1 Purpose and aims

We propose a comparative study of rest-frame ultraviolet (UV) and optical spectra of a sample of strongly star-forming galaxies in the local Universe and a sample of gravitationally lensed galaxies at redshifts $1 \lesssim z \lesssim 3$, corresponding to a time span from around 15% to 40% the age of the Universe, the time at which the majority of stars in the Universe were formed.

For the local Universe, we wish to combine archival far-UV spectra from the Hubble Space Telescope (HST) Cosmic Origins Spectrograph (COS), as well as an ongoing observational campaign with same instrument, and ancillary data from the Sloan Digital Sky Survey (SDSS).

At high redshifts, we have a sample of gravitationally lensed galaxies Observed with spectrographs at the Keck and Magellan observatories. Due to the gravitational lensing effect, these objects are spatially resolved and have very high signal-to-noise ratios, allowing to study them in a level of detail usually not attainable at these distances. We propose to give a standardized treatment of galaxies at all redshifts, allowing for direct comparative studies of their properties and enabling us to identify and characterize evolutionary trends. Furthermore, we aim to employ the results of these comparative studies to improve the understanding of spectral features which are expected to become extremely important tracers of cosmological parameters in the earliest epochs of the Universe with the launch of the future James Webb Space Telescope, scheduled in 2018.

The project is expected to **a)** improve our understanding of star formation in the Universe and the highly complex processes governing gas in star-forming galaxies, **b)** study how these have evolved over cosmological time spans, and **c)** use these insights to help design observation strategies for the first galaxies in the Universe with the future James Webb Space Telescope (JWST), scheduled for launch in 2018.

2 Survey of the field

Some galaxies undergo episodes of extremely high-paced star formation, during which their neutral gas is turned into stars at rates much higher than in typical, quiescent galaxies. The high star formation rates mean that these galaxies also have an extraordinary large population of the hottest and most massive, but also very short lived, type O and B stars. These stars radiate a large part of their energy output in the hard ultraviolet wavelength ranges. This highly energetic radiation strongly affects the surrounding gas, ionizing and heating it, resulting in strong line emission by cascading recombining or decaying, collisionally excited electrons. Radiative pressure and stellar wind from the hot stars and kinetic energy from frequent supernova blasts stir up the gas, resulting in bulk outflows and strong velocity gradients in the neutral gas. The star formation episodes are often triggered by merging or interactions with other galaxies of intergalactic gas, which further adds to the kinematic complexity of these galaxies. The feedback from young stars and supernovae can accelerate substantial bodies of gas to escape velocity,

The spectrum of starburst galaxies is dominated by the smooth continuum emission of young, hot type OB stars, with strong emission peaks from atomic and ionic lines superimposed onto it. The intrinsically strongest of these lines by a broad margin is Lyman α, the transition between the ground state and the first excited level of neutral Hydrogen. As much as 2/3 of all ionizing photons, and 1/3 of the total ionizing energy, gets reprocessed into this single, narrow emission feature (Dijkstra, 2014). The strength means that this line is often detectable in narrow filters when the galaxy is otherwise too faint to be observed in stellar continuum or other emission lines, and its location in the far-UV range means that it stays within the transparent windows of the Earth's atmosphere even at high redshifts. This renders Ly α a crucially important tool for detecting galaxies of low stellar mass but strong star formation – which are abundant in the early universe – and for spectroscopically verifying redshifts, which can only be determined very crudely by imaging techniques. In cosmology, this helps more accurately mapping galaxy positions, masses, clustering properties, etc. and thus trace not only galaxy evolution, but also cosmological phenomena like structure formation and the ionization history of the Universe.

Lyman α is however a strongly resonant line, interacting strongly with the neutral gas in the galaxies where it arises, and is very vulnerable to absorption by dust. The strong scattering affects both the observed morphology, strength and spectral line profile of the transition in ways depending intricately on a multitude of parameters like neutral gas column density, clumping, bulk outflows, dust content, kinematic line widths and others (e.g. Wofford et al., 2013; Atek et al., 2008, 2009; Rivera-Thorsen et al., 2015; Kunth et al., 1998; Giavalisco et al., 1996; Östlin et al., 2014; Hayes et al., 2014), and the observed properties in Lyman α are statistically almost completely decoupled from its intrinsic properties. For the Lyman-α observed to be correctly interpreted – e.g. regarding how large a fraction of galaxies at high redshifts are expected to be detectable in a given survey, or what the typical masses of said galaxies are, etc. – it is necessary to know which mechanisms regulate Lyman α radiative transfer and escape, and how they interact. Multiple studies have been made to map this (e.g Atek et al., 2008, 2009; Hayes et al., 2005, 2007, 2009; Östlin et al., 2009; Kunth et al., 1998). The most ambitious such study is the Lyman Alpha Reference Sample (LARS, Hayes et al., 2013; Östlin et al., 2014; Hayes et al., 2014), a study of a sample of intrinsically Ly α-bright, strongly star forming galaxies at multiple wavelengths and using using multiple instruments, from X-ray observations to 21 cm radio interferometry. The aim was to understand these galaxies in depth and create a baseline of comparison to observations at high redshifts. For this project, I led the production of Rivera-Thorsen et al. (2015), in which we analyzed far-UV absorption lines in spectra of the sample galaxies obtained with HST-COS. We analyzed the connections between physical parameters like line width, outflow velocity, column density, and with global parameters determined from imaging (Hayes et al., 2014) and radio observations (Pardy et al., 2014), and basic properties of the observed Lyman α line.

The galaxies of LARS are however only a fraction of the low redshift star-forming galaxies that have been observed with HST-COS. A number of other samples, including the references mentioned above, exist, all selected from various criteria but with a moderate-to-strong star formation activity, totalling around 80 galaxies by out current estimate. A uniform and carefully designed analysis of these in the same way we did for Rivera-Thorsen et al. (2015) and Rivera-Thorsen et al. (2017) is the aim of the first partial project of this proposal. We also plan to complement this research with a single-object study of unprecedented depth and detail, through data currently being acquired with Hubble Space Telescope. What the archival study provides in width, this study provides in depth; and together, they could yield very important insights into the nature of starburst galaxies and the connections between star formation and the gas from which they form.

Galaxies at high redshifts ($z \gtrsim 1$) are generally too distant to be resolved even with the best telescopes, or just barely resolvable. However, if the line of sight to the galaxies have a massive galaxy or galaxy cluster, the gravity of this can bend the light from the background source and act as a naturally occurring lens, magnifying the image and amplifying its light by orders of magnitude. **Project Megasaura** is a sample (PI: Dr. Jane Rigby, NASA Goddard Space Flight Center) of 17 such gravitationally lensed galaxies at redshifts $1 \lesssim z3$. Thanks to the strong lensing, these galaxies are sufficiently bright that they can be observed in strong continuum, such that an absorption line analysis is possible, which does not happen often at these distances. Furthermore, the data quality is good enough that spatially resolved studies are possible. The spectra cover a rest-frame wavelength range containing, but not limited to, the one of most of the local-universe HST-COS spectra, containing most of the spectral features of the local galaxies, allowing for an apples-to-apples comparison of spectral features between the high and low redshift samples. In particular, the SNR is good enough to determine systemic zero-point velocities for the galaxies from stellar absorption and nebular emission, something which has been a problem for past works of this kind (e.g. Jones et al., 2013). Furthermore, the Lyman-α lines are in some cases well enough resolved that it can be compared to a grid of existing semi-analytical outflow and radiative transfer models (Schaerer et al., 2011). This is to our knowledge the first time it is possible to run analyses designed for the data quality of local-universe objects to be put to use on objects at such large distances, and it would be of great interest to see how the connections between ISM conditions and Lyman α line properties compare to those we know from the local Universe.

The spectra for Project Megasaura also contain a number of near-UV emission lines which are not usually observed in local samples due to the wavelength coverage of the detector at COS. Most important is the semi-forbidden line C III] λ 1909. As surveys push past redshifts $z \gtrsim 7$, we look into a time when the first galaxies had not yet fully ionized the intergalactic gas in the Universe, and the amounts of neutral gas present in the Universe at these early times strongly suppress Lyα which we rely on at lower redshifts. Spectroscopic confirmation of redshifts this high must rely on detection of alternative rest-frame UV emission lines, and the C III] 1909 and its forbidden [C III] 1907 line are promising candidates (Stark et al., 2014; Jaskot & Ravindranath, 2016). The lines are however not universally present in star-forming galaxies (Rigby et al., 2015); the line strength seems to be correlated with extreme starburst conditions like high ionization, low metallicity, and hard UV spectrum (Stark et al., 2014; Jaskot & Ravindranath, 2016). The presence of these lines in combination with the ones used for our usual diagnostics will allow to establish better connections between these lines and physical conditions in the ISM of the galaxies, and establish or describe with better precision which biases etc. are related to the detection of these lines: Which galaxies are detected in these lines, how strongly, which galaxies and how many go undetected, etc. These insights are of great importance for designing observation strategies for galaxies at extremely high redshifts with the upcoming James Webb Space Telescope, and this research could help put us at the forefront of research with this extremely important telescope once it is launched in 2018.

3 Project description

We wish to carry out a project with two main parts: one at low redshifts and one at high redshifts. Both aim to understand the intricate and complex mechanisms that govern star formation and feedback, and some of their most important observational signatures. The datasets available provide us with a unique opportunity to analyze these galaxies in a uniform way and thus draw evolutionary connections in these mechanisms from times when the universe was only around a quarter of its current age, and to the present day. This is possible thanks to the natural lensing effect of the gravity of foreground galaxies, which enhance and amplify the light of these distant galaxies enough to give a much higher data quality than could otherwise have been reached.

Local universe

Archival starburst galaxies with HST-COS

Far-UV spectroscopic observations of star-forming galaxies in the local Universe have been done for a number of years now, with various aims, purposes and selection criteria(e.g. Heckman et al., 2011, 2015; Alexandroff et al., 2015; Wofford et al., 2013; Henry et al., 2015; Rivera-Thorsen et al., 2015). For the first subproject, we wish to obtain archival data from a number of such campaigns including, but not limited to, the ones mentioned above, totalling around 70 galaxies, all observed with the Hubble Space Telescope Cosmic Origins Spectrograph, along with auxiliary data from e.g. SDSS and other large samples where available. We will then analyze these spectra in a uniform way, extending the coverage of galaxy types, masses etc. of the Lyman Alpha Reference Sample, and dramatically improving the statistical significance of the original sample. Besides measuring

SAFE: Star formation, lyman-Alpha, and Feedback in Eso-338

Complementary to the statistical sample, this subproject takes the opposite route by studying one single target in a detail unprecedented in the far Ultraviolet wavelength range. SAFE is an ongoing campaign led by Prof. Östlin at Stockholm University, using HST-COS to take far-UV spectra of a particularly interesting galaxy, known as ESO 338-IG04, placing the circular aperture of the Cosmic Origins Spectrograph on board the Hubble Space Telescope on 12 different locations of the galaxy, covering both luminous regions of strong star formation, and the faint and diffuse gas in the outskirts of the galaxy, allowing to perform a tomographic study of its interstellar and circumgalactic gas. The method is akin to Integral Field Spectroscopy, in which a spectrum is acquired for each pixel in an image grid; but the far-UV wavelengths cannot penetrate the Earth's atmosphere, and no spaceborne integral field units exist. Combined with results from previous observations with e.g. HST imaging (Hayes et al., 2009; Östlin et al., 2009; Östlin et al., 1998), The ESO X-Shooter optical spectrograph (Guseva et al., 2012; Sandberg et al., 2013, Rivera-Thorsen et al., submitted to ApJ), and the MUSE optical integral field spectrograph (Bik et al., 2015), these observations are expected to yield important new insights about stellar population, ISM distribution and dynamics, and Lyman α radiation transfer.

High-redshift universe

Project Megasaura

Project Megasaura is a sample of 17 star forming galaxies at redshifts between 1 and 3, corresponding to times when the Universe was between 15% and 40% of its current age. These galaxies are strongly lensed by foreground galaxies or clusters. The galaxies have been observed in the optical and infrared with Magellan/MagE and Keck/ESI, and imaged by HST and Spitzer. The strong lensing gives an unusually fine signal-to-noise, allowing for detailed studies in both emission and absorption. In itself, the sample is a unique opportunity to study star-forming galaxies in the epoch where the majority of stars in the Universe were formed, including stellar population, ionization conditions, electron temperatures, detailed outflows, chemical enrichment, and more. However, together with a local sample, it also holds the promise of disentangling intrinsic, evolutionary changes over cosmic time from changes in cosmic environment, and help understand star formation, galaxy evolution, and Lyα transfer and escape both locally and in the early Universe. Besides a comparative study of these properties at high and low redshifts, we also plan to study in details some of the near-UV emission lines present in the Megasaura datasets. As mentioned above, these lines are seen as promising tools for observations at extremely high redshifts with JWST, and the presence of these lines together with the ones used for our local-Universe diagnostics gives us a unique opportunity gain insights about the physics governing the observable fingerprints of these lines and thus help design observational strategies for observing the first galaxies once JWST has been launched.

Preliminary timeline

Months 1 – 6 Local star-forming galaxies. This project is fairly straightforward regarding methodology and well-defined in scope, and much of the machinery for the analysis is already in place from earlier work (Rivera-Thorsen et al., 2015,?). However, some measure of manual work is required, which will of course mean an increase in time requirements with around 80 objects expected to be suitable for the project.

Months 7 – 16 Megasaura I. Comparative study of lensed galaxies with the local galaxies studied in the first paper.This paper will present the sample and characteristics that are directly comparable to the low redshift sample like characteristics like e.g. stellar population, gas and dust content, temperature, heavy element enrichment, characterization of gas in- or outflows etc., analogous but not limited to what is listed in Tables 2 and 3 of Östlin et al. (2014) and parts of what is presented in Rivera-Thorsen et al. (2015). Like the previous paper, we expect there to be a comparatively large amount of work performing a large number of diagnostics and characterizations for the sample galaxies.

Months 17 – 24 Megasaura II. In this project, we plan to focus on the near-UV emission lines of the lensed galaxies. Star-forming galaxies are not well studied in these lines; at low redshifts they fall in a range of poor detector coverage of the HST/COS; and at higher redshifts, they are often too weak to be observed with current instruments. With the coming launch of the JWST, however, these lines are going to play an important part in pushing the limits for high-z observations. High-redshift galaxies are typically detected by their Lyman emission, but at redshifts beyond $z \sim 7$, the neutral fraction of the IGM is high enough to effectively quench the majority of Lyα radiation. The JWST will on the other hand be able to reach much deeper and detect these metallic rest frame NUV lines, like e.g. Mg II, C III], and Fe II. The combined findings of Megasaura I and the Local HST Legacy Starbursts will provide the foundation to better understand and interpret these lines.

Months 25 – 30 (?) SAFE I. SAFE contains enough data that two years' activity could probably be dedicated to analyzing this dataset alone. How much time should be dedicated to this depends on the initial results of data analysis, weighed up against which questions arise during the work on the two Project Megasaura papers. A short version of a SAFE paper should at least consist of a mapping of the neutral and ionized ISM phases along the line of sight towards the clusters in the relevant pointings, a characterization of Lyman α in all COS pointings. This will provide a detailed mapping of properties directly comparable to, but more detailed than, the ones known from the Lyman Alpha Reference Sample and from the first projects of this proposal, and could help discern various possible explanations for e.g. observed Lyman α. A further elaboration on this work could either be in collaboration with modeling experts (Schaerer et al., 2011; Laursen et al., 2009a,b; Gronke & Dijkstra, 2016; Verhamme et al., 2006, 2008) or, if the data quality of the Megasaura galaxies permits it, comparative spatially-resolved studies based on these and SAFE, like an extended version of the work presented by Bordoloi et al. (2016)

4 Significance

This is to our knowledge the first time it will be possible to bring high quality diagnostics designed for galaxies in the local Universe to use at such high redshifts, which can yield important insights about the star formation history and galaxy evolution of the Universe.

The proposed project will also help to better understand the nature of star forming galaxies in the local Universe by dramatically improving the sample size and statistical robustness of existing studies like e.g. Rivera-Thorsen et al. (2015), and improve the coverage of galaxy types in terms of e.g. stellar population, mass, ionization, metallicity, etc.

The SAFE sub-project will bring unprecedented detail in the study of the Lyman α line and how it is influenced by gas properties in the emitting galaxy, which in turn is important to our interpretation and understanding to large amounts of cosmological data based in this line.

The direct comparison between observational signatures at high and low redshifts will allow us to calibrate our understanding of near-UV emission lines which will play a crucial role in future studies pushing the frontier of how far and deep into the early Universe we can see with the launch of the James Webb Space Telescope.

5 Preliminary results

The local starbursts subproject, which is planned to be the first step, builds on analysis done and developed for the Lyman Alpha Reference Sample (Rivera-Thorsen et al., 2015), but aims to extend the statistical robustness and parameter space coverage of this work. This means that the methodology is tested and known to work, and much of the machinery for this analysis is in place. This machinery will also be used for parts of the SAFE project and, in a shape modified to be appropriate for the different data format etc., also for one part of Project Megasaura. Much of the rest of the work will rely on well known astrophysical diagnostics.

6 Results

With this project, we expect to gain important understanding of the conditions under which the majority of stars in the Universe have formed.

We expect to gain new insights about both local an distant galaxies undergoing episodes of intense star formation, and how they influence and are influenced by their environment, and to draw evolutionary connections from a uniform analysis of galaxies at different redshifts.

We expect to get improved knowledge of connections between Lyman α escape and a set of key observables in the local universe, how these change under varying circumstances, and how they compare to the situations in the early, high-redshift universe.

We expect to be able to answer at least a subset of these questions for galaxies at larger distances and earlier phases in Cosmic history, and look at how these connections and mechanisms have evolved in time.

We expect to be able to draw connections between astrophysical properties of the galaxies and the observational signatures of key emission features in the near-UV, which are expected to be crucial for galaxy studies at extremely high redshifts which will be made possible by the James Webb Space Telescope, and we expect this to bring valuable contributions to the design of observation strategies to look for the first galaxies in the Universe with JWST.

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