Star formation, feedback and Lyman α over cosmological time

Project overview

Main goal: To investigate the nature of star-forming galaxies in the epoch when the most stars in the Universe were formed (redshift 1-3), and how they compare to star forming galaxies in the local Universe, ultimately attempting to disentangle intrinsic properties of the galaxies from environmental differences over cosmological time spans.

Short outline: We propose a two-pronged project consisting of a local-Universe and a high-redshift part. In the local-universe part, we propose to combine Hubble Legacy observations of various samples of local star-forming galaxies, including but not limited to programs 11727, 13017 (PI Heckman), 12928 (PI Henry), 12539 (PI Bergvall), and 11522, 12027 (PI Green), totalling an estimated 50 objects spanning a number of samples and papers (e.g. Wofford et al., 2013; Alexandroff et al., 2015; Heckman et al., 2015; Henry et al., 2015). The idea is to give then a homogeneous treatment in inspired by the applicant's earlier work on the Lyman Alpha Reference Sample (LARS, Östlin et al., 2014; Hayes et al., 2014) presented in Rivera-Thorsen et al. (2015) (hereafter RT15), to expand the coverage of galaxy ages, masses etc. presented herein and provide a more statistically solid basis for comparison. On top of this, data is currently being acquired with HST of the nearby starburst ESO 338-04 (SAFE, GO 14806 PI: stlin); 2 pointings with STIS and 12 pointings with COS, covering both hot central star clusters and the outer, diffuse Lyα halo tracing (parts of) the galaxy's neutral gas. Part of my project would be the analysis of these data, carrying out a careful mapping and characterization of its ISM on a (coarsely) spatially resolved basis.

At high redshifts, I propose an analysis of spectroscopic rest-frame optical and UV spectra from Project Megasaur (PI: Rigby), observed with Magellan/MagE and Keck/ESI of 17 lensed, star-forming galaxies at $1 < z < 3$. The high signal-to-noise ratio of these spectra, and the fact that the objects are spatially resolved due to lensing, makes them ideal for bridging the gap between high- and low-redshift samples: They have high enough redshifts for cosmological evolution to be significant, while simultaneously being of high enough quality that detailed analyses of Lyα, stellar and nebular metal absorption lines, nebular emission etc., like the ones done on the local samples, is possible. Thus, a detailed, multi-parameter characterization is possible of these objects, allowing to thoroughly evaluate differences and similarities between these and the local objects. The lensed spectra contain a wealth of rest-frame NUV lines, including nebular emission in e.g. Mg II and Fe II (see e.g. Bordoloi et al., 2016; Rigby et al., 2015), which are typically not included in the low-redshift HST-COS samples due to the detector range of the COS. These lines are going to play a very important role in deep, high-redshift galaxy surveys with the upcoming James Webb Space Telescope (JWST). With a homogeneous, larger COS sample of local galaxies, and solid characterizations of stellar populations, ISM kinematics etc. in hand, this knowledge can in turn be used to calibrate our understanding and interpretation of the rest-frame NUV line emission. This project can therefore serve as a bridge between low and high redshifts, as well as between the legacy of HST and the future of JWST.

Background

It is difficult to overestimate the importance of understanding star formation and feedback for extragalactic astronomy in general. The majority of stars in the Universe are formed during episodes of strong star formation, and the hot OB population in these galaxies give rise to intrinsically strong Lyman α emission which is invaluable tools to probe e.g. the Universe's star formation history, clustering properties and structure formation, marks the end of the epoch of reinization, etc. However, since Lyα is resonantly scattered, the photons travel much longer optical paths on their way out of the galaxy, dramatically transforming thew line shape, morphology of the emerging radiation, and dramatically increases the probability of being absorbed by dust grains on the way. These effects can be countered by a number of other mechanisms, e.g. bulk outflows, low dust content, low kinematic line width, low neutral gas covering fraction and column density, high clumpiness of the neutral medium, and more (see RT15) for details). Also the reionization and reheating of the early Universe is believed to be driven in large part by star-forming galaxies, however, to do so, enough ionizing photons must not only be produced, but also be able to escape into the intergalactic medium, which does not seem to be possible if conditions in the galaxies at the time were like at present. It is clear that a strong evolution must have happened, and Lyα studies can help us understand this evolution. We have recently begun to understand how Lyα and Lyman Continuum partially escapes through the same channels, and how to read information about the neutral medium important for Lyman Continuum escape from Lyα profiles(Verhamme et al., 2015). More importantly; the correct understanding of Lyα emission is also important to infer the true luminosity function of galaxies in the Universe from the one we observe in Lyα.

Lyman α is not the only important emission line in this wavelength range. As we venture into the neutral epoch of the Universe (redshifts $\gtrsim$ 7), as will be possible with the launch of the James Webb telescope, the IGM suppresses Lyα strongly (e.g. Laursen et al., 2009; Dijkstra et al., 2006; Dijkstra, 2014, and references herein). However, with the strongly improved sensitivity that will be at our disposal with JWST, other nebular emission lines in the rest-frame NUV can gain importance as beacons. However, it's been shown by Rigby et al. (2014) that the emission of Mg II 2796, 2803 does not correlate with that of Lyα, implying that a more thorough understanding of the origin of these NUV lines is necessary to correctly understand and compare observations of these to more nearby surveys based on Lyα luminosities.

This proposed project aims to (A). consolidate our current knowledge of the connections between kinematics and Lyα transfer and escape in the local Universe; to (B) create grounds for direct comparison between these and the galaxies at high redshift, and finally (C) by the aid of (A) and (B), investigate the connection between kinematics and other ISM features, Lyα, and NUV metal emission, and thus pave the road for future JWST-based surveys to be more easily understood in the context of current knowledge.

Project Megasaura (PI J. Rigby) is a sample of 17 strongly lensed, star forming galaxies at redshifts between 1 and 3 which have been observed in the optical, NIR and MIR with Magellan/MagE and Keck/ESI, and imaged by HST and Spitzer. The strong lensing gives an unusually fine signal-to-noise, allowing detailed studies in both emission and absorption lines. 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; but furthermore, it allows testing of the detailed knowledge of local-Universe star forming galaxies which has been obtained within the last decade, on data from an entirely different epoch but of comparable quality. Such a comparison could potentially disentangle intrinsic, evolutionary changes over cosmological time, from changes in the environment, and help understand star formation, galaxy evolution, and Lyα transfer and escape both locally and in the early Universe. I propose at least two sub-projects centered on this sample: **The first** will consist of a general characterization of the objects wrt. age, mass, stellar population, SFR etc., in order to establish a baseline towards future results can be compared; and furthermore, it will contain an analysis of kinematics in the ISM and a comparison to properties in Lyα. Where possible, I have been granted permission to fit the Lyα emission profiles against the grid of semi-analytical expanding-shell models developed by the expert group at Geneva Observatory (Schaerer et al., 2011), which I believe could add significant value to these kinematic analyses in terms of comparability to local-Universe galaxies. It is the hope that this will enable us to test the insights obtained from local samples in a high-redshift setting, and possibly reveal systematic differences between local and high-redshift galaxies. **The second** proposed paper on Project Megasaura will be focused on NUV nebular and stellar emission lines of e.g. Fe II, MgII, and C III], and the connection between their line profiles, line strength etc. to stellar and kinematic ISM properties. The hope is, besides learning more about the individual galaxies, could help calibrate these NUV emission lines as a tool for future cosmology. If there should be time over, looking deeper into the spatially resolved subsets of the sample and spatially mapping choice properties should be interesting, and holds the possibility of comparisons to the low-redshift SAFE project (see below). Fig. 1 shows an example finding chart of MagE observations of one of the Megasaura (left), and a curve of running averaged signal/noise per pixel of this and two other spectra.

The Lyman Alpha Reference Sample: is a sample of originally 14 galaxies (since extended with 28 galaxies more, the analysis of which is still underway), established with the goal of studying local-Universe analogs of high-redshift star-forming galaxies in as great detail as possible in order to learn which mechanisms govern Lyα radiative transfer and escape. The sample has been observed with a large range of instruments and wavelength ranges, from archival X-Ray data from Chandra and XMM, to 21 cm eVLA interferometry. The back bone is a set of multi-band HST ACS and WFC3 imaging and COS spectroscopy. My main contribution to this project has been the analysis of these COS spectra, published in RT15. Through this work, I have gained a deep and highly specialized knowledge of the atomic and ionized ISM in these galaxies, its kinematics and geometry, and its interplay with the Lyα photons. Fig. 2 shows some core results from LARS in spectroscopy. In the left panel is the results of AOD computations for one of the galaxies, more closely explained in the caption. In the middle panel is shown a plot of EW(Hα) vs. maximum velocity-binned neutral covering fraction in the sample galaxies (see RT15 for more detail). Here, we found strong correlation, suggesting that strong SF feedback perforates the surrounding neutral medium, carving pathways for Lyα to escape. Testing whether this correlation holds for a larger sample is one of the motivations for the HST Legacy sub-project. Right panel shows observed Lyα of LARS 1, together the best-fit model of the Geneva grid, and intrinsic Lyα as traced by Hα. We also propose a similar Lyα profile analysis in this larger COS Legacy sample and for the Megasaura for which Lyα emission strength and S/N allows it.

The third proposed paper will consist of running a larger number of archival COS observations of local star forming galaxies (see the first page for suggested proposal IDS) through the same machinery as was the LARS, to provide a stronger statistical reliability and a larger population coverage to the sample, such that a wider variety of star-forming galaxies at high redshifts have as close and statistically sound representation in the sample as possible. This would help consolidate our current knowledge about local Universe conditions, and to draw conclusions about similarities to and differences from the high redshift Universe with much stronger confidence.

SAFE — Star clusters, lyman-Alpha, and Feedback in Eso 338-04: Star forming or starburst galaxies are often messy, strongly interacting systems with complex kinematics and a strong internal variation in stellar population, star formation activity etc., as has often been shown in the literature at low redshifts; and e.g. Bayliss et al. (2014) show that this can also be the case with lensed, high-z galaxies. This presents challenges to both observing and modelling them. SAFE is an attempt to map both star clusters, neutral and ionized ISM, intrinsic and emerging Lyα and other properties across an entire galaxy in the UV - something that would normally be done with an IFU in the optical. For lack of space-borne IFUs, however, this is an attempt to essentially turn the COS into a coarse-grained one. It was originally devised as a means to create a realistic input for Lyα radiative transfer simulations, but the insights it will bring should be interesting to the broader star-forming galaxy community in many ways, as is hinted by Bayliss et al. (2014). **A fourth subproject** will be to work on SAFE. The project includes a large amount of data, and there will be a lot to do, but the work can be broken into smaller portions. Should the assignment grow from 2 to 3 years, SAFE holds enough data and complexity to take up a significant part of a third year, but some of the more low-hanging fruit like Lyα profile mapping over spatial regions can most likely be packed into a smaller project of a shorter time span.

Timeline

Months 1-5 *Local HST Legacy COS galaxies*. Much of the computational machinery for this is already in place; so the core analysis of this should be relatively straightforward.

Months 6-14 *Megasaura I*. This paper will contain a relatively large number of measurements and diagnostics, and likely a nontrivial amount of data reduction/combination etc., and will require a considerable amount of work.

Months 15-20 *Megasaura II*. The proportions of the two Megasaura papers is uncertain, but a total of 14 months for both seems realistic.

Months 16-24 *SAFE*. This project contains material for large amounts of work, but can be split up into smaller parts. If the position gets extended to a third year, SAFE can very well expand to fill a large chunk of this .

Months 25-? If the assignment expands to a third year, the option should be kept open that results from the first two years could lead to exciting questions. Otherwise, SAFE is likely to hold data enough for a good part of this, and a comparison to the spatially resolved Megasaurs could be interesting.

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Figures

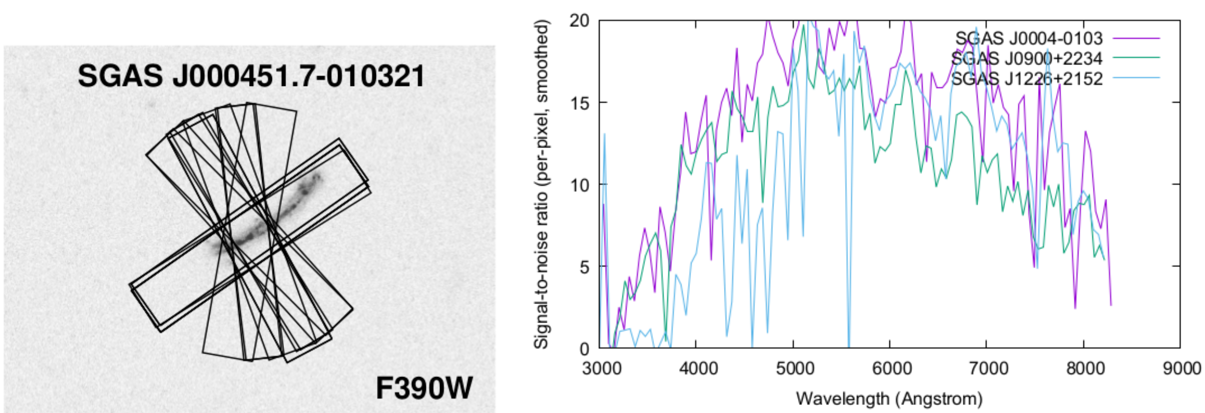

Figure 1: Example finding chart for Magellan/MagE observations of a Megasaur (left), and averaged SNR per pixel in the combined spectra of same galaxy (purple) and two other sample galaxies (right). Images provided by J. Rigby.

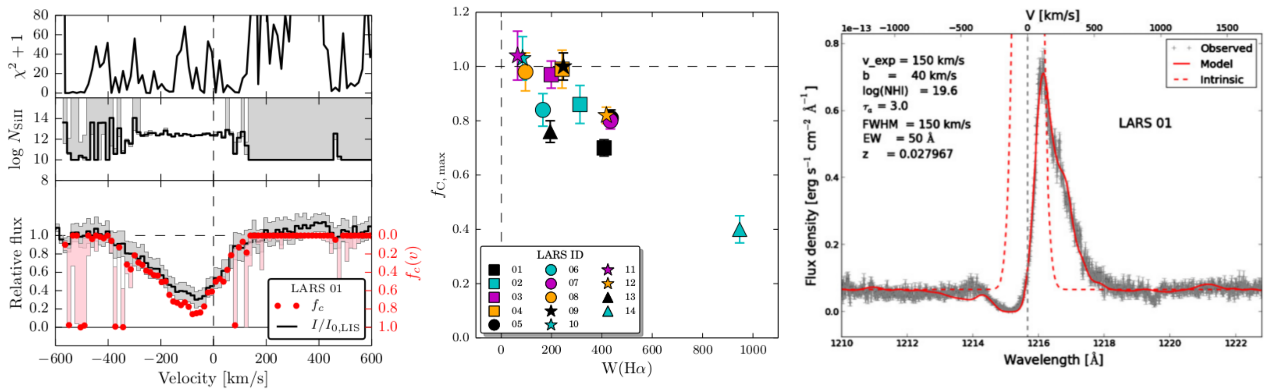

Figure 2: eft: Result of Apparent Optical Depth analysis of a LARS galaxy. Middle panel shows inferred column densities with errors, lower panel shows computed per-bin covering fractions, overlaid on the averaged LIS metal absorption profile; from RT15. Center: Hα EW vs. Maximum covering fraction for the LARS galaxies; from RT15. Right: Lyα profile of LARS 1 (black), with intrinsic Lyα inferred from Hα (dotted red) and the best-fit model from the catalog of the Geneva group (Orlitova et al, in prep.), from Östlin et al. (2014).

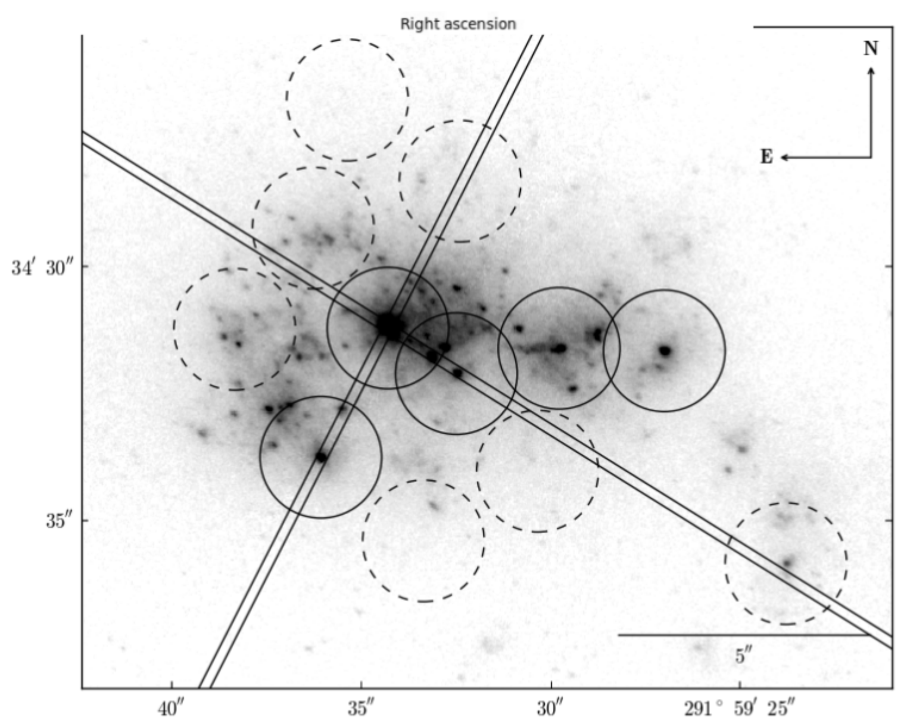

Figure 3: STIS and COS pointings for the SAFE project., overlaid on HST UV continuum image of ESO 338-04. Image from SAFE proposal by stlin.