object and was therefore not fit for analysis.

The reason the model seems to overlap poorly between the Lega-C and G102 data is because the software fits the 3D-HST data and Lega-C data independently and furthermore they might not have been scaled perfectly through the software either. Looking at the spectrum the first thing that comes to mind is an old galaxy that is elliptical or an S0 type spiral galaxy, reminiscent of the nearby galaxy seen in Figures 3 and 4. There are no emission lines that stand out from the rest of the spectrum as there would be in a galaxy with ongoing or recent star formation. We do not see a lot of weak absorption lines and curves though. In fact if we compare this to the spectrum of an elliptical galaxy, one dominated by the old M and K stars, they look strikingly similar. Noticeable are the 4000 Å break and the G-band around 4300 Å.[6] Around 6580 the model seems to predict a small peak which would would be an Hα line, though it doesn't appear in the actual data. Two strong absorption lines that the model predicts, which are also in the spectra are the 5175 Å Magnesium line and the 5892 Å Sodium line. These two are some of the stronger features of a typical S0 or elliptical galaxy.

As a total the model gives a very good picture of the galaxy matching almost every single emission and absorption line in the spectrum for this galaxy. It gives a more nuanced picture of the lines in the Lega-C part of the spectrum, which is due to the much higher resolution of this data and that was to be expected. For the Lega-C part of this model, the χ^2 value is a beautiful 1.06, which supports the claim that the model generally fits well. For the G102 and G141 the χ^2 is also as low as 1.08. This just tells us that for this galaxy the model actually gives us a very accurate depiction of the galaxy spectrum.

In Figure 17 the grey data is the Lega-C data and the orange data is from the G141 grism. This spectrum was chosen because it had a high enough redshift that the Hα emission line would be within the observable part of the spectrum - and had clear emission lines. In the left part of the spectrum, the most noticeable feature is the emission line right at 5000 Å, this would be the 5007 Å line originating from [OIII] and next to it the half as high 4959 Å emission line, also from [OIII] - not to be confused with the SFR indicator [OII]. Left of these two is the 4861 Å emission line from Hβ. Further to the left around 4300 Å appears a large absorption cleft coming into a peak on the right side of it, this peak is very likely the 4101 Å Hγ emission line. Now looking at the data on the right, there is the very obvious mountain that is the 6563 Å and 6583 Å Hα emission lines with the little bump on the curve being the 6716 Å and 6731 Å SII(Sulphur II) emission lines. Just past 9000 Å we see another small bump, this one being the 9068 Å SIII emission line, and another SIII emission line at 9532 Å.

The Hα indicates a strong, ongoing or recent star formation period, probably making it a young, spiral galaxy or possibly a starburst galaxy. The biggest difference between a starburst galaxy and a young Sc galaxy is to be found at lower wavelengths than this was observed at due to the high redshift. By the presence of the clear emission lines at higher wavelengths, the fact that the Hδ is visible within the dip, and the relative(to the spectrum) strengths of the Hα and [OIII] emission lines, it can be assumed to be a starburst galaxy, though the many small wiggles in the data would suggest the spectrum is more alike an Sc spectrum.[6]

For this galaxy the model makes a good fit, but it is obvious that the high resolution of the actual data on the left is difficult for the model to take into account, perhaps lowering the resolution of the data would help here. The χ^2 for the Lega-C part of the spectrum is a slightly higher 2.15, agreeing with the fact that it hasn't fit the emission lines as well, which is also more difficult compared to a relatively flat spectrum as in Figure 16. On the righthand data it also seems to miss some peaks though still making a rather good fit with a $\chi^2 = 1.070$. The software probably assumes it to be a starburst galaxy with a very smooth spectrum, when it could just as well be an Sc galaxy with more small peaks.

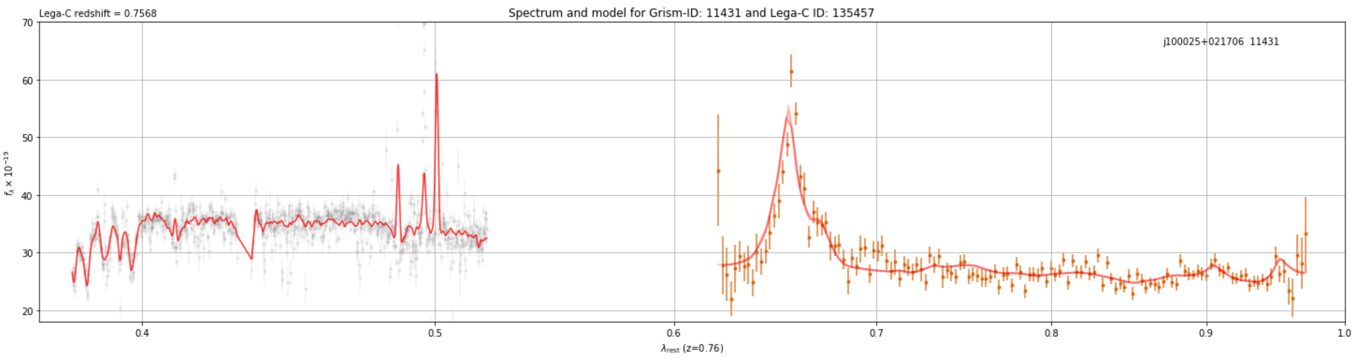

Figure 17: Full spectrum for the galaxy with 3D-HST group ID: 11431. On the x-axis the unit is Angstrom and on the y-axis the unit is $\frac{erg}{cm^2 \cdot s \cdot \mathring{A}}$. The left, grey data is Lega-C data and the right, orange part is data from the G141 grism. The model is fitted to the spectra over all, also using velocity dispersion and redshift from the Lega-C data.

7 Conclusion

Using the data from the 3D-HST survey and the Lega-C survey, we were able to look at some key parameters such as stellar masses and SFR through emission lines from the spectra. We were also able to compose a representative sample of galaxies at a redshift up to 1 and study their properties as a population to find trends in galaxy distributions. Furthermore we were able to compose complete spectra of more than 50 galaxies at redshifts up to 1. We were also able to apply models to some of these spectra and study which emission and absorption lines were in the two chosen spectra. Additionally we calculated χ^2-values for both models and found them to be good fits for both the Lega-C and 3D-HST data for both galaxy spectra.

Some great possibilities for further work would be applying models to more of the galaxies, and finding the strengths and flaws of the models to improve them for further use. Additionally, if we started looking more thoroughly at every single galaxy in the sample, we would likely find some more galaxies with data that could not be used, but also more interesting galaxies to study further.

The data could also be used to study the evolution of galaxies further to understand our galactic neighbourhood better.

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