White Paper In Support of a Science and Technical Requirements Study for a
UV/Optical/Surveyor in Advance of 2020 Decadal Survey

Definitive Determination of Galaxy Luminosity Functions at Energies Above the Hydrogen Ionization Edge, Covering 11 Billion Years of Evolution

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Science Motivation – The timing and duration of the Epoch of Reionization is crucial to the subsequent emergence and evolution of structure in the universe (c.f. Madau et al. 1999, Ricotti et al. 2002, Robertson et al. 2015). The relative role played by star-forming galaxies, active galactic nuclei and quasars in contributing to the Metagalactic Ionizing Background (MIB) across cosmic time remains uncertain. Deep quasar counts provide some certainty to their role, but the potentially crucial contribution from star-formation is highly uncertain due to our poor understanding of the processes that allow ionizing radiation to escape into the intergalactic medium (IGM). Moreover, the fraction of ionizing photons that escape from star-forming galaxies (f^e_{LyC}) is a fundamental free parameter used in models to "fine-tune" the timing and duration of the reionization epoch that occurred somewhere between 13.4 and 12.7 Gyrs ago at redshifts between $12 > z > 6$.

Galaxy luminosity functions at high redshift (Bouwens et al. 2006; Labbe et al. 2010; Gonzalez et al. 2009; Finkelstein et al. 2014) along with a host of assumptions for the clumping factor, the ionizing output and the initial mass function of the first stellar assemblages, have been used to constrain f^e_{LyC} to ~ 0.2, fulfilling the requirement to power the EoR – provided contributions to the LyC from the unobserved population of galaxies at the faint end of the luminosity function are included. Of all these assumptions, the uncertainty in f^e_{LyC} is universally acknowledged as the least understood parameter (Ellis 2014), requiring observation for quantification.

Ionizing radiation escape is a mysterious process. Heckman et al. (2001) have pointed out that mean galactic column densities for H I range from 10^{21} cm^2 for normal galaxies to 10^{24} cm^2 for nuclear starbursts. Yet it only takes a H I column density of 1.6×10^{17} cm^2 to produce an optical depth $\tau = 1$ at the Lyman edge.   Escape from such large mean optical depths requires that the galaxy interstellar medium (ISM) to be highly inhomogeneous, peppered with low neutral density, high ionization voids and chimneys created by supernovae or the integrated winds from stellar clusters.   This implies that escape will be extremely dependent on local geometry, requiring resolutions of star cluster sized structures with typical diameters ~ 30 to 100 pc. Such objects subtend angles of ~ 0.003 to 0.010 arcseconds at redshifts of 2 or 3.

Direct observation of Lyman continuum (LyC) photons emitted below the rest frame H I ionization edge at 911.7 Å becomes increasingly improbable at redshifts $z > 3$, due to the steady increase of intervening Lyman limit systems towards high z (Inoue & Iwata 2008).   A key project James Webb Space Telescope (JWST) is to search for those sources responsible for reionizing the universe. However, neither JWST nor the Wide-Field InfraRed Space Telescope (WFIRST), will be able to address the key question of, "How Does Ionizing Radiation Escape from Star Forming Galaxies?"

The far-UV and near-UV bandpasses provide the only hope for direct, up close and in depth, detection and characterization of those environments that favor LyC escape. By quantifying the evolution over the past 11 billion years ($z < 3$) of the relationships between LyC escape and local and global parameters such as: metallicity, gas fraction, dust content, star formation history, mass, luminosity, redshift, over-density and quasar proximity, we can provide definitive information on the LyC escape fraction that is so crucial to answering our key question. Our goal is a definitive determination of L_{900} galaxy luminosity functions over a redshift range from 0 to 3 and will allow us to test whether the escape fraction of low luminosity galaxies is luminosity dependent.
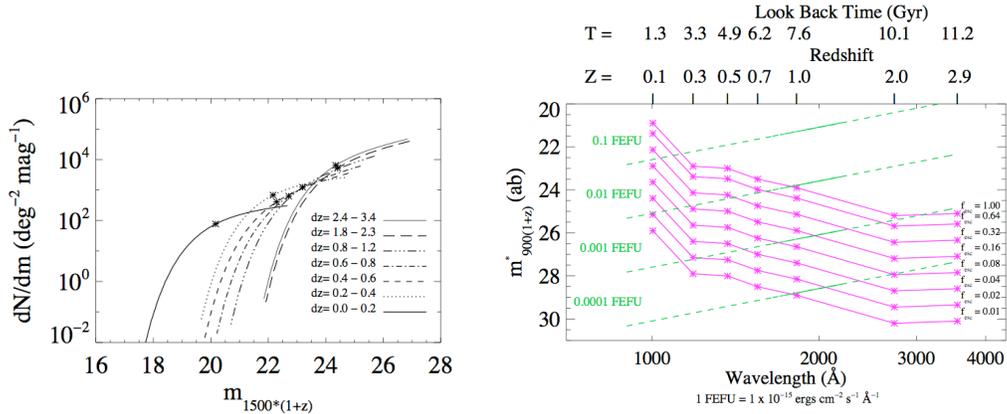
Figure 1 Left panel – Surface densities as a function of observer's frame apparent magnitude for galaxy populations with redshifts between 0 – 0.2, 0.2 – 0.4, 0.4 – 0.6, 0.6 – 0.8, 0.8 – 1.2, 1.8 – 2.3, 2.4 – 3.4, estimated following Arnouts et al (2005). There are 100s – 10,000's of galaxies per square degree. Right panel- the purple asterisks show the characteristic apparent LyC magnitudes (ab) m∗900(1+z) as a function of look back time, and in redshift and wavelength space, for different escape fractions. Contours of constant flux units are overplotted as green dashes marked in FEFU fractions defined in the abscissa subtitle.

Observational Requirements – We have undertaken a study (McCandliss et al. 2008; McCandliss 2012) to estimate the flux detection requirements for escaping Lyman continuum photons from star-forming galaxies, as a function of redshift, guided by the galaxy luminosity functions of Arnouts et al. (2005), shown in the left panel of Figure 1. In the right panel of Figure I we provide ionizing continuum flux estimates for "characteristic" (L^*_{UV}) star-forming galaxies as a function of look back time and escape fraction. We find ab-magnitudes for L^*_{UV} galaxies of ~ 30 having escape fractions of 1% between redshift of 2 to 3. We note that the faint end of the higher redshift luminosity functions are ~ 10x fainter than L^*_{UV}, so the detection requirements for the faintest galaxies with similar escape fractions will be 10x lower (although some theorist argue that small galaxies should have high escape fractions).

We will take $f_{900} = 10^{-20}$ erg cm^{-2} s^{-1} Å^{-1} as a representative flux. This is a challenging flux level to reach, requiring a product of effective area, time and bandpass ~ 2.5 x 10^9 cm^2 s Å at 2000 Å to reach a S/N of 5. A telescope with an effective area ~ 15,000 cm^2, observing for ~ 5 hours with either a filter or spectrograph bandwidth of 10 Å can satisfy this requirement, assuming no significant background. Additional requirements include a sample size exceeding 25 objects per luminosity bin per redshift interval to yield an rms deviation of < 20% for each point. The total angular area of the sample should exceed > 1 degree (a the characteristic angular scale BAOs), by a fair margin to beat down cosmic variance. Redshifts are required for each object.

Instrumental Requirements – These observational requirements can be met with a 10 – 12 m class UV telescope with multi-object spectroscopic capability with a spectral resolution of ~ 200 – 1000. The diffraction limit for a 12 m telescope at 2000 Å is ~ 0.003 arcseconds satisfies the spatial sampling requirement. A 2 arcminute wide focal plane at f/24 and 12 m requires a ~170 mm detector FOV. The TRL for such UV detectors and multi-object spectrographs is TRL ~ 5; for 12 m space qualified mirrors diffraction limited at 2000 Å is likely TRL ~ 1. Such a telescope could be compatible with a Habitable-Exoplanet Imaging mission.