OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jun **Proposal type:** short-term

Ionizing Radiation from Galaxies at $z \approx 3$

P.I.: Richard Green (SO; *rgreen@email.arizona.edu*; 520-626-7088)

CoI(s): Xiaohui Fan (SO), Fuyan Bian (ANU), Jill Bechtold (SO), Buell Jannuzi (SO), Dan Stark (SO), Ian McGreer (SO), Romeel Davé (UWC), Kristian Finlator (DCC), Stéphane Charlot (IAP), Alyson Ford (NRAO)

Abstract of Scientific Justification

The goal of the proposed investigation is to measure the escape fraction and infer the spectral shape of ionizing radiation from star-forming galaxies at $z \approx 3$. Models require star-forming galaxies to account for H I reionization, since the population of quasars alone at $z > 3$ is insufficient. However, determining the intensity of Ly continuum radiation produced by the galaxies is very model-dependent, requiring assumptions about the shape of the emergent spectral energy distribution (SED) across the Lyman limit. The details of the SED depend on recent star-formation history (SFH) and the escape fraction of ionizing photons after neutral absorption and dust scattering in the host galaxy. This investigation will explore the direct association of quasar metal absorption-line systems with $z \approx 3$ star-forming galaxies to determine directly the escaping ionizing SED. The observational approach is to exploit the extensive complement of existing data in the NOAO Deep-Wide Survey Bootes field. Bian et al. (2013) analyzed the $z \approx 3$ galaxy luminosity function from a large photometrically selected sample. In that same field, there are 6 AGES quasars with $z > 3.5$ and $R < 19.6$ (as well as 8 with $z > 2.7$) with an average of 12 of Bian's objects per quasar sightline within 2'. The observational program is to observe the quasars at high resolution with MAESTRO on the MMT. Spectroscopic redshifts for the galaxies would come from MODS on the LBT. Each galaxy will have a modeled FUV/NUV SED at energies spanning the Lyman limits of H I to He II and an inferred SED for ionizing the absorbing clouds in the vicinity. From that, the escape fraction as a function of UV wavelength can be determined directly for a significant sample of objects.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT	f/5	MAESTRO	*		4	dark	Mar–May	Feb–Jun	yes	no
2	LBT	f/15	MODS			2	dark	Mar–May	Feb–Jun	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a * appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	NDWFS Bootes Field	14:23:34	+34:34	$R = 19$, $z > 3$ quasars & $R = 25$, $z = 3$ galaxies

Approval for Instrument Use from PI: RG&JB are PI approvers for MAESTRO

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

The goal of the observing program is to measure the escape fraction and infer the spectral shape of ionizing radiation from star-forming galaxies at $z \approx 3$. Star-forming galaxies are required by models to account for HI reionization, since the population of quasars alone at high z is insufficient. It is difficult, however, to translate measurements of the luminosity function (LF) of distant galaxies into predictions of the reionization history, because of significant uncertainties in the spectral energy distribution (SED) of the galaxies, in the fraction of ionizing photons that escape into the intergalactic medium (IGM) and in the contribution of fainter, as of yet undetected galaxies.

Several analyses have explored the connection between the galaxy luminosity function (LF) at high z and the transmission of the Lyα forest (e.g., Shull et al. 2012). Other studies have tied the evolving LF to the Lyα forest at lower redshifts after H reionization is complete (e.g., Haardt & Madau 2012, Kuhlen & Faucher-Giguère 2012). Lyα forest data are best determined for $z < 6$, when reionization is probably complete on average. The even lower-z Lyα forest provides valuable constraints in two ways. First, realistic reionization scenarios should continuously connect to the post-reionization IGM probed by the forest. Secondly, measurements of the galaxy UV LF are available over the full redshift interval covered by the Lyα forest data. Where the data overlap, comparison of the Lyα forest and the UV LF provides constraints on the escape fraction (f$_{esc}$) and minimum luminosity down to which the LF must be integrated in order to account for all the ionizing photons measured using the forest. Since f$_{esc}$ and the UV LF faint-end are degenerate if all that is known is the ionizing emissivity, then actually measuring f_{esc} breaks that degeneracy and allows valid extrapolation to higher z.

However, determining the intensity of Lyman continuum radiation produced by the galaxies is very model-dependent, requiring assumptions about the shape of the emergent spectral energy distribution beyond the Lyman limit, which depends on recent star-formation history and the escape fraction of ionizing photons after neutral absorption and dust scattering in the host galaxy (and IGM). The proposed program will explore the association of metal absorption-line systems with $z \approx 3$ star-forming galaxies along quasar sightlines, to infer more directly the shape of the ionizing spectrum emerging from the galaxies. Models show galaxies still dominating the H I ionizing background at redshifts as low as 3; below that, quasars take over (Fig.1).

The reason that galaxies dominate at $z \geq 3$ is the relatively sharply peaked quasar LF at $z \approx 2$. Although Faucher-Giguère et al. (2009) used the integral determination of Hopkins et al. (2007) for Fig. 1, that qualitative behavior of the quasar LF remains the same, even for the more definitive determination from SDSS of Ross et al. (2013). Haardt & Madau (2012) used a different determination of the quasar LF with respect to ionizing flux, getting a higher overall contribution. In that case, star-forming galaxies do not dominate the contribution to diffuse ionization until $z \approx 3.3$. Derivation of the quasar diffuse ionizing flux is complicated by the correction for the quasar escape fraction, which probably does not exceed 50% at these redshifts for luminous quasars and likely decreases substantially for lower luminosity objects. With those corrections, star-forming galaxies may well dominate to somewhat lower redshifts. This proposed investigation will be sensitive to the change in the mix of ionizing sources over that critical redshift interval.

An examplar of recent observational determinations is that of Steidel and his collaborators (Rudie et al. 2012). They observed the Lyα forest in 15 sightlines of quasars in the immediately lower interval of $2.5 < z < 2.9$, around which they also imaged and obtained spectra for 886 galaxies with $2.0 < z < 2.8$. A key result was that nearly half of absorbers with $logN(HI) > 15.5$ were within the circum-galactic medium (CGM) of measured galaxies, while occupying only 1.5% of the volume. After correcting for that effect, they found that the mean free path for a Lyman limit photon considering only IGM opacity is 147 Mpc at $z \approx 2.4$ (Rudie et al. 2013), and reduced to 121 Mpc if the CGM effects are included. That value is smaller than several previous values in the literature, with implications for the number density or escape fraction of ionizing sources in their redshift range.

Relating the changing ionization state of the IGM directly to the evolving population of star-forming galaxies requires much more knowledge than we currently have. The unseen ionizing spectrum radiated by the full ensemble of stars in a galaxy depends sensitively on the star formation history (SFH) and on the metallicity of the contributing populations. The spectrum of the radiation that actually escapes from the galaxy is strongly modified by internal absorption and scattering from both gas and dust. Regions of extremely active star formation can blow out the interstellar medium, creating a transparent view to a relatively small subregion of the galaxy. Extrapolating that observed spectrum to represent the full mass as determined from IR luminosity poses considerable uncertainty. Nestor et al. (2013) provide the current benchmark determination of the escaping H I ionizing flux from Lyman Break (LBG) and Lyman Alpha Emitting Galaxies (LAE) at $z \approx 3$. They find that the diffuse intensity actually exceeds the requirement to keep the IGM ionized, although it is consistent within the errors. They derive an escape fraction of 5-7% for the LBGs and 10-30% for the fainter LAEs. The fiducial model of Kuhlen & Faucher-Giguère (2012) of the ionizing flux from star-forming galaxies with a range of luminosities bounds an escape fraction from 2-8%, with a median of 4% at $z \approx 4$.

This investigation will use the absorbing systems detected along quasar sightlines as probes of the ionizing conditions at varying impact parameters from $z \approx 3$ galaxies projected near those lines of sight. The ionization state of the CGM for absorption systems with galaxies of low impact parameter is a direct probe of the escaping ionizing flux. Use of metal line absorption with a range of ionization probes the SED over a factor of 4 in energy from the Lyman limit. The modeling apparatus of Finlator and Davé will be used to construct best-fitting ionizing spectra as a function of impact parameter from the projected foreground galaxies. Direct comparison to the predicted ionizing flux from stellar population synthesis allows the determination of the wavelength-dependent absorption and scattering for each close projection, the escape fraction as a function of energy. From the properties of absorbers well separated from luminous individual sources, the shape of the diffuse ionizing spectrum can be derived, and compared as a sanity check to previous determinations from published absorption systems. If that shape is significantly different from the ensemble of inferred CGM ionizing spectra from individual sources, we have evidence of the influence of the less luminous galaxies that cannot be directly observed spectroscopically, with either different covering fractions as functions of wavelength, or different effective stellar populations producing the ionizing continuum.

Analysis of the quasar absorption systems will concentrate on the metal lines rather than the Lyα forest to gain information over a factor of 5 in energy of the ionizing spectrum. CII, C IV, Si II, Si IV, N V, and O VI line ratios probe the depth of the H I, He I, and He II troughs in the ionizing continuum SED. Haardt & Madau (2012) models that contain a quasar/galaxy mixed ionizing SED at $z \approx 3$ fit the ratios for many known systems. Fig. 2 shows various models of the SED of the diffuse ionizing radiation, and their fits to quasar absorption line ratios (by component) as input to photionization calculations. A substantial fraction of systems are not well modeled by the assumed spectral shape. The plots also show modifications to the shape of the diffuse ionizing spectrum that encompass more of the observations. Multiple explanations for the change of shape are possible; as discussed below, a more sophisticated projection of the emitted ionizing spectrum from the galaxies would be an important improvement.

Our framework for providing a robust theoretical interpretation of metal absorbers involves cosmological radiation hydrodynamic simulations in which gas cooling, star formation, galactic outflows, and the ionizing background owing to star-forming galaxies are all modeled self-consistently. The treatments for hydrodynamics, star formation, and galactic outflows are detailed in Oppenheimer & Davé (2008). We have verified that our method performs well in idealized tests, hence it is a complete framework for solving problems in a cosmological setting. Our simulations will predict the spatially-resolved abundances of carbon, silicon, oxygen, and iron as well as the local radiation field. We will then use a ray-casting approach coupled with an ionisation solver to produce mock quasar spectra. In Finlator et al. (2013), we used this framework to model OI absorbers at z=6, finding reasonable agreement with the observed number of systems per path length. Thanks to a new multifrequency radiation transport solver, we can now model high-ionization systems as well. Our first study shows agreement with observations of CII and CIV absorbers throughout z=3 to 6 (Finlator et al. 2014). More importantly, we find that the radiation field experienced by metal absorbers is significantly enhanced by the local galaxy, emphasising the current proposal's value.

References

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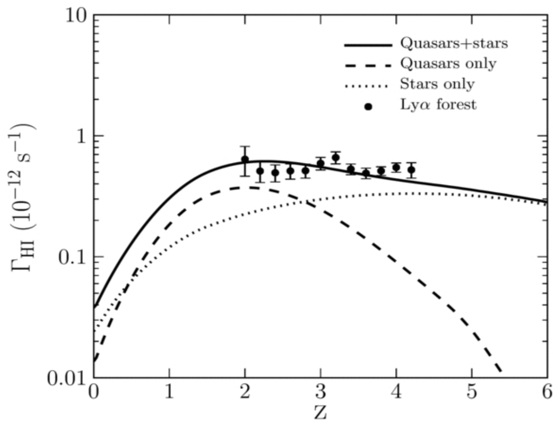

Fig 1. Photoionization rate of H I from Faucher-Giguère et al (2009), showing the epochs at which galaxies dominate.

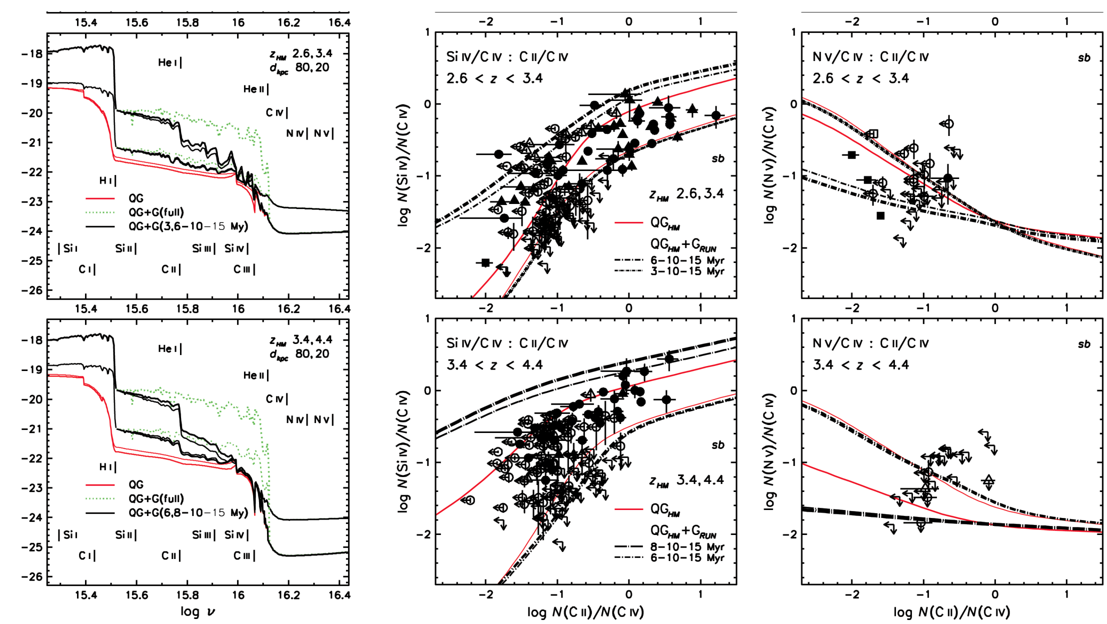

Fig. 2 Derivations of the diffuse ionizing continuum SED and fits to observed quasar absorption line ratios from Boksenberg (2013), based on Boksenberg et al. (2003).

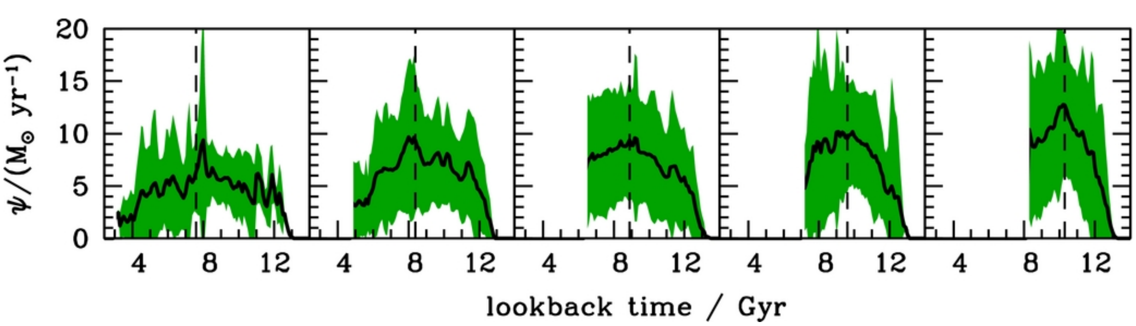

Fig. 3. Star Formation Histories for high-mass galaxies at z~1 modeled by the hierarchical-assembly based synthesis code of Pacifici et al. (2013). Note that they are significantly different from single-burst and exponential decay models, with the effect that more high-mass stars are likely to be present when figuring the emitted ionizing flux.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

The project exploits the extensive complement of existing data in the NOAO Deep-Wide Survey Bootes field (Jannuzi & Dey 1999). Bian et al. 2013 analyzed the $z \approx 3$ galaxy luminosity function from a photometrically selected sample of 14,485 galaxies down to a limiting magnitude of $R \approx 25.0$, corresponding to $M_{1700} \approx -20.5$, which is the fitted value of M* for combined surveys. Over the area of the NDWFS field, that leads to a surface density of ≈0.5 object/sq.arcmin, with $2.7 < z < 3.3$, which gives a natural basis for selection of foreground galaxy groups close to quasar sightlines. In that same field, the AGES survey has identified over 4000 quasars; specifically, there are six quasars with $z > 3.5$ and $R < 19.6$ (as well as eight additional with $z \geq 2.7$). There are on average twelve ≈ 3 galaxies within 2' of the quasar sightlines, and a comparable number with $2.3 < z < 2.7$.

The observational program has two major components. One is to observe the quasars with MAESTRO on the MMT to measure the metal-line absorbers associated with the galaxies along the sightline. It delivers a spectral resolution of $\approx 25,000$ in median $0.7''$seeing through a $1''$slit. The brighter objects have already been observed at moderate dispersion with Blue Channel, so the priority will be placed on those with metal absorbers in the redshift range of interest. With the currenly measured throughput, a quasar with $R \approx 19.6$ would take 10 hours of exposure for S/N = 20:1 in the continuum per spectral resolution element under good conditions. The combined sample has 6 quasars with $R \leq 19.0$, so we can tolerate some variability in conditions. The total request for this year is therefore for 4 nights of dark time; should the data for the first 3-4 objects be of expected quality, an additional request would follow in a year.

To associate absorption systems with local sources of ionization, spectroscopic redshifts are needed for the photometrically selected galaxies. These will be obtained from multi-object mask observations with MODS on the LBT. In good transparency and median or better seeing, two-hour total exposures will capture the LAEs down to the limit of $R \approx 25.0$, and give 3σ continuum detections for the LBGs at $R \approx 500$ with full spectral coverage in dual-grating mode. At three fields per night we request two nights to cover the majority of the high-z sightlines.

For each proximate galaxy we will derive the observed SED based on the NDWFS photometry and additional spectral information in the rest-frame UV. Bian et al. (2013) found that approximately half the $z \approx 3$ candidate galaxies for $22.0 < R < 22.5$ had IRAC detections in both the $[3.6\mu]$ and $[4.5\mu]$ bands and $[3.6] - [4.5] > 0.0$. The latter condition eliminates low-redshift interlopers. The mid-IR detections allow a strong anchor of the SED near the peak of the stellar flux contribution.

The emitted ionizing SED will then be predicted from modeling the observed SED at energies below the Lyman limit with the SFH approach of Charlot's group, as described in Pacifici et al (2013), which goes beyond a simple tau model of a single burst to include hierarchical assembly. The technique uses a comprehensive library of star-formation and chemical enrichment histories tied directly to semi-analytical models of hierarchical galaxy assembly of De Lucia & Blaizot (2007). A library of one million SEDs is constructed by combining the library of SFH and chemical enrichment history with the latest version of the Bruzual and Charlot stellar population synthesis models, with the galaxy nebular emission model of Charlot & Longhetti (2001), and with the two-component dust model of Charlot & Fall (2000). The Bayesian approach adopted by Pacifici et al. (2012) is applied to constrain the stellar masses, star-formation rates, and SFHs of the galaxies in the observational sample. The typical SFH for the best-fitting synthesized SED is much more extended in time than that imposed by a τ (single burst) model, as shown in Fig 3. That outcome will obviously increase the modeled number of more massive stars still available to contribute to the ionizing SED. The individual galaxies to be measured at $2 < z < 3$ are clearly at an early stage of assembly, making the distinction with τ models all the more important. The predictions of these models will be optimized by using updated prescriptions of the ionizing spectral energy distributions of young galaxies, which have been shown to provide good fits to the ultraviolet and optical nebular emission of star-forming galaxies at $2 < z < 3$ (Stark et al. 2014, MNRAS, in press). Each galaxy near a quasar sightline will then have a modeled FUV/NUV SED at energies spanning the Lyman limit, including dust absorption and scattering.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

4 nights on MMT Blue channel and 2 nights on LBT MODS are the full request for this year.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). **(up to one page)***

The PI received 3 nights in April/May of this year on MMT Blue Channel for observations of faint quasars for determining the luminosity function. The observations are reduced and analysis is underway. Note that Bian's thesis observations were published in Bian et al. (2013).