In response to Request for Information NNH12ZDA008L: ***Science Objectives and Requirements for the Next NASA UV/Visible Astrophysics Mission Concepts***

EXTRAGALACTIC LYMAN-ALPHA EXPERIMENTS IN THE NEARBY UNIVERSE

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Abstract. The universe has been statistically studied in the HI Lyman-alpha emission line only at redshifts (z) above 2. Thus despite living in a universe where Lyα is the brightest spectral feature of the most abundant species of baryonic matter, 75 per cent of our cosmic history is left unexplored. Here we outline the scientific case and approximate requirements for a space-based UV facility that could efficiently cover the remainder. Lyα is the most important spectral beacon in high-z astrophysics, where studies of galaxy formation, the cosmic web, and the epoch of reionization all rely upon Lyα population statistics. The unbiased assembly and study of a large sample of Lyα-galaxies at low and moderate redshifts is the only method through which we can truly rely upon Lyα as cosmological diagnostic tool. Simultaneously such observations would enable unprecedented studies of galaxy evolution and massive star formation across the latter 3/4 of cosmic time. A new UV-optimized mission with spectroscopic ($R \sim 10,000$) and spectrophotometric capabilities at $\lambda = 1200-3500$Å is the only way that these goals can be realized. We therefore strongly recommend the inclusion of these capabilities in a future facilities, and we are willing and able to contribute more detailed goals, requirements, and specifications and realistic simulations.

Authors are keen to participate in the workshop in Baltimore

1. Lyman-alpha Astrophysics and its Application

The HI Lyman-alpha emission line (Lyα) is the de facto spectroscopic feature of evolving galaxies in the high-redshift universe [1]. Reprocessing roughly 40 per cent of the intrinsic ionizing energy ($h\nu > 1$ Ryd) into a single high-contrast feature, Lyα surveys are able to probe the most abundant populations of faint, low-mass galaxies [2]. Simultaneously, and at luminosities 4 orders of magnitude brighter, Lyα-selection also recovers the most energetic systems in the known universe [3]. Because of the high survey efficiency of Lyα, such catalogues have been used for any number of studies of cosmic star-formation and galaxy clustering [4, 5, 6].

Lyα also occupies a prestigious place among observables from high-z galaxies, because it encodes further information that is unique and exclusive to the $n = 2 \rightarrow 1$ transition. Specifically Lyα also enables: studies of cosmic reionization [7], estimates of kinematic and gaseous properties of the ISM [8], a test of population III star-formation [9], a probe of the cosmic web [10, 11], and a diagnostic of circumgalactic gas via its polarization [12]. This is an impressive toolkit for a single monochromatic feature, and does not even mention the enormous impact of Lyα absorption studies.

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The convenient rest-wavelength of 1216 Å means that in principle all of the above studies may be executed, using identical methods, across the entire epoch of galaxy formation and assembly: $z = 2$ to 10 [13], and in principle up to ~ 20. This power of Lyα has motivated new generations of instrumentation for 8–10 m ground-based telescopes: Subaru/HyperSuprimeCam, VLT/MUSE[14], and the HETDEX[15]. Combined with very high-z science goals laid out for ELTs and JWST (specifically NIRISS), *the future of Lyα-related astrophysics is secured for the coming decades.*

This puts us in a situation that is very bright but, for two main reasons is also very unsatisfactory. Firstly Lyα is a resonance line and undergoes a complicated radiative transfer through the ISM. Indeed this is the very origin of some of the Lyα-specific science cases listed above, but also implies that the general use of Lyα photometry for cosmological purposes is severely biased. At this point, it is worth remembering that in high-z science, every calibration that relates an observable to a physical property has been derived in studies of nearby galaxies. At high-z the information required to empirically study radiative transport is completely ruled out by the large physical sampling scales, the lack of photons, and the redshifting of critical spectral features to the mid IR: detailed studies can only be performed in nearby galaxies. The second unsatisfactory element of Lyα astrophysics is that the universe at $z \lesssim 2$ is almost completely unexplored, at least statistically. This not only comprises 75% of cosmic history, but it includes the peak in cosmic star-formation, the emergence of the dominant Hubble sequence, dense galaxy clusters, and so on; the transition to the modern universe remains poorly studied in the UV.

2. Lyman-alpha Astrophysics and Low-redshift Observations

Early searches for $z > 3$ Lyα emitters (LAEs) found only their absence[16], although at that point it was not clear why the Lyα universe seemed so dark. Concurrently, observations of nearby starburst galaxies with the IUE were also finding a lack of strong Lyα emission [17, 18] although here the situation was clear: Lyα photons were being produced (shown by their strong Hα), but their emission heavily suppressed. This immediately raises the questions of *why?* and *what are the high-z implications?*

Regarding *why*, Lyα has a very high absorption cross section with dust, so the dust content must be a factor. However the chance of this absorption depends on the path the radiation takes, and thus for a resonant photon HI also enters in the most fundamental way. The geometry of galaxies is such that dust and HI give rise to an intricate and highly complex transport problem in which Lyα emission is regulated by dust [19] and its distribution [20], metallicity [21], HI content and kinematics [22], covering fraction [23], filling factor, and clumping [24]. See Fig. 1. Most of these properties are impossible to measure in high-z galaxies directly, and the bulk of the dependencies have been shown in small samples of nearby galaxies observed with IUE, HST, or GALEX, or have not been rigorously tested at all. Furthermore, the only current Lyα imaging program of nearby galaxies failed to find any correlations with dust on small scales, but did show Lyα scattering haloes that are significantly extended beyond Hα and the UV continuum, and clearly illustrated the difficulty of deriving aperture-integrated global quantities at both high- and low-z [25].

Two approaches lead low-z Lyα science: the *targeting of known galaxies* at $z \lesssim 0.1$ with HST, and *blind surveying for LAEs* at $\langle z \rangle = 0.3$ with GALEX grism spectroscopy. At $z < 0.1$ we are able to study galaxies in exquisite detail, and place constraints on many of the quantities known to govern Lyα transmission. Importantly, current radio facilities at

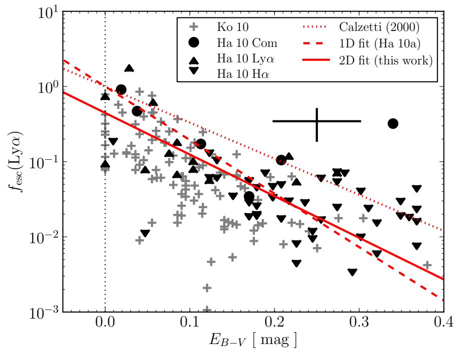

Figure 1. A comparison between the Lyα escape fraction and dust content of individual galaxies at $z = 2 - 3$ [13]. Clearly there is an anti-correlation between the two quantities, but the spread exceeds 1 dex (note the logged ordinate axis). This spread will likely be the combined effect of (some/all of) the many other quantities discussed in Section 2. Understanding why requires large, and unbiased samples of *nearby* galaxies.

21 cm give us direct access to the HI gas. Our own HST program, *LARS – the Lyman-alpha Reference Sample* (Fig. 2), has obtained Lyα, UV, and optical imaging and UV spectroscopy for 14 nearby starbursts with precisely this motivation. HST, however, was not optimized for this kind of science and, costing six orbits per target, extending LARS by the factor of ten to the $\gtrsim 100$ targets required for statistical coverage over the parameter manifold would require a *SuperLarge* HST program. Plausible, but better served with a new UV facility.

Lyα-selection with GALEX can reach statistical significance, and enables similar galaxy selection to that employed at $z > 2$. This is vital to examine the evolution of the luminosity function (LF)[26], the escape fraction [13], and prevalence fraction [27], and provide *the only datapoint in the last 75% of cosmic time* (Fig. 3). However with a 50 cm mirror GALEX is restricted to bright galaxies and unable to (a) probe the faint end of the LF (the critical part for reionization) and (b) find many $z \gtrsim 0.4$ objects (NUV spectroscopy at $\langle z \rangle = 0.9$ has found fewer than 10 galaxies [28]). Furthermore with the FUV channel of GALEX centering on Lyα emission at $z \sim 0.3$, spatial sampling and photon-statistics are reduced substantially compared to the very nearby universe, and indeed these galaxies are too faint to make HI detections or study the kinematics of the neutral gas, even with HST.

3. Lyman-alpha Experiments in the Nearby Universe

Our objective to be attained with the future UV telescope is to unambiguously determine the restframe UV and Lyα properties of the galaxy population that are a relevant for high-z astrophysics, and to do so at a redshift that makes the population amenable to detailed physical studies: $z \lesssim 2$. In tracing star-forming regions across the latter 3/4 of the universe, this will have direct application in galaxy evolution, and will provide synthesis information for very high-z galaxy and reionization studies provided by JWST and ELTs, and for computational models of galaxy formation.

Specifically for Lyα, to $z \lesssim 2$ this would include **blind surveys using both Lyα- and UV continuum-selection**. Driven by the increase in survey depths compared to GALEX and HST, we would measure the LF (including the faint-end slope), Lyα-fraction among UV galaxies (and other selection, e.g. Hα), global Lyα escape fraction, and EW distribution. In a sample of ~ 1000 objects (10-fold increase over today) we would track the evolution of these properties at statistically significant levels in several bins across the latter half of cosmic history. Working at $z < 2$, and down to $z \sim 0.2$, we would not only be able to say how the galaxies evolved, but would obtain all the information necessary to say why, and what physical processes shape the distributions. We would address a number of specific outstanding issues such as the disappearance of Lyα blobs, and the blind survey and comparison of Lyα with ionizing (Lyman continuum) radiation – see the responses

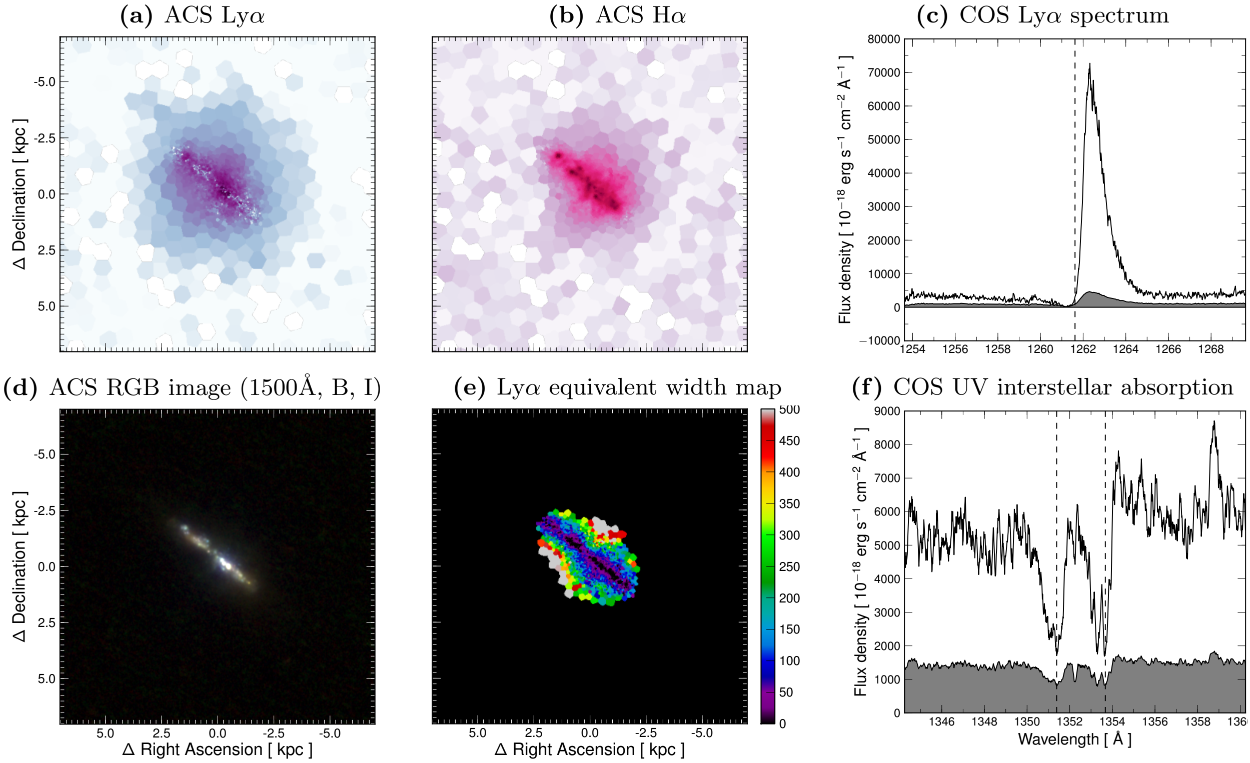

Figure 2. Results from the LARS program for Mrk 1486. Emission lines are continuum-subtracted and images are Voronoi binned for reliable surface photometry at faint isophotal levels. Lyα and Hα photons originate in the same nebulae, but Lyα clearly extends way beyond the nebulae in which it formed. This is most likely the result of scattering of photons by HI, and may also be seen in the equivalent with map: in the central regions the EW is low ($\lesssim$ 10Å) as Lyα photons scatter out of the line of sight, but increases dramatically with projected distance from disk to values in excess of 500Å, as photons are scatter forming a diffuse halo. For reference, the intrinsic EW for star formation at equilibrium is 80Å. The spectra from HST/COS show a smooth and asymmetric (P Cyg-like) emission profile for Lyα and ISM absorption features (OIλ1302, SiIIλ1304) that are blue-shifted from their expected velocities. Both of these phenomena are consistent with Lyα being transmitted through out-flowing neutral gas, but note also the significant residual intensity in the core of the absorption lines, which suggests a covering fraction below unity.

to this RFI by C. Scarlata and S. McCandliss. This physical completeness would come through observations surveying for, and specifically targeting the Balmer series, oxygen, nitrogen and sulphur lines, and direct and indirect HI measurements. Naturally this implies synergies with ground-based telescopes including ELTs, space-based NIR platforms such as EUCLID/WFIRST and JWST, and radio facilities, (ALMA, possibly including the SKA).

For a complete picture, **detailed observations in the UV** are necessary. Spectroscopy would provide the only unambiguous tracers of the kinematics of the neutral ISM, gas covering fractions, and diagnostics of the massive stellar population. All of these have direct impact on Lyα, which remain to be studied at high statistical levels at any redshift, but all are also of immediate interest in their own right given that there are no evolutionary studies of any of them. Thus intermediate resolution UV spectroscopy would be necessary.

As shown by the LF, it is invariably the case that most of the objects found by a survey are faint. This usually restricts detailed followup studies to smaller subsets of the overall population: systematic and complete followup is performed at magnitudes where it is efficient, and successively more piecemeal, biased, or "ambitious" followup is attempted for the fainter systems. However the entire philosophy of analogue studies mitigates this issue and, by carrying the capability to observe down to Lyα in the restframe, one could also target

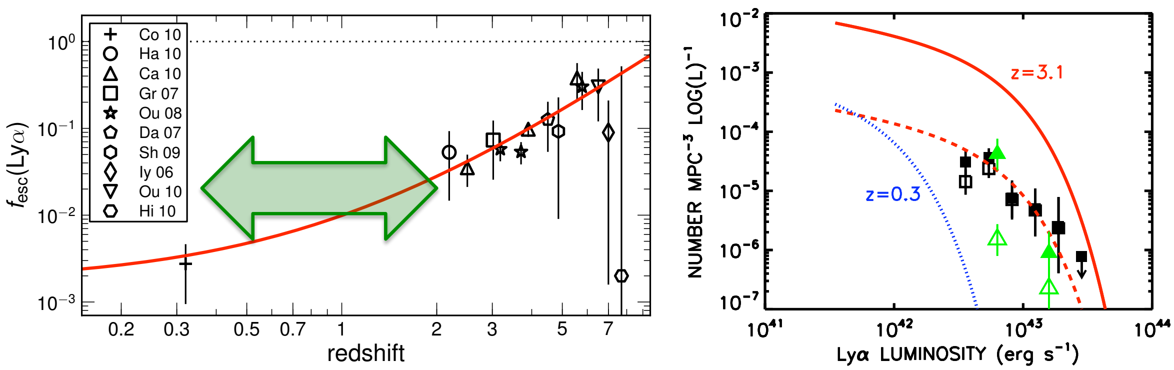

Figure 3. *L*eft: Evolution of the Lyα escape fraction [13], which shows a clear and monotonic upwards evolution from the nearby universe to $z \sim 6$, after which point it reverses and the decreases. This shows the power of Lyα in probing the evolution of the galaxy population and also, most likely, the epoch of reionization. The green arrow shows the gap between $z \sim 0.4$ and 2.2, which constitutes > 7 Gyr of evolution. The point at $z = 0.3$ is derived from the blue LF in the *r*ight panel [28], which also shows the well-constrained LF at $z = 3$ (red). Note the enormous change, which evolves even faster than the declining cosmic star formation. The black points show limited constraints available from GALEX/NUV at $z \sim 1$, which include just 8 star-forming galaxies. The main goal of the program presented here is to find and understand ~ 1000 galaxies in this redshift interval, when the evolution in both cosmic star-formation and Lyα emission is strongest, yet galaxies are still near enough for detailed followup.

very faint galaxies by concentrating on the very nearest systems. Contrasting $z = 0.5$ with $z = 0.01$, the luminosity distance decreases by a factor of 60, sampling scale by a factor of 30, and surface brightness dimming by a factor of 4. Thus detailed observations could be performed down to the faintest limits of the galaxy LF probed in the high-volume surveys, if the telescope carries **capabilities down to ∼1216Å**.

4. Basic Technical Requirements

To give a rough feeling for the kind of hardware these studies would need, we transcribe them into the approximate telescopic capabilities that would fulfill our scientific goals.

Wavelength Coverage. Our recommended survey capabilities are driven by the need to cover redshifts from where the angular scale permits efficient surveying ($z \sim 0.2$) to the atmospheric transmission ($U-$band, at $z \sim 2$). This corresponds to $\lambda = 1500 - 3500$Å for a spectrophotometer. For high-resolution instruments we would need coverage down to 1200Å.

Observing Modes. Surveys can be accomplished in either slitless spectroscopic mode or imaging with narrowband filters (or pseudo-narrowband filters synthesized from long-pass filters [29]). A $R \sim 100$ slitless spectrograph would be more straightforward, especially in the low background of the UV, but a set of redshift-appropriate narrow and broadband filter combinations would also provide excellent spectrophotometry, morphological information, and reduce contamination. Wide field imaging (1500–3000Å) should also be explored.

An intermediate-resolution spectrograph is essential for any detailed studies (kinematics, stellar populations, covering fractions) and the medium gratings of STIS and COS ($R \gtrsim 10,000$) are ideal. The most important gain over current facilities would come from multiplexing capabilities, where configurable slits, micro-shutter arrays (E.g. JWST/NIRSpec), or integral field capabilities would be revolutionary in the UV. Wavelength coverage should at least match the spectrophotometer; to 1200 Å would be preferred.

For thorough work at $z < 0.1$ an imager is vital. Spectroscopic apertures almost never capture diffuse Lyα components that can dominate the total output[25, 23]. Also it is only at $z \lesssim 0.1$ that scales < 100 pc can be explored. HST can image at 1200Å, but its PSF is not diffraction limited and the filters are suboptimal; ideally we would operate at resolutions of ≈ 10 pc for galaxies at 100 Mpc to resolve individual star clusters. This would most likely not be the same camera as for $\langle z \rangle = 1$ surveys, unless the focal length were adjustable.

Sensitivity. To well constrain the LF, we need to reach to a substantially small fraction of the characteristic luminosity, $L_\star$, which also evolves strongly with redshift. We adopt 10% for illustration: $0.1 L_\star^{z=0.3} = 6 \times 10^{40}$ erg s^{-1} [26], and gives a flux of 2×10^{-16} erg s^{-1} cm^{-2}. Reaching $S/N = 5$ (point-source) at the peak sensitivity of ACS/SBC (with filter) would take 22 hours, so substantial improvements in sensitivity would be necessary. Some would doubtless come from a larger, UV-optimized mirror, but higher QE detectors would also be important. Note also that such a program would depend upon sensitivity to low-surface brightness emission – therefore CTE problems on a readnoise-limited CCD are not tolerable.

Field of view. By interpolating between the $z = 0.3$ and 2 LF parameters to $z = 0.8$, we can estimate the density of galaxies. Very roughly we estimate the need to survey 600,000 Mpc^3, which at $z = 0.3 - 1.5$ implies an average area of ≈ 0.1 deg^2, or around the area of the combined goods fields. This would require a FoV that is substantially larger than WFC3/UVIS, but it is not up to the scale of GALEX.

5. Summary and Compatibility with Cosmic Origins Program

We have outlined the need for a sensitive UV-capable mission, carrying at least medium resolution spectroscopic and spectrophotometric capabilities, in order to perform high statistics survey work and detailed studies of the Lyα and UV properties of galaxies over the last 10 billion years. These goals are closely aligned with questions addressed by the COR Program: *How did the first stars influence their environments?*, *How did galaxies evolve?* and *How are the chemical elements dispersed?* Specifically, such observational campaigns at the highest redshifts targeting the first stars, feedback, and chemical enrichment, will be the direct analogues of the observations presented here, but in a regime with much weaker supplementary constraints. Regarding galaxy evolution, the impact of a homogeneous UV study across 10 Gyr should be transparent.

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