STAR FORMATION OVER COSMOLOGICAL TIME

Title of Research Opportunity: RO 18603: The Nature of Star-forming Galaxies at High Redshift

NASA Center: Goddard Space Flight Center

NASA Advisor: Dr. Jane Rigby

1. Statement of problem

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. To disentangle intrinsic properties of the galaxies from environmental differences over cosmological time spans. To provide calibration and an astrophysical frame of interpretation for observations with the future James Webb Space Telescope.

Short outline: We propose a two-pronged project consisting of a local-Universe and a high-redshift part. *At low redshifts*, we propose to combine HST-COS observations of existing samples of local star-forming galaxies from the Hubble Spectroscopic Legacy Archive. These include, but are not limited to, samples earlier published in **?????**. The Hubble Spectroscopic Legacy Archive contains ~ 175 HST-COS galaxy spectra classified as starburst, star forming or dwarf compact; if between one third and half of these have appropriate data quality, that will lead to a sample of 60-80 objects, with a minimum of 45 spectra from the samples of **?????** alone. In these, we will investigate neutral and ionized ISM and CGM properties like kinematics and column densities in a uniform way similar to our earlier work on the Lyman Alpha Reference Sample (LARS, **??**) presented in **?** (hereafter RT15) and **?**. This would expand the parameter space coverage of this work, dramatically improve the statistical robustness of conclusions drawn from these investigations about trends and interconnections of these properties. The increase in sample size would also allow for more sophisticated ways of looking for multi-parameter correlations like, clustering analysis etc.

Furthermore, data is currently being acquired with HST of the nearby starburst ESO 338-04 (SAFE, GO 14806 PI: Östlin); 2 pointings with STIS and 12 pointings with COS, covering both hot central star clusters and the outer, diffuse Lyα halo. Part of my project would be to complement the statistically oriented work above with an in-depth tomographic study of the ISM in this, one of the most complex and puzzling local starburst galaxies.

At high redshifts, we propose an analysis of rest-frame optical and UV spectra observed with Magellan/MagE and Keck/ESI of 17 lensed, star-forming galaxies at $1 < z < 3$, the sample called "Project Megasaura" (PI: Dr. Jane Rigby). 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 being of high enough quality that detailed analyses of Lyα, metal absorption lines, nebular emission etc., like typically done on 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.

Furthermore, the lensed spectra contain a wealth of rest-frame NUV lines, including the important [C III] λ1907, CIII] λ 1909 doublet. This line is by many considered the most promising beacon for detecting and determining redshifts of hot, low-mass galaxies in the neutral Universe beyond $z \gtrsim 6.5$ (e.g. **???**). At these redshifts, the neutral gas content of the IGM strongly attenuates Lyα, which is the most important observable feature at lower redshifts. This line is typically not included in local samples due to the wavelength coverage of the Cosmic Origins Spectrograph. The Project Megasaur spectra contain both this line and Lyα, and have high enough S/N to analyze some of the most important tracers of neutral ISM properties in absorption. The combination of these features provides a unique opportunity to bridge the knowledge and methodologies of high and low redshift samples, and to provide important tools for pushing the boundary for how deep into the Universe's past we can see with future James Webb observations.

2. Background and relevance to previous work

2.1. **Project Megasaura.** Project Megasaura is a sample of 17 star forming galaxies at redshifts between 1 and 3, which are strongly lensed by foreground galaxies or clusters. The galaxies 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 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. 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.

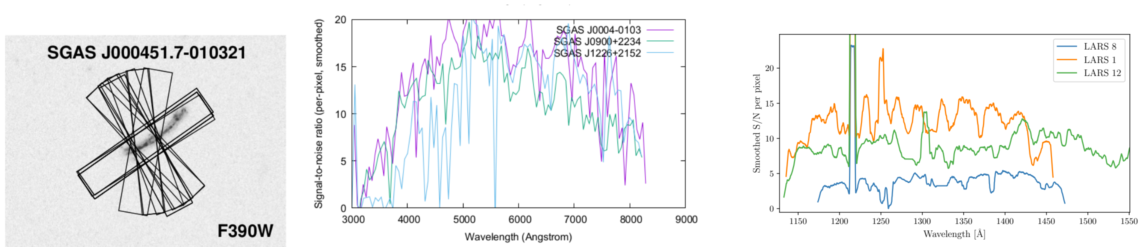

FIGURE 1. *Left and middle*: Example finding chart for Magellan/MagE observations of a Megasaur galaxy (left), and averaged S/N per pixel in the combined spectra of same galaxy (purple) and two other sample galaxies (right). Images provided by J. Rigby. *Right*: For comparison, S/N for three of the COS spectra of LARS.

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. For comparison is shown S/N of some of the COS spectra of LARS galaxies of **?**, hinting that the S/N ratios are cat least comparable. Subsets of the sample have been studied in depth earlier. Two them are included in **?**, who performed studies of neutral kinematics and covering fractions to constrain escape of ionizing photons, with a large overlap in methodology with **??**. However, these authors did not go deeper into the Lyα/kinematics connection, something we aim to to do with at least a part of the sample.

Two of the sample galaxies have been subject to in-depth, spatially resolved studies (**??**). **?** compared the rest-frame NUV emission lines to low-redshifte systems

Galaxies like these have been studied in smaller numbers by e.g. **?????**. **?** performed the Apparent Optical Depth analysis to their small sample of lensed galaxies at redshifts $3 < z < 4$, and found large outflow velocities and low covering fractions of neutral gas. However, they did not have auxilliary data of a quality allowing for an accurate comparison with Ly α radiative transfer models; something we believe possible with the Project Megasaura data. **??** focused on near-UV emission and absorption lines of MgII, FeII, and CIII in spectrsoscopic samples of lensed galaxies at redshifts similar to Megasaura, in order , and it is the aim of this project to be able to analyze these galaxy spectra in ways that will make them directly comparable to the spectroscopic part of the existing Lyman Alpha Reference Sample (**?**) and its extension which is proposed as another part of this project.

2.2. **Local-Universe starbursts in the FUV and the Lyman Alpha Reference Sample.** The Lyman Alpha Reference Sample was motivated by the fact that Lyα radiation created in the inner, hot cores of star-forming galaxies and traceable through Hα, had been observed to be almost entirely decoupled from the Lyα emerging from the galaxies. Lyα is subject to strong radiative transfer effects when interacting with the neutral ISM on its way out of the galaxy of origin, and a wide spread of effects like gas column density, dust content, large-scale outflows, velocity width and more, conspire or compete to either facilitate or quench Lyα escape. It was clear that to correctly interpret the Lyα observations at high redshifts, which potentially hold the key to a large range of cosmological properties of the Universe, it was necessary with deep, resolved studies of nearby analogs in order to understand the processes that govern Lyα transfer and escape.

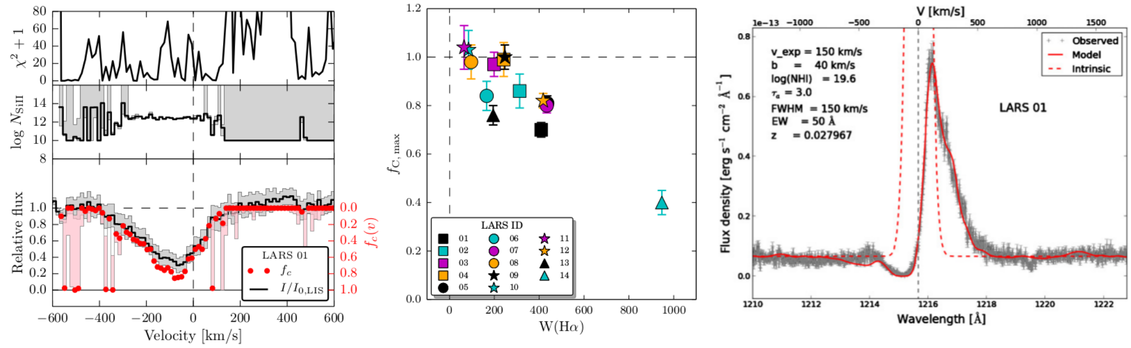

FIGURE 2. Left: Result of Apparent Optical Depth analysis of a LARS galaxy. Middle panel shows the inferred column densities with errors, lower panel shows computed values of f_C (see sect. **??**), overlaid on the averaged LIS metal absorption profile; from RT15. Center: Hα EW vs. Maximum covering fraction 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 (**?**), from **?**.

LARS is a sample of originally 14 galaxies (since extended with 28 more galaxies, the analysis of which is still ongoing), 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. One of the proposed projects is to run a larger number of archival COS observations of local star forming galaxies, 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.

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.

2.3. **SAFE.** 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. **?** show that this can also be the case with lensed, high-z galaxies. This presents challenges to both observing and modelling them.

SAFE – *Star clusters, lyman-Alpha, and Feedback in Eso 338-04* – 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,

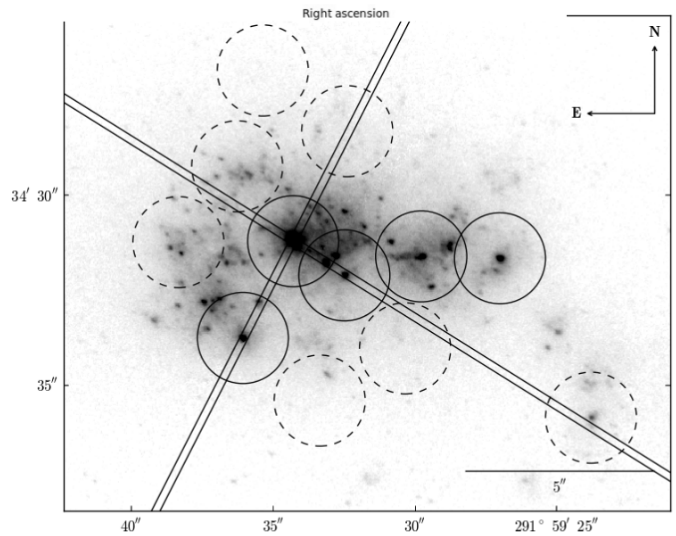

Figure 3. STIS and COS pointings for the SAFE project., overlaid on HST UV continuum image of ESO 338-04. Image from SAFE proposal by stlin.

this is an attempt to essentially turn the COS into a coarse-grained one. SAFE will complement the archival COS sample study described above by giving us a tomographic study of neutral ISM and CGM, Lyα scattering scenarios, etc.

3. General methodology, procedures to be followed, and timeline for completion of each step

The project is primarily going to rest on spectroscopic observations of star-forming regions and their surroundings in galaxies at $0 < z < 3$, in wavelength ranges from the FUV to the MIR, with auxiliary image data included.

This will be complemented with realistic outflow models, stellar population synthesis like Starburst99 (?, and citations therein), and photoionization simulation code like `cloudy` (?), as well as imaging data, lensing models etc. appropriate for the analysis.

The spectroscopic work will rest on standard procedures for determination of e.g. dust content, metal abundances by direct measurements of line strengths and electron temperature and density (See e.g. **?**), as well as empirical, strong line based methods (e.g. **?**)

Methodologies for the specific sub-projects are described in the outline below.

3.1. **Project outline.** The project for the first two years will fall in four major parts. Two of them are part of Project Megasaura, two of them focus on local starburst galaxies as analogs to the Megasaurs.

- **Local starburst galaxies in the FUV:** An analysis similar to the one in RT15 of 50-100 starburst and star forming galaxies in the HST-COS Legacy data archives. Systemic redshifts will be determined from SDSS spectroscopy, which will also be used to derive the usual optical emission line-based diagnostics like temperature, ionization, dust content, Oxygen abundance, etc. Metal absorption lines in the COS spectra will be used to measure kinematic and, where possible, geometric quantities like described in RT15, and Lyα, where present in emission, will be compared to these findings. Furthermore, we have obtained permission to fit the Lyα profiles of both high and low redshift galaxies to the grid of semi analytical Lyα radiation transfer models of **?**, and compare to the findings in neutral metal lines. Measurements will, to the extent it is possible, be run in a way directly comparable to the findings of RT15.
- **Megasaura I:** This subproject is the first step in the Megasaura work, and contains two steps. *Step 1* will consist in a characterization of the star forming knots in the galaxy sample: stellar population, dust content, starburst

age, metallicity from direct methods where applicable, otherwise from indirect methods, ionization level etc.; analogous to the properties listed in the first three tables of **?**. *Step 2* will be an analysis of ISM kinematics in absorption, looking for outflows etc., and a comparison with Lyman α features, to test the known correlations from low redshift surveys like LARS. The Megasaur spectra have sufficiently high SNR to determine precise zero-point velocities from stellar absorption lines, providing a unique opportunity to test the findings from low redshifts under early-Universe conditions.

Megasaura II: In this project, we focus on the UV emission lines of the lensed galaxies. We can derive kinematic properties from NUV Mg II and Fe II lines similar to the work of **?**, using the apples-to-apples comparison made possible by Megasaura I and the COS Legacy project as a baseline of comparison. Furthermore, the properties of Lyman-α emission features and model these lines, where applicable, by the outflow and radiative transfer model grid of **?**. This would get us one step closer to making the Megasaura sample directly comparable to the spectroscopic part of LARS and thus provide a bridge from the local to the high redshift Universe in terms of star formation properties. These lines could also provide us a follow-up study to **?** on the (non-) correlation of Mg II and Lyα emission in high-redshift star forming galaxies; this could triple the sample size for these investigations at a low cost due to the measurements having already been done in this and earlier papers. Finally, using the above results as a starting point would also allow for a deeper study of the properties governing the emission if C III] λ1909, combining an analysis inspired by e.g. **?** with later photoionization models by **?** and earlier found kinematic and physical properties of the medium, to help better constrain under which circumstances C III] is strong and detectable at very high redshifts, at which this line and its companion are expected to play a crucial role in redshift confirmation of the first galaxies with the launch of JWST next year.

SAFE: Star clusters, lyman-Alpha, and Feedback in Eso 338-04: is 18 orbits of HST observations of the nearby starburst galaxy ESO 338-04 being carried out during Cycle 24. The observations consist of two STIS pointings centered on the main starburst regions and giving very high resolution spectra covering both Lyα and Hβ, which maps the seed function of Lyα. On top if this is 12 COS pointing, covering a large fraction of the inner parts of the galaxy. About half of these are centered on major star-forming regions bright enough to be able to measure absorption in the continuum, while the rest cover the diffuse Lyα halo and probably mainly will catch Lyα and possibly other, faint, line emission. The data combined will enable an unprecedented complete mapping of a galaxy's ISM in the UV, essentially using COS as a coarse grained Integral Field Unit in the UV. The data will allow to map both the seeding of Lyα, the Lyα that eventually escapes, and for large parts the kinematics and geometry of the ISM which redistributes it.

3.2. Timeline.

Months 1-6: 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. However, some manual work is required for each objects, which of course will add up with a sample of an expented $\sim$ 70 galaxies.

Months 7-16: 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 17-24: Megasaura II. The proportions of the two Megasaura papers is uncertain, but a total of 18 months for both seems realistic. If the data turn out to merit even more work, it should be considered to split it into 3 papers instead.

Months 25-30: SAFE. This project contains material for large amounts of work, but can be split up into smaller parts. 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, and a characterization of Lyman 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. A further elaboration could contain comparisons to detailed radiative transfer models, or to spatially resolved Megasaura galaxies, if extended Lyα is found int those.

Months 30-36: It seems premature to plan this too specifically, because the results of the first 2 years' work will probably bring up quite a lot of interesting questions and details; but one interesting option would be to go in depth with the subset of the Megasaura galaxies which are well enough resolved spatially to have been observed with multiple pointings. Besides, as mentioned above, SAFE will bring very rich data, the analysis of which can probably expand well beyond six months.

4. Expected results and their significance and application

- From the HST-COS Legacy sample paper, we expect to get obtain a homogenized analysis of a large number of starbursts in the nearby Universe, improving statistical significance and a giving a better basis for direct comparison of properties like age, mass, ionization, star formation, ISM kinematics, Lyα escape etc. between samples which have so far been treated differently by various authors. This will enable us to learn more about the star-forming population in the local Universe, and the mechanisms that govern Lyα transfer and escape. Furthermore, it will provide an improved sampling coverage of the population and better statistics, both important for comparisons to and calibrations of High-z observations. This work will make strong use of NASA facilities and foster collaborations with the low-redshift community, specifically the LARS collaboration in Stockholm, Paris, Geneva, and more.
- From SAFE, we expect to obtain a map of unprecedented accuracy of the neutral ISM of a strong starburst galaxy, as well as its Lyα emission profile and seed function. It will give a detailed understanding of the interplay of dust, line width, outflow velocity, clumps, ionization, and Lyα from direct observations, which will directly aid in understanding the observations at high redshifts. Furthermore, it will provide much-needed realistic initial conditions for radiative transfer simulations carried out by theorists in Oslo and Geneva, and could foster further collaborations with these groups.

- From Megasaura I, we expect to obtain a characterization of the brightest starburst in the sample galaxies, their stellar population age, metal abundances, etc., from well-studied rest-frame UV and optical spectral features. We expect to obtain a detailed mapping of ISM kinematics, outflows etc., and be able to test the insights obtained from local samples against this sample. It will reveal systematic differences between local and high-redshift galaxies and, with the proper preconditions, provide a baseline for interpreting non-lensed observations at similar and higher redshifts.
- With Megasaura II, we expect to obtain knowledge about stellar winds, different ISM phases, and ISM kinematics through the less-studied, rest-frame NUV emission lines, in particular CIII] 1909, to expand existing single-object analyses to a small sample. The knowledge base collected from the previous projects is expected to help calibrate and guide the interpretation of these lines, in turn laying a solid foundation for future spectroscopic observation campaigns with JWST, which have the potential to dig deep into the early, neutral Universe.

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