

AN OBSERVATIONAL STUDY OF QUASAR HOST GALAXIES, RADIO
GALAXIES, AND LYMAN ALPHA EMITTERS

by

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Chapter 1

Introduction

This thesis is divided into three extragalactic observational studies focused on the properties of quasar host galaxies, radio galaxies, and Lyman alpha emitters (LAEs) at a redshift of one. In this Chapter, I give background and motivation for each topic. Chapters 2, 3, and 4 address each topic in turn. In Chapter 5, I discuss my plans for future studies of the $z \sim 1$ LAE sample.

1.1 Stellar Ages of Quasar Host Galaxies

An active galactic nucleus (AGN) is an accreting supermassive black hole (SMBH) near the center of its host galaxy. AGN display a wide range of observational features across the entire electromagnetic spectrum. Starting from the radio and proceeding to shorter wavelengths, we may observe varying degrees of the following features: 1) radio emission originating from synchrotron radiation in relativistic jets, 2) infrared (IR) emission due to thermal re-processing of ultraviolet (UV) photons by dust surrounding the AGN, 3) optical and UV emission attributed mainly to thermal emission from the accretion disc, and 4) X-ray emission from inverse Compton scattering of UV photons by relativistic electrons found in the corona of the accretion disc and sometimes the jet.

The features observed are thought to depend heavily on the orientation of the AGN with respect to an obscuring dusty torus (Antonucci 1993; Urry & Padovani 1995). This is called the unified model of AGNs and was proposed to explain the differences between type 1 and type 2 AGNs (see Figure 1.1). Type 1 AGNs have an orientation unblocked by the torus and display features indicative of processes occurring close to the SMBH. These features include broad emission lines and prominent optical and UV continuum light. On the other hand, type 2 AGNs are obscured by

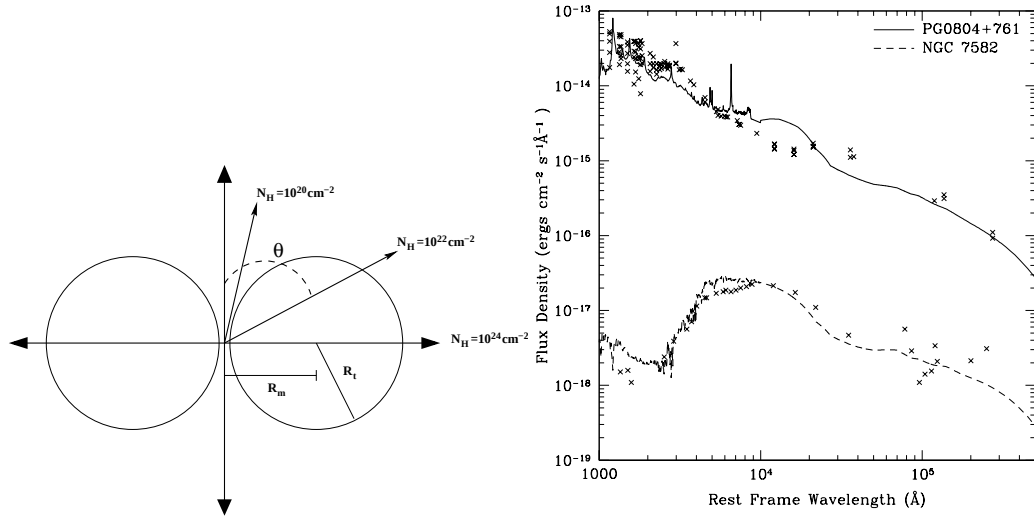


Fig. 1.1. — : **Right** The cross section of a simple dusty torus based on the AGN unification paradigm. **Left** Using this framework, spectral energy distributions for unobscured (top) and obscured (bottom) AGNs. Data points show observed flux density measurements for two local AGNs. Both right and left figures are reproduced from Urry & Treister (2007).

the torus and display narrow emission lines and strong IR continuum light.

For the purposes of this thesis, I study high luminosity type 1 AGNs with $M_V(\text{nuc}) < -23$, hereafter referred to as quasars.

If a small fraction of AGN energy output can be efficiently used to heat the surrounding environment (AGN feedback), then this can have a profound impact on the evolution of the host galaxy. AGN feedback has been employed to explain a large number of observables, including the absence of overly massive galaxies, the SMBH mass vs. bulge mass correlation, the formation of elliptical galaxies, and the similarity of SMBH accretion and star formation histories (Tabor & Binney 1993; Silk & Rees 1998; Springel et al. 2005; Hopkins et al. 2006; Croton et al. 2006; Cattaneo et al. 2006).

Of particular relevance to my study, a dominant picture for the formation and

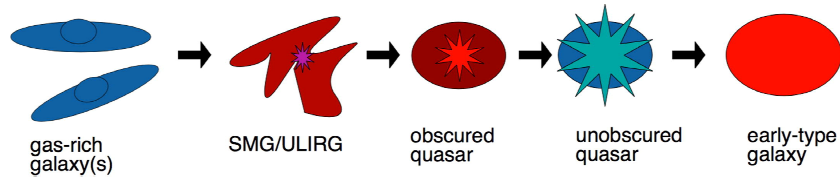


Fig. 1.2. — : Cartoon depiction of elliptical galaxy formation, reproduced from Alexander & Hickox (2012).

evolution of elliptical galaxies links galaxy mergers, starbursts, and quasars (e.g., see Sanders et al. 1988; Hopkins et al. 2006, and Figure 1.2). To first order, a gas-rich merger induces gas inflow triggering both star formation and quasar activity. Some small percentage of quasar energy output is converted to thermal energy, assisting in the stoppage of further star formation and quasar activity. The resulting merger remnant then passively evolves into an elliptical galaxy.

This proposed close link between gas-rich mergers, starbursts, and quasar activity is observationally supported by evidence for recent star formation in galaxies hosting quasars (Canalizo & Stockton 2001; Miller & Sheinis 2003; Jahnke et al. 2004; Letawe et al. 2007). However, other studies (McLure et al. 1999; Hughes et al. 2000; Nolan et al. 2001; Dunlop et al. 2003) present evidence in support of local quasars predominantly residing in normal massive elliptical galaxies. The discrepancies in these studies may be due to relatively small sample sizes and systematics. For example, if not properly accounted for, the strong emission from the central point source can mimic a young stellar population in the quasar host galaxy. Additionally, there are other results suggesting that major mergers are not responsible for triggering AGN activity (e.g., Kocevski et al. 2012); however, for high luminosity AGNs (such as quasars), it is generally agreed that mergers play an important role (e.g., Treister et al. 2012).

Modulo deficiencies in AGN unification models, quasar hosts can be studied via their type 2 counterparts. Using this strategy, most of the optical and UV continuum light from the AGN is obscured, allowing for a more direct study of the host galaxy's stellar population. Additionally, large samples of these type 2 objects have been identified by the Sloan Digital Sky Survey (SDSS). From 4000 Å break measurements, Kauffmann et al. (2003) found that high luminosity AGNs have younger mean stellar ages than normal early-type galaxies. Additionally, they found that a large fraction of powerful type 2 AGNs have experienced significant starbursts in the past 1-2 Gyr. However, the powerful ($L[\text{OIII}] \sim 10^{41} \text{ erg s}^{-1}$) AGNs studied by Kauffmann et al. (2003) are about one magnitude fainter than the nuclear luminosities found in quasar studies. For this reason and for potential deficiencies in AGN unification models, additional study is required to develop a clear understanding of quasar host galaxies.

In Chapter 2 of my thesis, I develop and implement a method to provide stellar age constraints for the host galaxies of nearby ($z < 0.3$) quasars. The observational strategy is to observe spectroscopically quasar host galaxies offset from the bright central point source to maximize the signal-to-noise of the stellar light. The central quasar is also spectroscopically observed, so that any nuclear light scattered into the off-axis spectrum can be efficiently modeled and subtracted. In my analysis, I subtract residual scattered quasar light, while simultaneously modeling the constituent stellar populations of the host galaxy. I test the reliability of this technique via a Monte-Carlo routine in which the correspondence between synthetic spectra with known parameters and the model output is determined. I apply this model to a preliminary sample of 10 objects, and I compare my results to previous studies.

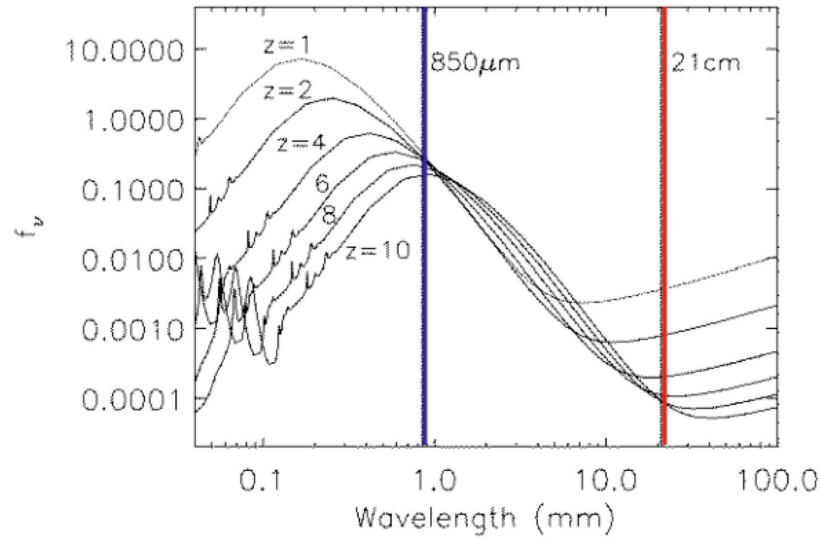


Fig. 1.3. — : Typical submillimeter galaxy spectral energy distribution at $z = 1 - 10$. The vertical blue and red lines highlight the submillimeter and radio bands, respectively.

I show that this technique has many advantages, especially for objects with high nucleus-to-host flux ratios.

1.2 Deep Radio Surveys of the A370 and A2390 Cluster Fields

Early radio surveys were mainly limited to extremely bright (> 1 mJy) and rare objects consisting of radio quasars and radio galaxies. These surveys, while providing some of the highest redshift objects known at the time, were clearly not representative of the objects found in non-radio surveys. Current deep radio surveys are able to reach flux densities of ~ 10 μ Jy and consist mainly of star-forming galaxies and radio-quiet AGNs. For star-forming galaxies and AGNs, synchrotron

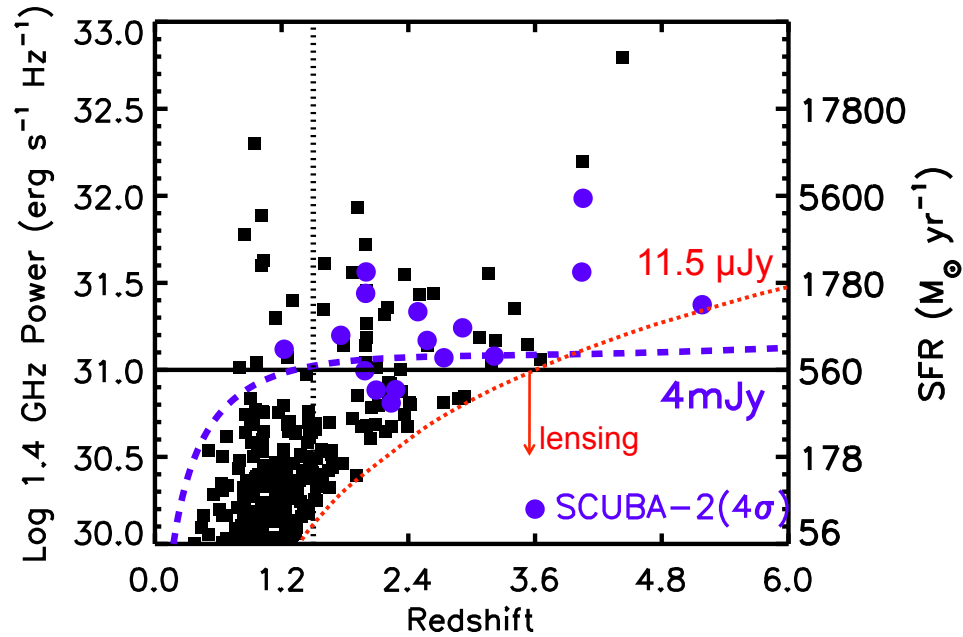


Fig. 1.4. — : Radio luminosity vs. redshift for all $L_{1.4 \text{ GHz}} > 10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$ GOODS-N radio sources with spectroscopic or photometric redshifts (black squares). This cutting edge Karl G. Jansky Very Large Array survey has a 5σ flux limit of $11.5 \mu\text{Jy}$ (red dotted curve). A red arrow indicates the effect of gravitational lensing magnification on the effective flux limit. The blue dashed curve shows the flux limit obtainable with a deep submm SCUBA-2 survey. This curve is computed by converting a 4 mJy $850\mu\text{m}$ flux limit into a radio luminosity assuming an Arp 220 spectral energy distribution (as shown in Figure 1.3). Blue circles show radio sources with submm counterparts. This figure is adapted from Barger et al. (2014).

radiation is emitted, respectively, from supernovae and relativistic jets. These deep radio surveys are now able to provide key information about the nature of objects typically studied in non-radio bands.

To illustrate this point, I discuss a field of study where deep radio surveys have been essential due to their high-resolution unobstructed view of the universe. Submillimeter (Submm) galaxies are dust obscured star-forming galaxies that can have star formation rates in excess of 1000 solar masses per year. However, submm galaxy surveys observed with single dish submm telescopes have very poor resolution,

and the submm sources are not easily found in rest-frame UV or optical catalogs due to their large extinctions. Deep radio data, which are very sensitive to star-forming galaxies and not obstructed by dust, have proven useful for pinpointing the counterparts of the submm galaxies for spectroscopic and multiwavelength study (e.g., Barger et al. 2000; Ivison et al. 2002; Chapman et al. 2003).

With the help of radio data, we now know that bright submm galaxies are predominantly massive star-forming galaxies at a median redshift of ~ 2.2 (Chapman et al. 2005). An extremely massive and dusty population occurring so early in cosmic time places strong constraints on models of galaxy evolution. If these objects are already common at high redshifts ($z > 4$), then they could pose a significant challenge to Λ CDM models of galaxy evolution (e.g., Granato et al. 2004; Baugh et al. 2005; Hopkins et al. 2005; Lukić et al. 2007). For this reason, accurately determining the redshift extent of the submm galaxy population is an area of intense study.

In Figure 1.3, I show that submm observations are a redshift independent probe (due to a negative K-correction; $1 < z < 8$) of dusty star-forming galaxies, while the positive K-correction of the radio band results in faint observed 1.4 GHz fluxes for high-redshift objects. However, in Figure 1.4, I show that deep radio images of lensing cluster fields have the potential to detect the majority of the high-redshift submm sources. Thus, deep radio surveys continue to be an important means of investigating these high-redshift objects.

In Chapter 3 of my thesis, I contribute to this field by presenting 1.4 GHz catalogs for the cluster fields A370 and A2390 observed with the Very Large Array. I construct differential number counts for each field and find results consistent with previous studies. I emphasize the need to account for cosmic variance. These high

resolution, ultra-deep radio catalogs will be vital to future multiwavelength studies.

1.3 $z \sim 1$ LAEs

$\text{Ly}\alpha$ emission is a primary tool for studying the highest redshift galaxies. Furthermore, $\text{Ly}\alpha$ emission is one of the very few probes of the reionization period. In particular, a sharp decline in the number density of $\text{Ly}\alpha$ emitters (LAEs) at high redshift is expected as we probe closer to the epoch of cosmic reionization (e.g., Miralda-Escudé & Rees 1998; Malhotra & Rhoads 2006). To interpret future $\text{Ly}\alpha$ based surveys, we need to understand the properties that facilitate the escape of $\text{Ly}\alpha$ emission and how LAEs are drawn from the overall galaxy population. In particular, we need to bridge the gap from low-redshift surveys, where LAEs can be studied in detail, and higher redshift surveys, where $\text{Ly}\alpha$ is one of the only observable emission lines.

To first order, the intrinsic production of $\text{Ly}\alpha$ photons in a galaxy is proportional to the star formation rate (Kennicutt 1998; Schaerer 2003). However, $\text{Ly}\alpha$ photons are resonantly scattered by neutral hydrogen until they escape or are absorbed by dust. Thus, a star-forming galaxy may have strong $\text{Ly}\alpha$ emission due to a favorable geometry, dust content, kinematics, neutral column density, or some combination of these factors. This makes the observed $\text{Ly}\alpha$ flux and line profile notoriously hard to interpret (e.g., Neufeld 1991; Kunth et al. 2003; Finkelstein et al. 2007; Schaerer & Verhamme 2008; Östlin et al. 2009).

The baseline model for LAEs is a central $\text{Ly}\alpha$ source surrounded by an expanding shell of neutral hydrogen with some entrained dust content (e.g., see Figure 1.5). This picture is motivated by the idea that LAEs are starbursting galaxies ca-

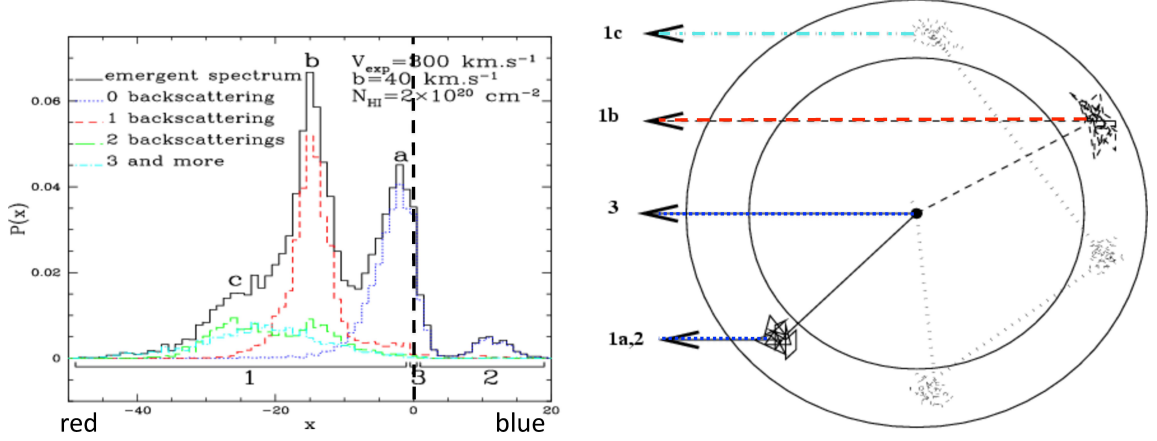


Fig. 1.5. — : Baseline radiative transfer model for LAEs, adapted from Verhamme et al. (2006). In this example, a central monochromatic Ly α source has its emergent line profile altered by an expanding dust-free shell. A general characteristic of these expanding shell models is a red ($x < 0$) asymmetric Ly α profile.

pable of driving large outflows. These models are able to reproduce red asymmetric Ly α lines that resemble observations. However, at high redshifts the intergalactic medium (IGM) may also absorb a significant portion of the blue wing of the Ly α line. Furthermore, there are studies that indicate that this simple expanding shell model is not consistent with all observables (e.g., Kulas et al. 2012). Clearly, observational constraints – ideally without intervening IGM – are needed to help us understand what factors play the dominant role in determining whether a star-forming galaxy is or is not a LAE.

Recently, a substantial $z \sim 0.3$ LAE sample and a handful of $z \sim 1$ LAEs have been found by searching for emission-line objects in *Galaxy Evolution Explorer* (GALEX; Martin et al. 2005) FUV and NUV pipeline spectra, respectively. The advent of these low-redshift LAE catalogs (Deharveng et al. 2008; Cowie et al. 2010) has been very exciting, and many follow-up papers have been written (e.g., Finkelstein et al. 2009a,b; Atek et al. 2009; Scarlata et al. 2009; Cowie et al. 2011). Since

the *GALEX* grism pipeline only includes objects whose UV continuum magnitudes are bright enough to generate measurable continuum spectra, only a fraction of the emission-line objects are extracted. However, the procedure enables the selection of a substantial sample of $z \sim 0.3$ sources. When compared to $z \sim 0.3$ UV-continuum selected galaxies, these $z \sim 0.3$ LAEs appear to be relatively young, compact, and metal poor (Cowie et al. 2010, 2011).

However, it is not clear that the properties of these low-redshift ($z \sim 0.3$) sources are representative of high-redshift LAEs. At the most fundamental level, LAEs are about an order of magnitude fainter at $z \sim 0.3$ than they were in the past, but there may be many other changes in their properties (e.g., Finkelstein et al. 2009b). The first redshift where LAEs comparable in luminosity to the high-redshift galaxies are seen is $z \sim 1$. However, only a handful of $z \sim 1$ LAEs have *GALEX* detectable continuum spectra. Thus, we need to remove the pipeline’s continuum-selection requirement ($\text{NUV} < 22$) in order to study a large sample of $z \sim 1$ LAEs.

In Barger, Cowie, & Wold (2012), we solved this problem by obtaining a flux-limited sample of $z \sim 1$ LAEs for the *Chandra* Deep Field-South (CDFs). To do this, we converted the multiple *GALEX* grism images into a three-dimensional (two spatial axes and one wavelength axis) data cube. We then treated the wavelength “slices” as narrowband images in which we searched for emission-line galaxies. Through simulations, we showed that we could recover more than 80% of the sources with $f(\text{Ly}\alpha) \gtrsim 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$, which corresponds to $L(\text{Ly}\alpha) \gtrsim 10^{42.5} \text{ erg s}^{-1}$ at $z \sim 1$. By comparing our sample to X-ray data, existing optical spectroscopy, and deep *U*-band imaging, we determined that nearly all of our new LAEs are real and that the UV spectroscopic redshifts based on the $\text{Ly}\alpha$ identifications are reliable.

In Chapter 4 of my thesis, I apply the data cube search method to all of the deepest *GALEX* grism fields (CDFS-00, 353 ks; GROTH-00, 291 ks; NGPDWS-00, 165 ks; COSMOS-00, 140 ks), which correspond to some of the most intensively studied regions in the sky. This work provides the first large sample of $z = 0.67 - 1.16$ LAEs (N=60) that can be used to investigate the physical properties of these galaxies. I catalog the candidate $z \sim 1$ LAE samples in each field and give optical redshifts from both archival and newly obtained observations. With X-ray, UV, and optical data, I determine the false detection rate (cases where the emission line is either not confirmed or is not Ly α) and the AGN contamination rate of my sample. With the remaining LAEs, I compute the LAE galaxy luminosity function (LF) at $z \sim 1$ and use this to investigate the evolution of the Ly α LF and the Ly α escape fraction over the redshift range from $z \sim 0.3$ to $z \sim 2$.

There are relatively large samples of known LAEs at redshifts of $z \sim 0.3$ and $z \sim 2$. Thus, my sample of $z \sim 1$ LAEs is useful for mapping the evolution of LAEs over a ~ 7 Gyr gap. This redshift regime is where the star-forming properties of galaxies change very rapidly and where the star formation begins to decline. This will be a key sample for connecting the low luminosity LAE sample at $z \sim 0.3$ to the higher luminosity LAE samples at $z \sim 2$.

In Chapter 5 of my thesis, I discuss my work in progress to constrain the physical properties of the $z \sim 1$ LAE sample. My first goal is to establish a UV-continuum selected $z \sim 1$ sample with luminosities and redshifts similar to the LAE sample but lacking Ly α emission. This will allow me to make relative measurements of various physical properties to determine what distinguishes LAEs from non-Ly α emitting star-forming galaxies. I present my efforts to date to establish this UV-

continuum selected control sample, and I present some preliminary results.

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Chapter 2

Host Galaxies of Luminous Quasars: Population Synthesis of Optical Off-Axis Spectra

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Abstract

There is increasing evidence of a connection between AGN activity and galaxy evolution. To obtain further insight into this potentially important evolutionary phase, we analyze the properties of quasar host galaxies. In this paper, we present a population synthesis modeling technique for off-axis spectra, the results of which constrain host color and the stellar ages of luminous quasars ($M_V(nuc) < -23$). Our technique is similar to well established quiescent-galaxy models, modified to accommodate scattered nuclear light (a combination of atmospheric, instrumental and host galaxy scattered light) observed off axis. In our model, subtraction of residual scattered quasar light is performed, while simultaneously modeling the constituent stellar populations of the host galaxy. The reliability of this technique is tested via a Monte-Carlo routine in which the correspondence between synthetic spectra with known parameters and the model output is determined. Application of this model to a preliminary sample of 10 objects is presented and compared to previous studies. Spectroscopic data was obtained via long-slit and integral-field unit observations on the Keck and WIYN telescopes. We confirm that elliptical quasar hosts are distinguishable (bluer) from inactive ellipticals in rest frame $B-V$ color. Additionally, we note a trend for radio luminous ($L_{5GHz} \gtrsim 10^{40} \text{ erg s}^{-1}$) quasars to be located in redder host galaxies in comparison to their less radio luminous counterparts. While the host color and age of our radio luminous sample is in close proximity to the green valley, our radio faint sample is consistent with quiescent star-forming galaxies. However, further ob-

servations are needed to confirm these results. Finally, we discuss future applications for our technique on a larger sample of objects being obtained via SALT and WIYN telescope observing campaigns.

2.1 Introduction

It is well established that active galactic nucleus (AGN) activity is due to accretion onto super massive black holes (SMBHs). Additionally, SMBHs are found to be common, existing in most, if not all, massive galaxies. Observationally, the SMBH mass is found to be tightly correlated to the bulge velocity dispersion raised to the fourth power (Gebhardt et al. 2000). However, the bulge extends well outside the gravitational influence of the SMBH. This correlation has led to the hypothesis that the bulge and SMBH co-evolve (Kormendy 2000). Additionally, models of galaxy evolution must include regulation mechanisms to adjust and quench star formation in massive galaxies after early times to prevent the over production of bright galaxies (Benson et al. 2003).

Evidence pointing toward the co-evolution of SMBHs / bulges and the need for regulation mechanisms has led to models which utilize AGN feedback to quench star formation. An example of a model of relevance to our studies is the hydrodynamic simulations of Hopkins et al. (2006). In this model, gas rich mergers induce gas inflow triggering both star formation and quasar activity. Some small percentage of AGN energy output is converted to thermal energy, assisting in the stoppage of further star formation and accretion. Simulations, which feature self-regulated SMBH growth, have been successful in reproducing various observables, such as the bimodal color-magnitude distribution (Cattaneo et al. 2006). However these models must operate on a very large range of scales (μpc - Mpc) and must incorporate many physical processes. Therefore it is desirable to further constrain these models observationally.

The goal of this work is to develop an off-axis method to provide stellar age and host color constraints during the quasar phase.

Unfortunately, studies of the underlying stellar populations are hampered by the overwhelming emission from the central quasar. Consequentially, progress has been slow and, in some cases controversial, in the struggle to place observational constraints on quasar host galaxies. One group of collaborators (McLure et al. 1999; Hughes et al. 2000; Nolan et al. 2001; Dunlop et al. 2003) believes that local quasar ($M_V(nuc) < -23.5$) hosts are predominantly normal massive elliptical galaxies. However, *Hubble Space Telescope (HST)* morphology (Hooper, Impey & Foltz 1997; Bennert et al. 2008), multicolor imaging (Jahnke, Kuhlbrodt & Wisotzki 2004), and spectral studies (Canalizo & Stockton 2001; Miller & Sheinis 2003) have

Table 2.1. : Test sample properties. $M_V(nuc)$ is the V-band absolute magnitude of the quasar. $M_V(host)$ is the V-band absolute magnitude of the host galaxies. Both of these quantities are derived from Bahcall et al. (1997) when possible, see Wolf & Sheinis (2008) for details. Radio luminosity is estimated utilizing the NASA/IPAC Extragalactic Database and assuming spectral index of -0.5. Host morphology is obtained via Hamilton, Casertano & Turnshek (2002). 'E' denotes elliptical and 'S' denotes spiral.

Object name	Redshift	$M_V(nuc)$	$M_V(host)$	$\log(L_{5GHz})$ erg s ⁻¹	Host morphology
3C 273	0.1583	-26.7	-23.2	44.1	E
4C 31.63	0.2950	-25.1	-25.1	43.3	E
PKS 1302-102	0.2784	-25.9	-22.9	43.0	E
PKS 0736+017	0.191	-23.2	-22.6	43.0	E
PKS 2135-147	0.2003	-24.7	-22.4	42.9	E
PKS 2349-014	0.1740	-24.5	-23.2	42.5	E
PG 1309+355	0.1840	-24.4	-22.8	41.3	S
PHL 909	0.171	-24.1	-22.2	40.0	E
PG 0052+251	0.1550	-24.1	-22.5	39.4	S
PG 1444+407	0.2673	-25.3	-22.7	39.2	S

found evidence inconsistent with a population of normal relaxed ellipticals. In fact, an on-axis spectroscopic study probing the inner region of nearby quasar hosts found young Sc-like stellar populations in half of their sample (Letawe et al. 2007). The discrepancies in these studies may be due to relatively small sample sizes, systematics, and the different radii probed (Lacy 2006). Additional study is required to develop a clear understanding of stellar properties of nearby luminous quasar hosts.

In Wolf & Sheinis (2008) we presented velocity dispersion measurements of a sample of nearby luminous quasar host galaxies. Future work will examine the relation between SMBH mass and velocity dispersion. In this paper, we develop a method to measure the stellar age and color of nearby quasar host galaxies at off-axis radii of 9 to 15 kpc. We observe off-axis spectra to minimize the observed quasar emission, thereby maximizing signal-to-noise. However even in off-axis observations, described in Section 2.2, scattered light from the central source can still contribute significantly to the observed light. Our technique of removing this scattered light is similar to previous studies (Boroson, Persson & Oke 1985; Miller & Sheinis 2003) and described in detail in Section 2.3.1. The modeling of the host spectra (Section 2.3.1) and the error estimation technique (Section 2.3.2) are based on quiescent galaxy models (Tremonti 2003; Cid Fernandes et al. 2005, hereafter CF05). Application of our model to our preliminary sample is found in Section 2.4. A comparison to recent spectroscopic and photometric studies is found in Section 2.5. Summary and conclusions are presented in Section 2.6. Appendix A contains comments on individual objects. Throughout this paper a cosmology of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ is adopted.

2.2 Observations

2.2.1 Sample

Our spectroscopic observing campaign has resulted in a sample of 28 nearby luminous quasars. This sample consists of objects previously imaged by Bahcall et al. (1997), with the addition of a few objects from Dunlop et al. (2003) and Guyon, Sanders & Stockton (2006). We demonstrate the capabilities of our spectral synthesis model on a subset of 10 objects. These objects have spectral data that display sufficient signal-to-noise and stellar continuum to constrain the stellar properties via the method discussed below. Additionally, this subset of ten objects has known stellar velocity dispersions (Wolf & Sheinis 2008), eliminating a potential free parameter of the model. This relatively small sample of quasars is not representative of the local quasar population, which consists of $\sim 10\%$ radio loud quasars. Our sample contains six radio loud and four radio quiet objects. We define an object as radio loud by the criteria established by Kellermann et al. (1994), $L_{5\text{ GHz}} > 10^{25} \text{ W Hz}^{-1}$, which is roughly $10^{41.5} \text{ erg s}^{-1}$ for our adopted cosmology¹. All quasars are local $z < 0.3$ and luminous $M_V < -23$. The properties of our test sample are summarized in Table 2.1.

2.2.2 Spectra

Data acquisition and reduction is described in detail in Sheinis (2002), Miller & Sheinis (2003), and Wolf & Sheinis (2008). In summary, seven of the ten objects

¹Kellermann et al. (1994) observationally determined the luminosity threshold assuming a cosmology of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $q_0 = 1/2$. We solve for the observed flux at $z = 0.2$ and then convert to our adopted cosmology. The specific luminosity is multiplied by the observed frequency to obtain the quoted 5 GHz luminosity.

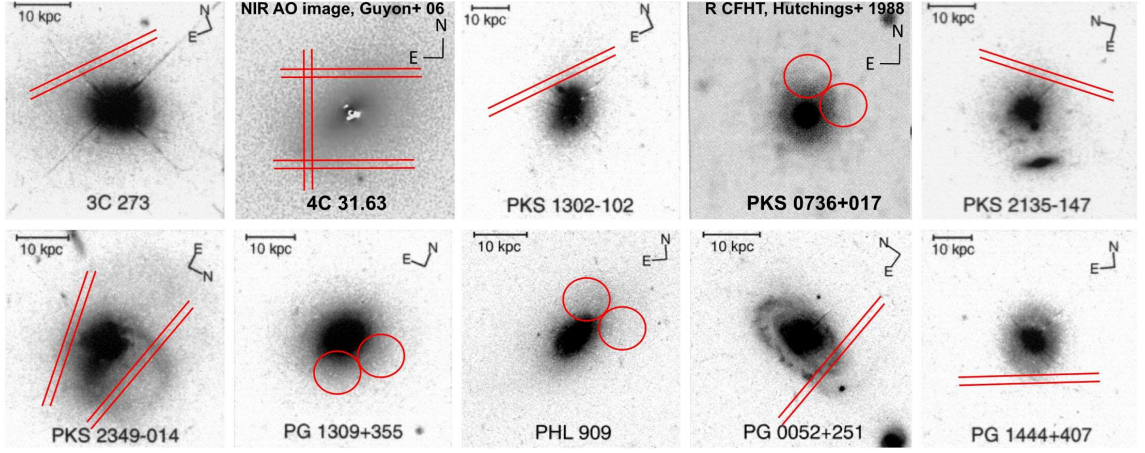


Fig. 2.1. — : Sample of observed quasar hosts with approximate off-axis slit and fiber positions indicated in red. The slit lengths are much larger than indicated, extending approximately $7'$ projected on the sky. For WIYN objects, only the off-axis fibers used for the host galaxy spectrum are shown. Objects are listed from left to right, top to bottom by most radio bright to least. All images are from *HST* (Bahcall et al. 1997) ($23'' \times 23''$) with the exception of 4C 31.63 ($10'' \times 10''$) (Guyon et al. 2006) and PKS 0736+017 ($30'' \times 30''$) (Hutchings, Johnson & Pyke 1988). Where indicated, the 10 kpc scale is computed for $\Omega_0 = 1.0$ and $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Bahcall et al. 1997). For our adopted cosmology this scale corresponds to $\sim 15.7 \text{ kpc}$.

were observed via the Low Resolution Imaging Spectrograph (Oke et al. 1994) on the Keck 10-m telescope. The remaining three objects were observed using a 82 fiber integral field unit (IFU), SparsePak (Bershady et al. 2005) which feeds the Bench Spectrograph on the 3.5-m WIYN telescope. Short on-axis observations, typically 1-2 minutes for Keck and 30 minutes for WIYN, and longer off-axis ($2''$ - $4.5''$ from the nucleus) observations, typically 0.5 - 4 hours, were obtained for each object. The approximate off-axis slit and fiber positions with respect to archival imaging is displayed in Figure 2.1. The properties of the off-axis pointings are summarized in Table 2.2. Keck objects have a rest wavelength range of ~ 3500 - $7000\text{\AA}$ at a spectral resolution of $\Delta\lambda \sim 11\text{\AA}$. WIYN objects have a rest wavelength range of ~ 3500 - $6000\text{\AA}$ at a spectral resolution of $\Delta\lambda \sim 5\text{\AA}$. All spectra were corrected for Galactic

extinction using the law of Cardelli, Clayton & Mathis (1989) and the A_V values from Schlegel, Finkbeiner & Davis (1998) as listed in the NASA/IPAC Extragalactic Database² (NED).

²<http://nedwww.ipac.caltech.edu/>

Table 2.2. : Off-axis spectral properties. Pointing designation indicates object and approximate off-axis position in arc-seconds. R_{obs} is the observed off-axis radius, as reported in Wolf & Sheinis (2008). Additionally, off-axis signal-to-noise, fraction of the observed off-axis spectrum which consists of scattered light, and telescope are shown. The scattered quasar light percentage is determined by the model output.

Pointing	$R_{obs}(\text{kpc})$	S/N $\text{\AA}^{-1}$ (5500-5700 $\text{\AA}$)	Quasar Scattering (3600-5900 $\text{\AA}$)	Telescope
3C 273 4N	11.79	18.6	68.8%	Keck
4C 31.63 2N	8.74	11.5	50.5%	Keck
4C 31.63 2.5E	10.92	9.4	34.6%	Keck
4C 31.63 3S	13.11	10.1	38.7%	Keck
PKS 1302-102 2.3N	12.79	9.3	68.4%	Keck
PKS 0736+017 4.5NW	14.18	8.3	49.5%	WIYN
PKS 2135-147 3W	12.47	12.3	70.8%	Keck
PKS 2349-014 4N	14.12	14.8	21.8%	Keck
PKS 2349-014 3S	9.47	18.8	25.2%	Keck
PG 1309+355 4.5SW	13.76	13.4	41.3%	WIYN
PHL 909 4.5N	12.97	11.7	77.8%	WIYN
PG 0052+251 3S	9.65	23.0	64.6%	Keck
PG 1444+407 3S	15.07	8.8	69.6%	Keck

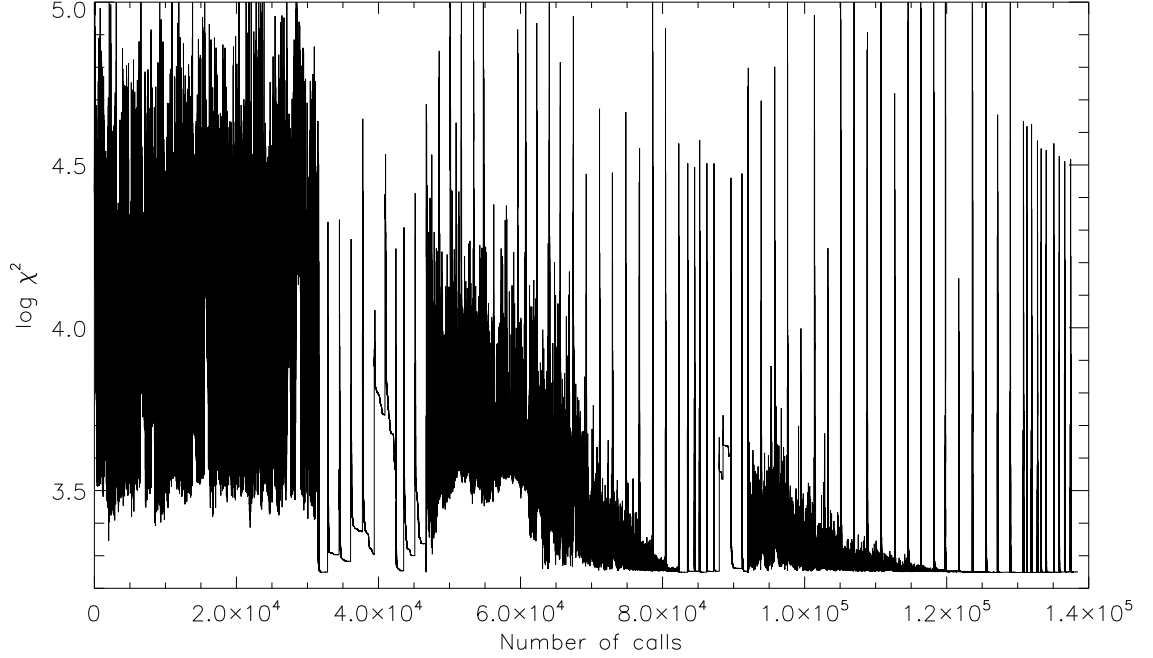


Fig. 2.2. — : Parameter space search for minimum χ^2 value. The three densely populated regions consist of 20 simulated annealing runs each. As the number of calls, or calculations of χ^2 , advances the 'temperature' is reduced to more restrictive values. These regions are separated by 10 straight downhill searches. This entire procedure is performed 20 times independently to determine the model's output.

2.3 Spectral Synthesis

2.3.1 Model

Our spectral synthesis code is a modified version of the model first discussed in Miller & Sheinis (2003), with the underlying stellar spectrum now modeled as a weighted summation of 15 instantaneous starbursts of various post burst ages. We model the off-axis spectrum, which consists of a stellar component and a scattered quasar component. Quasar light is scattered into the off-axis line of sight due to atmospheric seeing effects, as well as a small contribution from the intrinsic optical

point-spread function and astrophysically via dust and gas in the intervening line of sight. The stellar and scattered quasar components are modeled simultaneously to achieve the best χ^2 fit to the observed spectrum. Each model spectrum is masked in the same manner as the data for which it is intended (see Section 2.4). A model spectrum M_λ is of the form:

$$M_\lambda = \left(\sum_{i=1}^{15} x_i \text{ssp}_{i\lambda} \right) r_\lambda + Q_\lambda \xi_\lambda \quad (2.1)$$

with the following definitions:

- $\text{ssp}_{i\lambda}$ is the stellar component of the model which consists of a reduced basis of 15 simple stellar populations (SSPs) from the Bruzual & Charlot (2003), BC03, synthesis model, degraded to the instrument resolution, assuming solar metallicity, Padova-1994 models, and a Chabrier initial mass function (Chabrier 2003). Extensive simulations by CF05, have found this reduced spectral base ($t_i=0.001, 0.00316, 0.00501, 0.01, 0.02512, 0.04, 0.10152, 0.28612, 0.64054, 0.90479, 1.434, 2.5, 5, 11$ and 13 Gyr) to reliably produce observed spectral features while limiting redundancies in quiescent galaxies. Due to the increased complexity introduced by the scattered light subtraction, only solar metallicity is considered. Each SSP is normalized such that the area under the unmasked portions of the spectrum is unity. Normalization at a single wavelength ($\lambda_0=4020\text{\AA}$, as prescribed by CF05) was also investigated. For our sample, the alteration of the normalization convention does not affect the results of our model by more than $\sim 1\sigma$. x_i is the population weighting factor.
- $r_\lambda \equiv 10^{-0.4A_\lambda}$ is the extinction law used to model the in situ reddening. $A_\lambda(A_V, R_V)$ is defined by the Galactic law of Cardelli et al. (1989) assuming

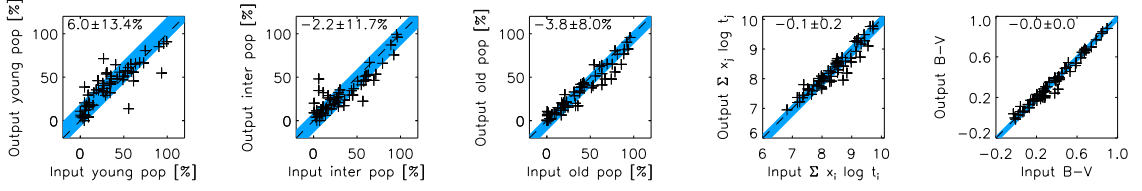


Fig. 2.3. — : Monte-Carlo simulation results for ideal noiseless off-axis spectra with 60% scattered quasar light contamination. 65 synthetic spectra, S_λ , are analyzed by the model to determine the reliability of the results. For each S_λ , the known young, intermediate and old population percentage and the known $\langle \log t_\star \rangle_L$ and rest frame $B-V$ input is compared to the model output as represented by 65 plus signs in each box. Ideally, all points would fall on the diagonal, denoted by a dashed line. The mean offset from the ideal and the standard deviation of the model output are displayed numerically in the upper left corner and graphically by the blue strip.

the mean value of R_V (3.1) in the diffuse ISM. A single extinction is assumed for the entire stellar component.

- Q_λ is the on-axis observed spectrum of the quasar normalized such that the area under the unmasked portions of the spectrum is unity. $\xi_\lambda \equiv a_1 + a_2\lambda + a_3\lambda^2 + a_4\lambda^3$ is the scattering efficiency curve, which modifies the observed quasar spectrum with the goal of modeling the scattered quasar light observed off axis. We have shown that this model component is necessary to reliably remove scattered quasar light (Sheinis 2002). The model assumes no host galaxy contamination to the on-axis spectrum. The dominance of the high luminosity quasar ($M_V < -23$) on-axis makes this assumption acceptable.

Finally, the individual pieces are combined as prescribed by equation (1) and the resulting model spectrum, M_λ , is normalized, dividing by a single constant, such that the area under the unmasked portions of the spectrum is unity (the normalized model is denoted $M_{\lambda n}$).

2.3.1.1 Parameter Range

Our model contains 20 free parameters: (1) an extinction parameter A_V , (15) SSP weighting factors x_i , (4) the scattering efficiency curve coefficients, $a_{[1:4]}$. The range of values to explore with the model is constrained in the case of x_i to be 0.0 to 1.0, where $\sum x_i = 1.0$. The range of values for A_V and $a_{[1:4]}$ were found in an iterative fashion. First the model was applied to the entire dataset with parameter ranges informed from the work of Sheinis (2002) and Miller & Sheinis (2003). The range was then increased as necessary to ensure the best χ^2 fit was not determined by the searchable parameter space. For example, the highest model A_V output obtained is 0.4; therefore, the model samples A_V from 0.0 to 1.0. We have tested the sensitivity of the model output to these boundary conditions by doubling the range and re-running the model on the observed data. No significant change in results is found.

2.3.1.2 Parameter Search

Having constructed a model, we then devised a reliable means to find the minimum chi-squared fit. The χ^2 fitting function is defined by:

$$\chi^2 = \sum_{\lambda} \left(\frac{O_{\lambda n} - M_{\lambda n}}{\sigma_{\lambda}} \right)^2 \quad (2.2)$$

$O_{\lambda n}$ is the observed off-axis spectrum, normalized in the same manner as $M_{\lambda n}$, and σ_{λ} is the observed spectral noise. The noise spectrum is generated by measuring the standard deviation of $O_{\lambda n}$ at three to four locations devoid of prominent spectral features. These measurements are then extrapolated across the wavelength range of $O_{\lambda n}$ by a low order fitting polynomial.

The starting point in the parameter search is defined in the following manner.

The initial stellar component is set to be 100% 5Gyr SSP. The reddening is randomly selected, constrained by its range. The scattering coefficients are also randomly selected but then scaled so that scattered quasar light comprises 60% of the off-axis model spectrum. Parameters $a_{[1:4]}$ are further constrained by rejecting any solutions which drive the resulting off-axis quasar flux, $Q_\lambda \xi_\lambda$, below zero.

Simulated annealing optimization (Press 1992) is utilized to search the 20-D parameter space. Simulated annealing evaluates the merit function, χ^2 in this case, and travels downhill in merit space to find a minimum within predefined tolerances. To help avoid local minima, a user defined parameter, traditionally called 'temperature', is set to determine the probability of traveling uphill in merit space. The higher the temperature the more probability of traveling uphill in the merit space. A zero value for temperature corresponds to a straight downhill search.

The utilization of this optimization routine, described below, is somewhat of an art. The temperature value must be decreased slowly so that the merit space can be adequately sampled, yet fast enough to arrive at a timely solution. After extensive experimentation the following implementation has been found to produce favorable results. First, twenty iterations of simulated annealing are performed with linearly decreasing temperature. If an iteration fails to find a minimum χ^2 value within a factor of two of the overall minimum then the next iteration is reset to the overall minimum; otherwise the next iteration starts where the previous iteration left off. At the completion of the simulated annealing runs, the ten best distinct solutions are used as input for straight downhill (temperature = 0) runs. The current global minimum is then used as the input to the next twenty iterations of simulated annealing. This procedure is carried out for a total of three loops; within each

loop the temperature parameter is set to more restrictive values. An example of this parameter space search is shown in Figure 2.2 for a typical χ^2 minimization. Overall approximately 150,000 points are sampled in the parameter space. This entire procedure is performed 20 times independently. The best χ^2 value of these runs, which consists of approximately 3×10^6 calculations of χ^2 , is defined as the model output.

2.3.1.3 Quantities of Interest

Guided by the analysis of CF05, we limit the scope of our project to a coarse, but well recovered, description of the stellar populations. Like CF05, we only attempt recovery of ‘young’ ($t < 100$ Myr), ‘intermediate’ ($100 \text{ Myr} \leq t \leq 1 \text{ Gyr}$), and ‘old’ ($t > 1 \text{ Gyr}$) stellar contributions (x_Y , x_I , and x_O , respectively). Additionally, we report the mean light-weighted stellar age,

$$\langle \log t_\star \rangle_L = \sum_{i=1}^{N_\star=15} x_i \log t_i \quad (2.3)$$

and the rest frame B-V color as derived directly from the listed BC03 SSP values. These quantities have been studied extensively in quiescent galaxy samples and to a lesser extent in AGN host galaxy samples. Thus, we may assess the consistency of our results to previous AGN host studies. Furthermore, we may compare these properties of quasar host galaxies to quiescent galaxy samples. Analysis of other quantities of interest (see CF05) are deferred to future studies.

2.3.2 Monte-Carlo Simulations

The error in our method is estimated via a Monte-Carlo routine. Synthetic spectra, S_λ , are generated with known parameters and then degraded by noise. The

same procedure used for the observed data is applied to determine the agreement between the known input and model output. In other words, $S_{\lambda n}$ replaces $O_{\lambda n}$ in the fitting routine. S_{λ} are constructed in the same manner as M_{λ} with the exception of metallicity, SSP base and added noise. Because the observed galaxies will likely include non-solar metallicities, even though the model grid does not, the metallicity is allowed to deviate from solar, and is randomly selected from $Z = 0.2, 1$ and $2.5 Z_{\odot}$. The SSP base is extended to include all 221 BC03 instantaneous bursts assuming a Chabrier initial mass function. A synthetic spectrum is of the form:

$$S_{\lambda} = \left(\sum_{j=1}^{3 \times 221} x_j \text{ssp}_{j\lambda} \right) r_{\lambda} + Q_{\lambda} \xi_{\lambda} \quad (2.4)$$

Poisson noise is added until the synthetic spectra obtain the corresponding observed noise as measured in the 5500-5700Å spectral window. The 5500-5700Å spectral range was selected because there are no prominent emission or absorption features; additionally, all observed spectra include this range. The value of A_V and $a_{[1:4]}$ are randomly selected, constrained by the applicable range. Parameters $a_{[1:4]}$ are further constrained by rejecting any solutions which drive the resulting off-axis quasar flux, $Q_{\lambda} \xi_{\lambda}$, below zero. The scattered quasar flux is then scaled to the contamination percentage of interest. The value of x_j is randomly selected to uniformly sample³ each stellar age bin (young, intermediate, and old). Thus, synthetic off-axis

³To uniformly sample each stellar age bin the following procedure is employed: The first of 65 synthetic spectra, S_{λ} , is randomly assigned a x_O value between 0-100%. x_I and x_Y are then randomly assigned the remaining flux. The second (third) S_{λ} is constructed similarly, except x_I (x_Y) is first assigned a value between 0-100%. This cycle is repeated beginning with the forth S_{λ} . To further illustrate the procedure let us consider the construction of the first S_{λ} . Suppose x_O was assigned a value of 72%. The program populates x_O by randomly selecting a SSP and a metallicity and then randomly assigning a percentage of the total x_O value. This process continues until $x_O=72\%$ to within $\pm 0.005\%$. x_I and x_Y are then populated in the same manner. Thus, the stellar components of the synthetic spectra are constructed.

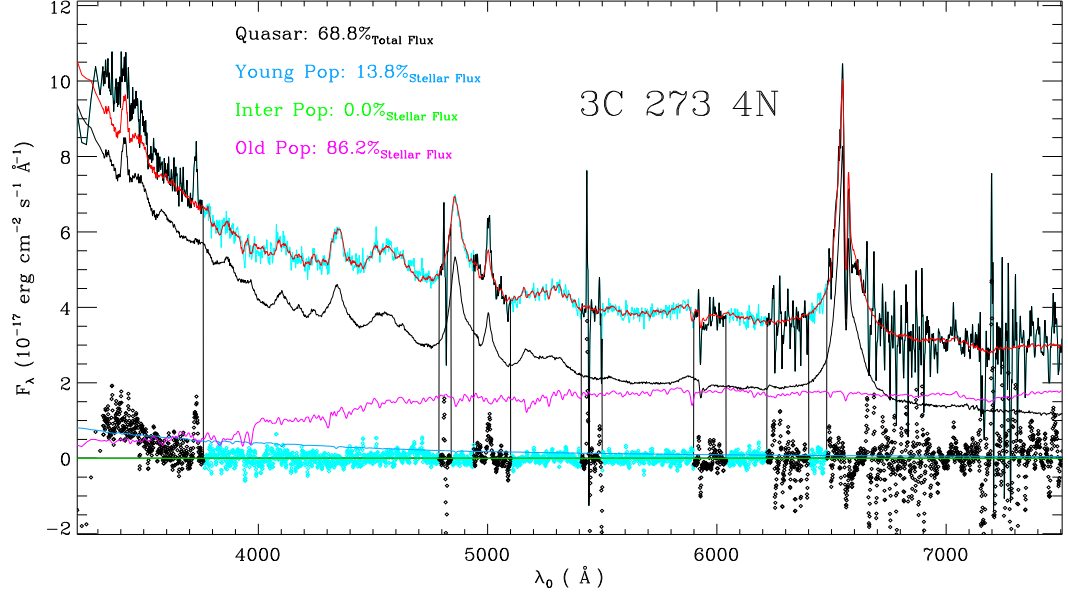


Fig. 2.4. — : Model fit to the 3C 273 4N pointing. The observed off-axis rest frame spectrum is highlighted in cyan, with masked regions indicated in black and by vertical lines extending to zero flux; masked regions that are narrow, [OIII] at 5007Å for example, are most easily seen by looking at the residuals at the bottom of the plot. The model output is over-plotted in red. The residual is shown with diamonds. Model components are also shown. The scattered light component is indicated by the thin black line and comprises 68.8% of the total observed flux. The stellar component is also shown, broken up into young (blue), intermediate (green), and old (magenta) bins. In this example, only the old stellar component, which comprises 86.2% of the stellar flux, is clearly visible. Results for all other pointings are found in Appendix A, Figure 2.A1.

spectra are generated with generalized metallicity and SSP base. Sixty-five unique S_λ are constructed to test the ability of the model to recover known input parameters. We will use this Monte-Carlo routine first to test the associated uncertainties in a noiseless test case (Section 2.3.2.1) and the reliability to recover the scattered nuclear light (Section 2.3.2.2), before we will apply it to our actual data to determine the errors and biases in the recovered model parameters (Section 2.4).

2.3.2.1 Model Performance Given Noiseless Spectra

A concern regarding the use of our multi-component model is inherent degeneracies. For instance, can a young stellar population mimic scattered quasar light? The legitimacy of the model relies on the subtle differences between the various components. The reddening function, which only operates on the stellar component, should be distinct from the scattering function which operates on the observed on-axis spectrum. The absorption features in the stellar component generally do not match quasar absorption lines. The scattering function, applied to the quasar spectrum, uniquely has broad-line components. However, can quantities of interest be reliably recovered given the many possible interactions between model components?

To test the ideal performance of the model we conducted noiseless Monte-Carlo simulations. For this purpose, the Sloan Digital Sky Survey (SDSS) composite quasar spectrum (Vanden Berk et al. 2001) was utilized as the on-axis quasar spectrum, Q_λ . The scattered quasar light was scaled to a value of 60%. The results of this test are shown in Figure 2.3. Referring to the figure, input versus output values of x_Y , x_I , x_O , $\langle \log t_\star \rangle_L$ and $B-V$ are shown for 65 synthetic spectra. Ideally, all points would fall on the diagonal, denoted by a dashed line (where input equals output). The mean offset from the ideal, $\text{mean}(\text{output}-\text{input})$, plus the standard deviation of the model output, $\pm \text{stdev}(\text{output}-\text{input})$, are displayed numerically in the upper left corner and graphically by the blue strip. The fitting routine reliably recovers $\langle \log t_\star \rangle_L$ and $B-V$ in the ideal case of noiseless spectra. The values of x_Y , x_I and x_O are less well constrained, with systematic offsets of up to 6% and one sigma deviations of up to 13.4%.

2.3.2.2 Scattered Light Verification Tests

Additional Monte-Carlo tests were conducted to check for consistency in the model. Inputting simulated off-axis spectra consisting of 100% scattered quasar light and a signal-to-noise of 10, the algorithm reliably assigned no flux to the stellar component (65 iterations resulted in a mean result of $99.92 \pm 0.01\%$ scattered quasar light). Inputting 100% stellar component ($S/N=10$), the algorithm reliably assigned no flux to the scattered light component (65 iterations resulted in a mean result of $2.32 \pm 1.59\%$ scattered quasar light). Finally, we tested the performance of the model when constrained to have a steep blue scattered quasar component, as observed in the off-axis spectrum of PHL 909. The error estimates were not significantly affected by this alteration; for details see Appendix A (PHL 909).

2.3.2.3 Limitations

Table 2.3. : Modeled off-axis stellar populations, $\langle \log t_\star \rangle_L$ and rest frame color are shown. Host stellar population offset and $\pm 1\sigma$ error are shown in parentheses as estimated with Monte-Carlo simulations. Δ denotes the observation with non-concurrent on and off-axis observations.

Pointing	Young stell pop - % flux	Inter stell pop - % flux	Old stell pop - % flux	$\langle \log t_\star \rangle_L$	$B - V$
3C 273 4N	13.8 (-3.0±16.9)	0.0 (+0.3±19.1)	86.2 (+2.6±13.8)	9.40 (-0.01±0.24)	0.77 (-0.00±0.05)
4C 31.63 2N	15.7 (-1.9±16.2)	0.0 (-1.8±16.5)	84.3 (+3.7±9.6)	9.00 (+0.06±0.28)	0.69 (+0.01±0.06)
4C 31.63 2.5E	18.3 (-1.1±16.4)	0.5 (-2.3±17.7)	81.3 (+3.4±11.8)	9.18 (+0.00±0.32)	0.74 (-0.00±0.05)
4C 31.63 3S Δ	0.0 (-2.1±17.0)	25.3 (-1.0±18.2)	74.7 (+3.1±9.9)	9.73 (+0.03±0.26)	0.83 (+0.01±0.05)
PKS 1302-102 2.3N	0.0 (-5.6±27.0)	12.4 (+4.3±26.7)	87.6 (+1.3±14.8)	9.34 (+0.09±0.49)	0.76 (+0.02±0.12)
PKS 0736+017 4.5NW	0.0 (+4.2±21.3)	0.0 (-5.7±23.2)	100.0 (+1.5±12.4)	9.56 (-0.05±0.32)	0.83 (-0.01±0.07)
PKS 2135-147 3W	0.0 (-2.0±22.6)	0.0 (-0.6±23.7)	100.0 (+2.6±12.0)	9.52 (+0.01±0.34)	0.82 (-0.00±0.07)
PKS 2349-014 4N	6.3 (-2.5±11.4)	0.8 (+0.0±11.3)	92.9 (+2.5±9.6)	9.52 (+0.01±0.20)	0.79 (+0.00±0.04)
PKS 2349-014 3S	11.1 (-4.7±12.7)	15.3 (+0.8±13.2)	73.6 (+3.9±8.8)	9.54 (+0.06±0.21)	0.78 (+0.00±0.03)
PG 1309+355 4.5SW	11.7 (-2.1±14.4)	9.5 (+1.9±16.1)	78.9 (+0.2±10.7)	9.33 (+0.02±0.26)	0.76 (+0.00±0.06)
PHL 909 4.5N	0.0 (-8.3±18.4)	43.8 (+4.9±20.0)	56.2 (+3.4±12.4)	9.45 (+0.14±0.45)	0.73 (+0.02±0.10)
PG 0052+251 3S	43.3 (-8.0±19.2)	16.5 (+4.5±20.9)	40.1 (+3.6 ±11.5)	8.09 (+0.09±0.34)	0.32 (+0.03±0.05)
PG 1444+407 3S	9.5 (-7.8±23.8)	58.2 (+2.6±27.6)	32.2 (+5.2±17.7)	8.86 (+0.15±0.42)	0.52 (+0.03±0.09)

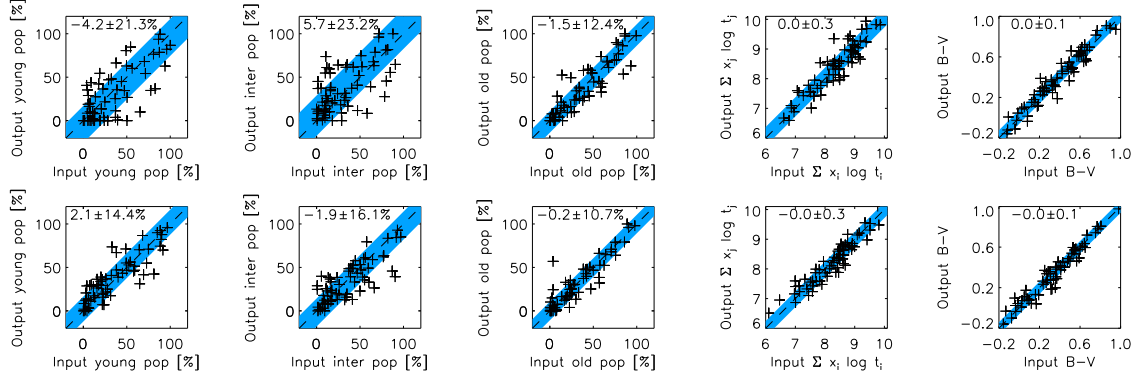


Fig. 2.5. — : **Top row**: Monte-Carlo simulation for PKS 0736+017 (off-axis pointing of most limiting signal-to-noise). **Bottom row**: Monte-Carlo simulation for PG 1309+355 (off-axis pointing of $\sim$ average signal-to-noise and quasar contamination). 65 synthetic spectra are analysed by the model to determine the reliability of the results. For each S_λ , the known young, intermediate and old population percentage and the known $\langle \log t_\star \rangle_L$ and rest frame $B-V$ input is compared to the model output as represented by 65 plus signs in each box. Ideally, all points would fall on the diagonal, denoted by a dashed line. The mean offset from the ideal and the standard deviation of the model output are displayed numerically in the upper left corner and graphically by the blue strip.

Errors associated with the: 1) population synthesis model (BC03) (template mis-match), 2) inadequacy of the scattering efficiency curve, 3) non-Poisson noise and 4) the application of a single simplistic extinction law are not represented in our Monte-Carlo simulations. Despite these deficiencies, similarly constructed quiescent models have demonstrated consistency when compared to competing techniques (e.g. see CF05). In Section 2.5 we address this issue by comparing our results to recent studies of quasar host galaxies. Finally, it should be noted that the error estimates obtained reflect the one sigma performance of the model. Although currently applied to a relatively small sample, stronger error statements will be possible with the increase of our sample. With this in mind, when possible, we consider our objects as an ensemble.

2.4 Application of Model and Simulations to the Test Sample

In this section we apply our model to the test sample to constrain the stellar age and host color. We then conduct 10 (one for each pointing) tailored Monte-Carlo simulations to estimate the reliability of our results.

The following caveats should be considered in the application of our model to the test sample. For each object, concurrent on and off-axis observations have been obtained, with the exception of the 3S pointing of 4C31.63 ($\Delta t \sim 1.5yr$). The possible variability of this quasar over this time period is not accounted for by the model. Line-of-sight stellar motions are not modeled for Keck objects. Our instrument resolution, $\sigma_v \sim 300 \text{ km s}^{-1}$, being greater or of the order of the measured velocity dispersions (Wolf & Sheinis 2008) should result in minimal errors. For WIYN objects, with $\sigma_v \sim 110 \text{ km s}^{-1}$, the measured velocity dispersions are used to smooth the model stellar component, $sfp_{i\lambda}$. Narrow emission line regions and sky residuals are uniquely masked for each object, giving these regions no weight in the χ^2 fitting. The broad components, and in some cases entire broad lines, are left unmasked, though most or all of the H-alpha region is masked out in many objects due to significant sky residuals in the red end of the spectrum. Typically, ~ 2200 spectral data points are fit for Keck objects; ~ 1600 spectral data points are fit for WIYN objects. Figure 2.4 depicts the result of the method applied to 3C 273 4N. The results for all other off-axis pointings are presented in the appendix, Figure 2.A1. Table 2.3 summarizes these findings.

The reliability of these results are then determined with tailored simulations. Synthetic spectra are generated with features representative of the observed spec-

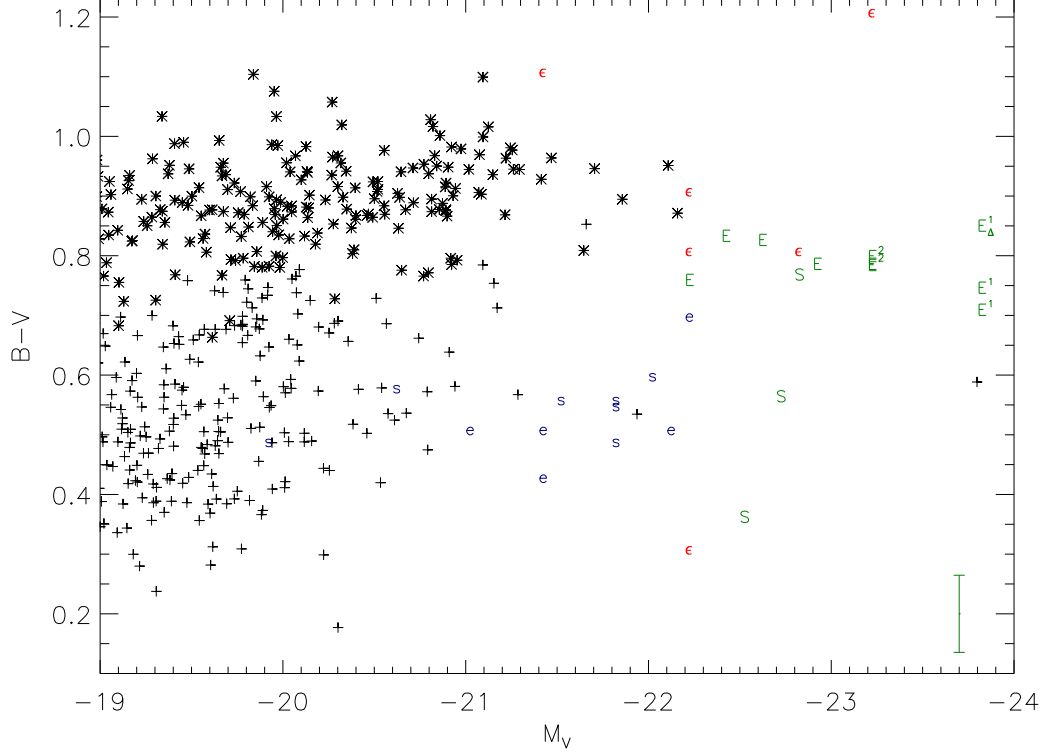


Fig. 2.6. — : Rest frame color-magnitude diagram for local quiescent galaxies and active host galaxies. Black plus signs indicate ($z < 0.4$) quiescent late-type galaxies, while black asterisks indicate ($z < 0.4$) quiescent early-type galaxies (Wolf et al. 2004). J04 quasar hosts are blue lower case letters ('s' for spiral or disc, 'e' for elliptical morphology). H07 BL Lac hosts are all elliptical and are indicated by red 'e'. Quasar hosts from this work are indicated by green upper case letters ('S' for spiral or disc, 'E' for elliptical morphology). A typical error bar is shown for our sample in the lower right. '1' and '2' denote objects with multiple pointings, 4C 31.63 and PKS 2349-014 respectively. Δ denotes the observation with non-concurrent on and off-axis observations.

tra by (1) degrading S_λ to the observed noise level, (2) applying the same mask constructed for the observed spectrum, (3) using the appropriate observed on-axis spectrum as Q_λ and (4) scaling the scattered quasar light to the observed contamination level as determined by the model output⁴. An example of a simulation with

⁴The contamination percentage is well recovered as tested by the Monte-Carlo routines; for example, the contamination percentage for PKS 0736-017 is recovered within $\pm 3.6\%$. This observation has the most limiting signal-to-noise and provides an estimate of the error upper limit.

the same on-axis spectrum, noise characteristics, applied mask and percent scattered quasar light as the observed off-axis spectrum of PKS 0736+017 is displayed in Figure 2.5 top row. The bottom row of Figure 2.5 presents the simulation results for PG 1309+355. The PKS 0736+017 off-axis pointing has the worst signal-to-noise, while the PG 1309+355 off-axis pointing has $\sim$ average signal-to-noise and quasar contamination. The results of all simulations are shown in Table 2.3. Throughout the rest of the chapter, mean offsets are applied to model results and Monte-Carlo one sigma errors are quoted.

2.5 Comparison to Recent Studies

We compare our spectroscopically derived rest frame $B-V$ host colors to the available results from imaging studies. These imaging studies spatially subtract the point spread function of the AGN to reveal the host galaxy. Our method, which spectrally subtracts the scattered quasar light, provides a complimentary technique to constrain the host $B-V$ colors.

Our off-axis method probes a population of luminous quasars unattainable by most other spectroscopic techniques. The stellar properties of this population have yet to be determined for a large well defined sample. This deficiency is due to the overwhelming emission from the central quasar. Previous off-axis studies (e.g. Hughes et al. 2000) have dealt with this problem by carefully selecting distant ($\sim 5''$) off-axis slit positions. This can significantly reduce the typical scattered light observed off axis ($\sim 20\%$). Our approach is to more rigorously model the quasar light scattered off axis. This allows for 1) scattered light fractions of up to $\sim 80\%$ and 2) more freedom in slit positioning. Furthermore, our method draws from established

quiescent population synthesis models to more robustly model the stellar content and to estimate the reliability of our results.

Recent advances in on-axis observational techniques have allowed for the study of luminous quasars (Jahnke et al. 2007; Letawe et al. 2007). For objects with $M_V(nuc) > M_V(host)$, our method can complement these studies by observing off-axis ($\gtrsim 9kpc$) stellar content with favorable signal-to-noise. We note that on-axis studies require nucleus-to-host ratios of $\lesssim 15$ to detect stellar absorption features (L07). Objects such as NAB 0205+02, HE 0530-3755 and 3C 273 cannot be observed on-axis due to this criterion. Off-axis studies do not have this limitation. Thus, our method is needed to obtain optical stellar spectra for these objects.

In the following subsections we compare our study to previous imaging and spectroscopic work in more detail. Furthermore, we quantify how our sample compares to applicable SDSS AGN studies.

2.5.1 Recent Photometric Studies

Host $B-V$ colors have been reported for nearby ($z < 0.197$) quasars by Jahnke et al. (2004), hereafter J04, and for nearby ($z < 0.139$) BL Lacs by Hyvärinen et al. (2007), hereafter H07. J04, studying multicolor data from a sample of AGN distributed around the classical dividing line in luminosity between Seyfert 1 galaxies and quasars, found bulge dominated hosts to have bluer colors than expected compared to their quiescent counterparts; disc hosts were also on average bluer, but not by a significant amount. H07, also studying multicolor data, found their exclusively elliptical BL Lac hosts to be on average bluer than expected compared to their quiescent equivalent. Table 2.4 shows the mean $B-V$ colors for the host galaxies in J04 and H07, as well as in our sample and for quiescent galaxies of various morphologies

(from Fukugita, Shimasaku & Ichikawa 1995). In agreement with J04 and H07, we find the rest frame $B-V$ color for the elliptical host galaxies of our sample to be bluer than one would expect given their quiescent morphological counterparts. This provides confirmation that elliptical quasar hosts are distinguishable in $B-V$ color from inactive elliptical galaxies using a spectroscopic technique. Spirals hosts for our sample are found to be consistent with Sc galaxies which have a $B-V$ color of ~ 0.54 (Fukugita et al. 1995). A comparison to quiescent galaxies is also presented via a color-magnitude diagram, Figure 2.6. Quiescent COMBO-17 (Wolf et al. 2004) late-type galaxies (black '+'), and quiescent COMBO-17 early-type galaxies (black '*') are shown in relation to J04 hosts (blue lower-case letters; 's' for spiral or disc, 'e' for elliptical morphology), H07 hosts (red 'ε'), and this work (green upper-case letters; 'S' for spiral or disc, 'E' for elliptical morphology). Quiescent early and late-type galaxy designations are determined by the $U-V$ vs M_V cut as proposed by Bell et al. (2004) for $z=0.25$. A typical error bar is shown for our sample in the lower right of Figure 2.6.

Although we confirm bluer elliptical host galaxy colors, we find that our sample is on average much redder than J04. This offset may be due to the different effective radii probed since our method is only sensitive to the stellar content observed off axis. For example, if nuclear starbursts were a common occurrence in quasar hosts, then one might expect the outer stellar populations to exhibit redder colors. However, results from Kauffmann et al. (2003) suggest that the different radii probed may not be responsible for this observed offset. Studying a large sample of obscured AGN hosts, they find that star formation in the hosts of powerful AGN (approximately one magnitude fainter than a typical object in this study) is not concentrated

primarily in the nuclear regions; it is spread out over scales of at least several kiloparsecs. Furthermore, the host galaxies in the H07 study exhibit a wide range of host color gradients, with the majority displaying bluer colors off axis. This negative color gradient is also observed for radio galaxies (Govoni et al. 2000) and quiescent ellipticals (Peletier, Valentijn & Jameson 1990). Assuming these conclusions hold true for quasar hosts, one would expect our sample to be biased toward bluer colors rather than the observed red offset.

An alternative explanation for our redder host colors compared to the J04 study is that our sample is on average more radio loud⁵. The only J04 object which overlaps in $B-V$ color with our main sample is their most radio loud. The two objects from our sample which overlap in color with the main J04 sample are also our most radio quiet. This relation of color to radio luminosity is shown in Figure 2.7. Above $L_{5GHz} \sim 10^{40} \text{ erg s}^{-1}$, the host galaxies are systematically redder. Given the correlation between radio luminosity and bulge mass found for our sample (Wolf & Sheinis 2008, $L_{5GHz} \sim M_{bulge}^{3.56}$), $L_{5GHz} = 10^{40} \text{ erg s}^{-1}$ corresponds to $M_{bulge} \sim 10^{11.5} M_{\odot}$. The rms scatter of the correlation is 1.09 dex. This trend for radio loud objects to be located in redder hosts is not surprising; Best et al. (2005) found that radio-loud AGN are preferentially located in older more massive galaxies. However the distinct transition we see in our sample should be investigated on a larger sample.

How can this be understood in terms of stellar ages? The mean light-weighted age is correlated to various colors (e.g., $u-r$, Mateus et al. 2006). We verify this correlation for our color of interest, $B-V$, by constructing 65 test spectra, Figure 2.8. Using this relation we convert the $B-V$ colors of J04 to mean light-weighted

⁵Radio luminosity is estimated utilizing NED and NVSS (Condon et al. 1998). A spectral index of -0.5 is assumed. Upper limits are based on the sensitivity of NVSS $\sim 2.3 \text{ mJy @ } 1.4 \text{ GHz}$.

ages, Figure 2.9. While the observed color trend is more pronounced, it is found that all $\langle \log t_{\star} \rangle_L$ values above $L_{5GHz} = 10^{40} \text{ erg s}^{-1}$ are older than values below this threshold. Previous studies (CF05; Mateus et al. 2006) have studied the mean light-weighted age and found this quantity to be frequently associated with the most recent epoch of starbursts. Assuming major merger progenitors for our quasar hosts with a significant past starburst (e.g., see Hopkins et al. 2006), $\langle \log t_{\star} \rangle_L$ may indicate the approximate timing of the merger event. It should be noted that our definition of $\langle \log t_{\star} \rangle_L$ differs slightly from the definition adopted by CF05 and Mateus et al. (2006) due to different SSP normalization conventions (see Section 2.3.1). For our sample, conversion to this alternative definition modifies our reported $\langle \log t_{\star} \rangle_L$ results by $\sim 1\sigma$ or less.

To estimate this time-scale we divide the combined sample into two groups; a radio bright sample with $L_{5GHz} > 10^{40} \text{ erg s}^{-1}$ displaying an average $B-V$ color of 0.77 and a radio faint sample with $L_{5GHz} < 10^{40} \text{ erg s}^{-1}$ displaying an average $B-V$

Table 2.4. : Available rest frame $B-V$ host mean colors and quiescent mean colors. Reported errors are standard deviations of the mean. 'E' denotes elliptical and 'S' denotes spiral.

Sample	$B - V$
E Quasars (this work)	0.78 ± 0.01
S Quasars (this work)	0.55 ± 0.12
E Quasars (J04)	0.52 ± 0.05
S Quasars (J04)	0.56 ± 0.01
Quasars $L_{5GHz} > 10^{40} \text{ erg s}^{-1}$ (this work plus J04)	0.77 ± 0.02
Quasars $L_{5GHz} < 10^{40} \text{ erg s}^{-1}$ (this work plus J04)	0.50 ± 0.02
E BL Lacs (H07)	0.8 ± 0.2
E (Fukugita et al. 1995)	0.96
Sb-Sc (Fukugita et al. 1995)	0.57
Sc-Sd (Fukugita et al. 1995)	0.50

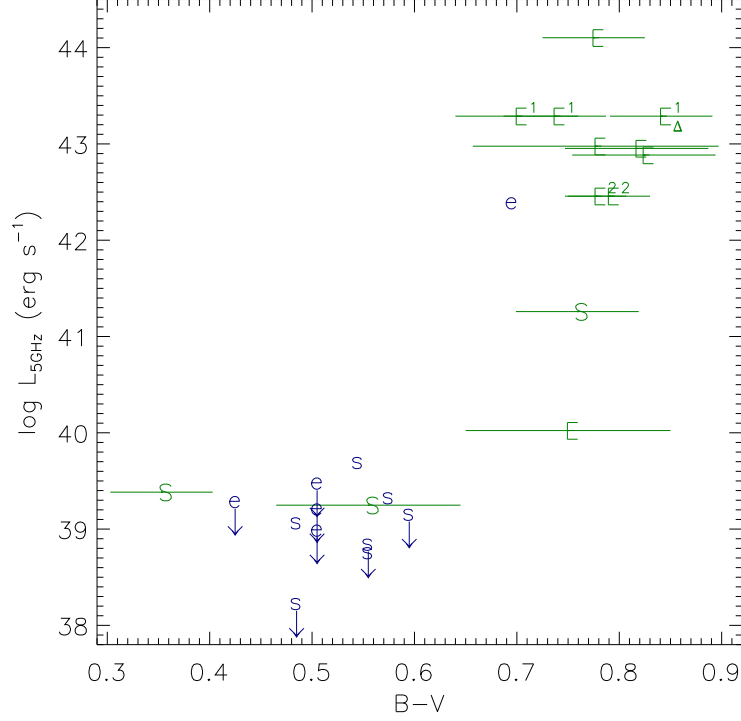


Fig. 2.7. — : Radio luminosity as a function of rest frame $B-V$ color. Green upper case letters indicate the results of this study, blue lower case letters indicate the results of J04. '1' and '2' shown above denote objects with multiple pointings, 4C 31.63 and PKS 2349-014 respectively. Δ denotes the observation with non-concurrent on and off-axis observations. H07's BL Lacs are not shown due to the expected significant beaming of radio emission.

color of 0.50 (average color for this grouping is also reported in Table 2.4). L_{5GHz} is found to correspond to bulge mass and may provide a more significant division than morphology whose classification is hampered by quasar point source subtraction and un-modeled tidal features. We find that, on average, $\langle t_{\star} \rangle_L = 2.7^{+0.6}_{-0.5}$ Gyrs⁶ for the radio bright sample and $\langle t_{\star} \rangle_L = 570^{+140}_{-110}$ Myrs for radio faint sample.

⁶ $\langle t_{\star} \rangle_L \equiv 10^{\langle \log t_{\star} \rangle}$

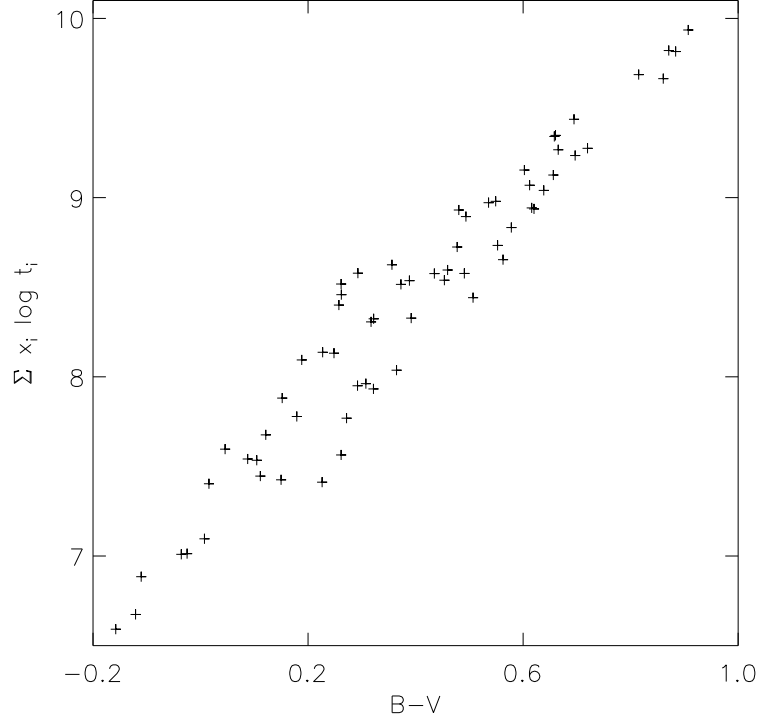


Fig. 2.8. — : Relation between mean light-weighted stellar age and rest frame $B-V$ color derived from 65 randomly constructed stellar components, $\sum_{i=1}^{15} x_i \text{ssp}_{i\lambda}$.

2.5.2 Recent Spectroscopic Study with Imaging

This result for radio loud objects compares remarkably well to recent findings of Canalizo et al. (2006) and Bennert et al. (2008). Canalizo et al. (2006) report preliminary deep Keck LRIS spectral analysis of luminous $z \sim 0.2$ quasar hosts which finds evidence for major starburst episodes with ages ranging from 0.6 Gyr to 2.2 Gyr. Incidentally at least two of the host galaxies studied by Canalizo & Stockton (2013) overlap with our sample, PKS 0736+017 and PHL 909. They find that both of these objects located in our radio bright group have massive 2.2 Gyr starbursts, consistent with our color and mean light-weighted age estimate. However, see Appendix A for an inconsistency in the derived stellar populations for PHL 909. Bennert et al. (2008), again studying PKS 0736+017 and PHL 909 along with three

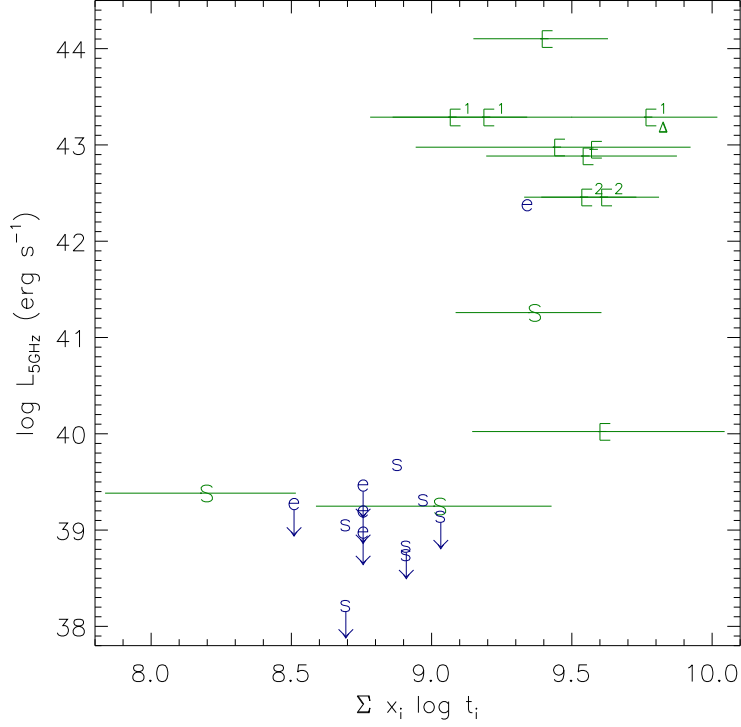


Fig. 2.9. — : Radio luminosity as a function of mean stellar age weighted by flux. Green upper case letters indicate the results of this study, blue lower case letters indicate the results of J04. '1' and '2' shown above denote objects with multiple pointings, 4C 31.63 and PKS 2349-014 respectively. Δ denotes the observation with non-concurrent on and off-axis observations.

other hosts in deep HST ACS images, find shells and tidal tails indicative of merger events. Consulting N-body simulations they conclude that in general the observed fine structure can be explained by either a recent minor merger or an older major merger ~ 1 Gyr ago.

Implications of a ~ 1 Gyr poststarburst quasar are discussed extensively in Canalizo et al. (2007) and Bennert et al. (2008). In summary the currently estimated (optically luminous) quasar lifetime [$10^6 - 10^8$ yrs (Yu & Tremaine 2002)] appears to be too short to be triggered at the same time as the starburst. Bennert et al. (2008) conclude that this may imply a scenario in which quasar activity is significantly delayed

or a scenario in which intermittent quasar activity encompasses a longer duration. Alternatively, a more recent minor merger could explain the observed quasar. Our results do not rule out this scenario. However, the average mass-to-light ratio for our sample being ~ 10 (Wolf & Sheinis 2008) constrains any recent ($t \ll 1 \text{ Gyr}$) starburst to be relatively insignificant in mass.

2.5.3 Off-Axis Studies

The off-axis ($5''$) spectroscopic study of Hughes et al. (2000, hereafter H00) consists of three matched subsamples of nine radio quiet quasars (RQQs), ten radio loud⁷ quasars (RLQs), and seven radio galaxies (RGs). Similar to our study, all quasars are luminous ($M_V \lesssim -23$) and local ($0.1 \leq z \leq 0.3$).

H00 determine the 4000 Å break strength, an indicator of the mean stellar age, for each object. The average values for RQQ hosts, RLQ hosts, and RGs all indicate younger mean stellar ages than local inactive elliptical galaxies, in agreement with our study. However, H00 notes wide scatter in their measured values. Additionally, measurements indicative of younger ages were typically associated with either poor signal-to-noise data or with spectra that show significant scattered quasar light. Thus H00 defer further analysis of the stellar populations to the followup spectrophotometric modeling conducted by Nolan et al. (2001, hereafter N01).

N01 develop two population synthesis models. The first model consists of a 0.1 Gyr SSP and a second SSP component whose age and contribution are allowed to vary to obtain the best χ^2 fit. Like our study, solar metallicity is assumed. However, two SSPs are used to construct the stellar population in contrast to our model

⁷Radio loud in H00 is defined as $L_{5 \text{ GHz}} > 10^{24} \text{ W Hz}^{-1} \text{ sr}^{-1}$, which is roughly consistent with our adopted definition.

which incorporates a base of 15 BC03 SSPs. N01 also develop a three component model which uses the observed nuclear spectrum of the RQQ, 0054+144, to account for scattered quasar light detected off axis. While our approach also uses observed nuclear light to model off-axis scattered light, our model does not assume a universal nuclear spectrum. The observed nuclear spectrum is matched to the off-axis observation (e.g. the model input for the quasar contamination in the 3C 273 off-axis spectrum is the observed 3C 273 nuclear spectrum). Additionally, it should be noted that whenever possible (9 out of 10 pointings) we have observed on and off-axis observations simultaneously to avoid variation in the quasar spectrum which could hamper an accurate scattered-light subtraction. As a final point, we allow for the continuum shape of the nuclear light observed off axis to be altered by the scattering efficiency curve, which we have shown is necessary for reliable scattered light removal (Sheinis 2002).

Interpretation of the N01 model output indicates that the stellar mass of all three subsamples studied (RQQ, RLQ, and RG) is dominated by old stars of age 8-14 Gyr. This result is used to support the claim that quasar hosts are “to first order, indistinguishable from ‘normal’ quiescent giant elliptical galaxies.” If we take N01’s derived age to be representative of the mean mass-weighted stellar age, then it is not clear that this quantity can be used to differentiate between late and early type galaxies. Mateus et al. (2006), studying 50,000 luminous galaxies from the SDSS, show that the distribution of mean mass-weighted stellar ages is not bimodal, as both star-forming and passive galaxies have formed a large fraction of their stellar mass at early times (~ 12.4 Gyr in the past). We may comment on the result of N01 by referring to the mass-to-light ratio derived from the measured stellar velocity

dispersion. Wolf & Sheinis (2008) found that the average mass-to-light ratio for our quasar host sample is ~ 10 , which supports the dominance by mass of old stars. However, as stated in Section 2.5.1 our color / $\langle \log t_{\star} \rangle_L$ determination indicates that quasar hosts are bluer / younger than quiescent ellipticals.

2.5.4 On-Axis Studies

J07 present a method that spatially subtracts the quasar point spread function from the on-axis spectrum to extract the host galaxy light. Unlike our method, which is constrained to collect light $\gtrsim 9kpc$ off axis, this technique allows for the inner regions of the host galaxy to be probed. Like our study, the J07 test sample consists of nearby ($z < 0.3$) quasars. However, this sample consists of quasars that are typically less luminous in optical and radio bands than our study. J07 model 13 host spectra with a two component BC03 SSP model. Eight of the spectra were deemed trustworthy, yielding a typical light-weighted stellar age of 1-2 Gyr. For a rough comparison, our sample average $\langle t_{\star} \rangle_L$ is approximately 2 Gyr. If we limit our sample to radio quiet objects, to more closely match the sample of J07, we find an average $\langle t_{\star} \rangle_L$ of 1 Gyr. Confidence in this comparison is hampered by the small number of objects probed and the sample mismatch: our targets are typically more luminous.

Despite this mismatch, there is one object that is modeled by both groups, the radio loud quasar PKS 1302-102. While J07 find a stellar age $< 100Myr$, our results indicate a predominantly old, $> 1Gyr$ stellar population. This disagreement may indicate a radial dependence on the stellar populations or model systematics.

L07, utilizing an on-axis method complementary to the J07 technique, examine the host galaxies of 20 luminous quasars whose redshifts and nuclear optical lumi-

nosities are well matched to our sample. However, their optically selected sample contains far fewer RLQs. L07 measure diagnostic absorption and emission lines and then compare these to known quiescent galaxy values. Half of their sample was found to have young Sc-like stellar populations. The sample examined by our study indicates a redder and hence older stellar population than a typical Sc galaxy. Our studies are again brought into closer agreement if we consider only our RQQ hosts. However, no secure agreement can be claimed due to our small RQQ sample. Further complicating the comparison, L07 also model PKS 1302-102 and find evidence for a young Sc-like stellar population. Additional interpretation of this disagreement is discussed in Appendix A.

2.5.5 Sloan Digital Sky Survey Studies

The Sloan Digital Sky Survey (SDSS) has been utilized to study AGN hosts by a number of groups. These studies benefit from a large well defined sample. Narrow-line AGN studies (Kauffmann et al. 2003, hereafter K03; Zakamska et al. 2003; Mateus et al. 2006, hereafter M06) and the broad-line AGN study by Vanden Berk et al. (2006, hereafter V06) are compared to this work below.

Table 2.5. : Comparison of derived $\langle \log t_\star \rangle_L$ values to those found in the SDSS study conducted by M06. Reported errors are standard deviations of the mean.

Sample	$\langle \log t_\star \rangle_L$
Quasars $L_{5GHz} > 10^{40} \text{erg s}^{-1}$ (this work plus J04)	9.4 ± 0.1
Quasars $L_{5GHz} < 10^{40} \text{erg s}^{-1}$ (this work plus J04)	8.8 ± 0.1
Passive (M06)	9.86
AGN hosts (M06)	9.66
'green valley' (M06)	9.53
Star-forming (M06)	8.91

K03 study the host galaxies of 22,623 local type 2 AGN. Modulo deficiencies in AGN unification models, quasar hosts can be studied via their narrow-line counterparts. From 4000 Å break measurements, K03 find that high luminosity AGN have younger mean stellar ages than normal early-type galaxies. Additionally, they find a large fraction of powerful type 2 AGN have experienced significant starbursts in the past 1-2 Gyr. This is similar to our findings: $\langle t_{\star} \rangle_L = 2.7^{+0.6}_{-0.5}$ Gyrs for the radio bright sample and $\langle t_{\star} \rangle_L = 570^{+140}_{-110}$ Myrs for radio faint sample. However, there is little overlap in luminosity between our samples. The K03 powerful ($L[\text{OIII}] \sim 10^{41} \text{ erg s}^{-1}$) AGN are about one magnitude fainter than our sample's nuclear luminosities. A smaller more luminous sample of SDSS narrow-line AGN has been examined by Zakamska et al. (2003). In qualitative agreement with K03, they too find evidence for relatively blue / young host galaxies.

M06 divide a sample of 50,000 SDSS galaxies into star-forming, passive, and AGN hosts spectral classes. The AGN probed by this study are comparable in luminosity to the K03 sample. M06 find a clear bimodal distribution for the mean light-weighted stellar age among star-forming and passive galaxies. As summarized in Table 2.5, median values of $\langle \log t_{\star} \rangle_L = 8.91$ for star-forming galaxies and $\langle \log t_{\star} \rangle_L = 9.86$ for passive galaxies are found. The green valley is located at $\langle \log t_{\star} \rangle_L \sim 9.53$ and the median $\langle \log t_{\star} \rangle_L$ for AGN hosts is 9.66. The M06 median $\langle \log t_{\star} \rangle_L$ for AGN hosts is heavily weighted toward the more numerous low luminosity objects. In agreement with K03, they find that the typical $\langle \log t_{\star} \rangle_L$ decreases for more luminous AGN. Our radio bright sample with $\langle \log t_{\star} \rangle_L \sim 9.4 \pm 0.1$ is in close proximity to the green valley (slightly younger and bluer). We find the radio faint sample with $\langle \log t_{\star} \rangle_L \sim 8.8 \pm 0.1$ to fall very close to the peak of the star-forming distribution. Qualitatively we find

this to be in overall agreement with our color-magnitude diagram, Figure 2.6.

V06 study the host galaxies of 4,666 local broad-line AGN. Like K03 and M06, they find that higher luminosity AGN hosts are bluer /younger than normal early-type galaxies. This sample contains ~ 1750 quasars with luminosities comparable to our study. However, the model employed by V06 fails when the on-axis host flux fraction falls below 10% or when the signal-to-noise is less than 10. These criteria prevent the study of $\sim 70\%$ of their luminous objects and would exclude the majority of the objects (7 of 10) in this study.

2.6 Summary and Conclusions

We have presented an off-axis technique to spectroscopically constrain the color and the stellar ages of quasar ($M_V(nuc) < -23$) host galaxies. Our method draws heavily from the quiescent galaxy model of CF05, utilizing a basis of BC03 SSPs and Cardelli et al. (1989) dust extinction in a similar fashion. Complicating our χ^2 fitting routine is the residual scattered quasar light (a combination of atmospheric, instrumental and host galaxy scattered light) which must be accounted for in the off-axis spectrum. Scattered light is modeled by altering the observed nuclear spectrum by a low order polynomial, while simultaneously fitting the constituent stellar populations of the host galaxy. Furthermore, Monte-Carlo simulations are tailored to each observed pointing. Thus, the ability of the model to recover known parameters from synthetic spectra is determined. It is found that quasar host $B-V$ color and $\langle \log t_\star \rangle_L$ are well recovered. These parameters are then compared to previous studies. Overall consensus is found giving further credence to our model (however, see Appendix A for discussion of individual cases that potentially disagree with previous results).

Our method probes a population of luminous quasars unattainable by most other techniques. The stellar properties of this population have yet to be determined for a large well defined sample. For the smaller sample ($N_{obj} \sim 20$) studies that can access this luminous regime, our method can be used in conjunction to gain further insight. For example, our technique can observe the off-axis ($R_{obs} \gtrsim 9kpc$) stellar content of objects (nucleus-to-host ratio $\gtrsim 15$) inaccessible to the on-axis studies of J07 and L07.

The full potential of this method has yet to be realized. To date, we have analyzed the properties of 10 quasar host galaxies. With this sample, we confirm that elliptical quasar hosts are distinguishable (bluer) from inactive ellipticals in rest frame $B-V$ color. Additionally, we note a trend for radio luminous quasars to be located in redder host galaxies in comparison to their less radio luminous counterparts. However, general conclusions await further observations. Currently we have 10 additional WIYN off-axis observations in the process of being reduced. Furthermore, time has been allotted on the WIYN telescope to increase our total analyzed sample size to ~ 25 objects. This sample will consist of roughly an equal number of RLQs and RQQs and allow for 1) more rigorous comparison to other studies due to the increase in sample size, 2) further verification of our technique with the targeting of L07 overlap objects (specifically HE 0914-0031 and HE 0956-0720), 3) investigation of the trends found in our preliminary sample. In the near future, the Robert Stobie Spectrograph (RSS) on the 11-m Southern African Large Telescope (SALT) will be employed in our ongoing observational campaign. This phase of the project will increase the observable sample by its location in the Southern hemisphere and by allowing for higher redshift objects to be targeted ($z \sim 0.5$).

Future work will build on the current model to analyze the narrow-line emission. This will provide insight into the star formation rate, the emission mechanism, the metallicity, and the stellar content (e.g. see L07). The completion of this program will provide important observational constraints on luminous quasars.

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A Comments on Individual Hosts

In this section, we describe the stellar populations found for individual hosts and compare these to previous studies. Objects are listed in order of greatest 5 GHz luminosity to least, as in Table 2.1. Unless otherwise mentioned: young $\equiv$ ($t < 100$ Myr), intermediate $\equiv$ ($100 \text{ Myr} \leq t \leq 1 \text{ Gyr}$), and old $\equiv$ ($t > 1 \text{ Gyr}$), where t is the age of the starburst. Additionally, stellar populations (young, intermediate,

and old) are reported by percent flux contribution. Results from the Monte-Carlo simulations, namely the mean offset and the one sigma errors, are utilized in the following comments. By convention, application of offsets may not force the percent flux contribution to be negative or greater than 100%. For output parameters without offsets applied see Table 2.3. Figure 2.4 and Figure 2.A1 are also shown without offsets applied. As mentioned in Section 2.3.2.3, error estimates reflect one sigma performance; thus we expect statistically 4 of our 13 pointings to lie beyond our error limits.

3C 273 (PG 1226+023) – The host galaxy is classified as an elliptical galaxy via HST imaging (Bahcall et al. 1997; Hamilton et al. 2002). The off-axis spectral analysis of Boroson et al. (1985) qualitatively found evidence for a significant contribution from an old stellar population. Our results, 88.8 ± 13.8 % flux contribution from an old stellar population at an observed radius of 11.8 kpc, are consistent with these studies. Somewhat below the 1σ error, a young stellar component is found by the routine. Residual OII and OIII narrow line emission is noted.

4C 31.63 (Q2201+315) – 4C 31.63 is a radio loud quasar whose host galaxy has been classified as an elliptical by HST imaging (Bahcall et al. 1997; Hamilton et al. 2002) and by near-infrared adaptive optics imaging (Guyon et al. 2006). Our results for the Northern and Eastern pointings are consistent with a predominantly old stellar population. Toward the south we find evidence for an intermediate stellar population not found in the other pointings. Note that the 3S pointing has non-concurrent on and off-axis observations, see Section 2.4 for details. No narrow line emission is found for this object.

PKS 1302-102 (HE 1302-1017) – The host galaxy of this radio loud quasar

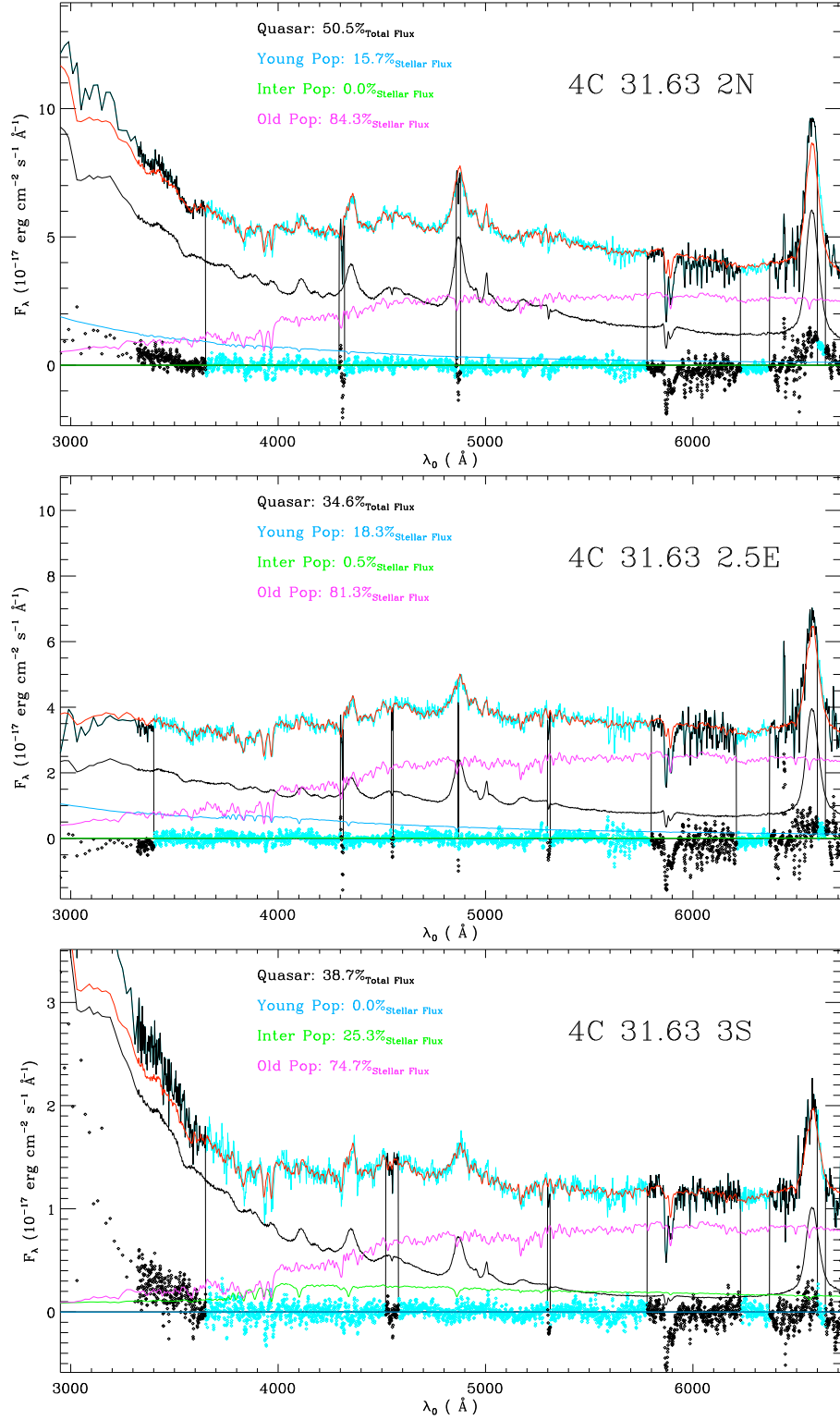


Fig. 2.A1. — : Model fit to the observed off-axis spectra. The meanings of the symbols and colors are the same as in Figure 2.4.

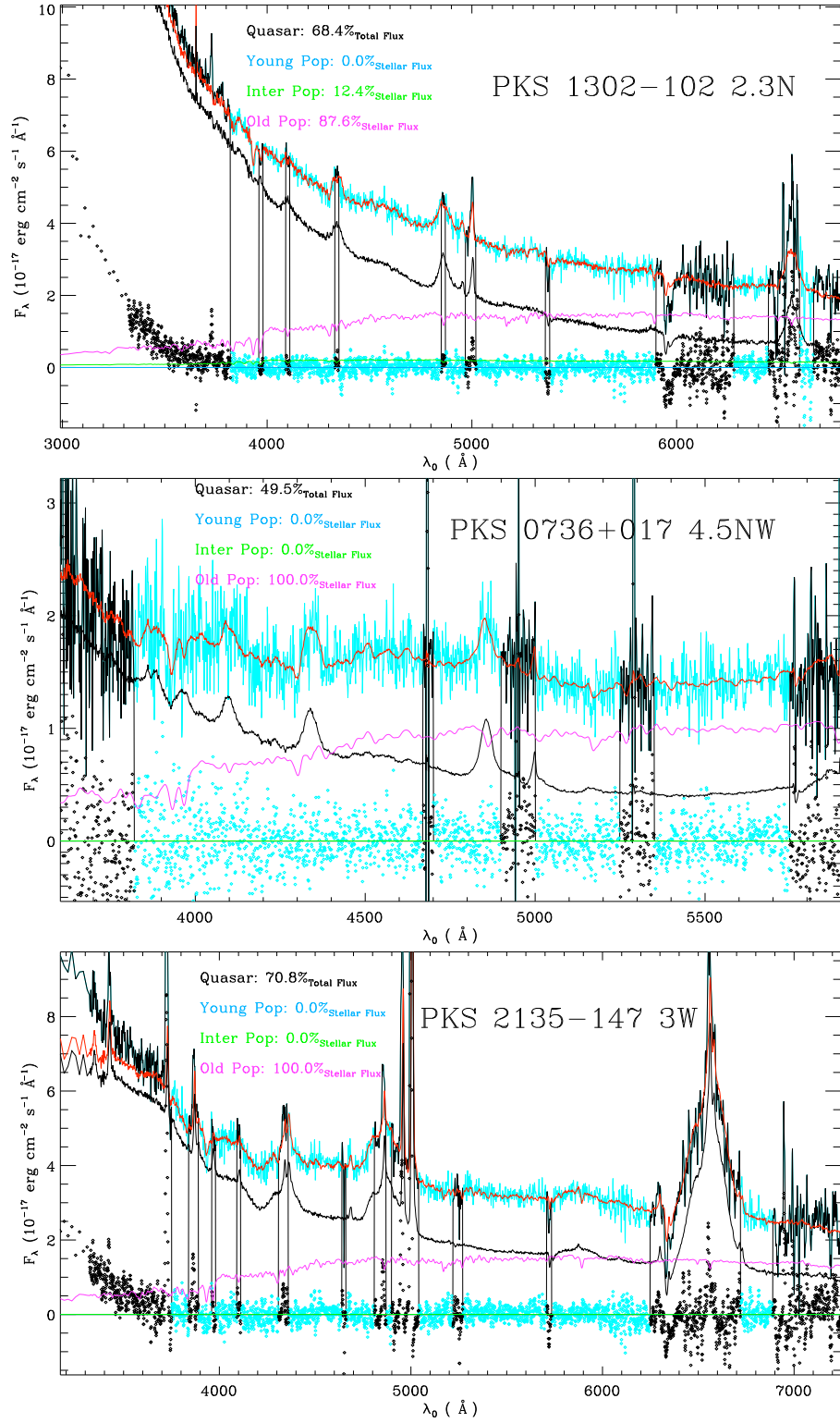


Fig. 2.A1. — : Continued

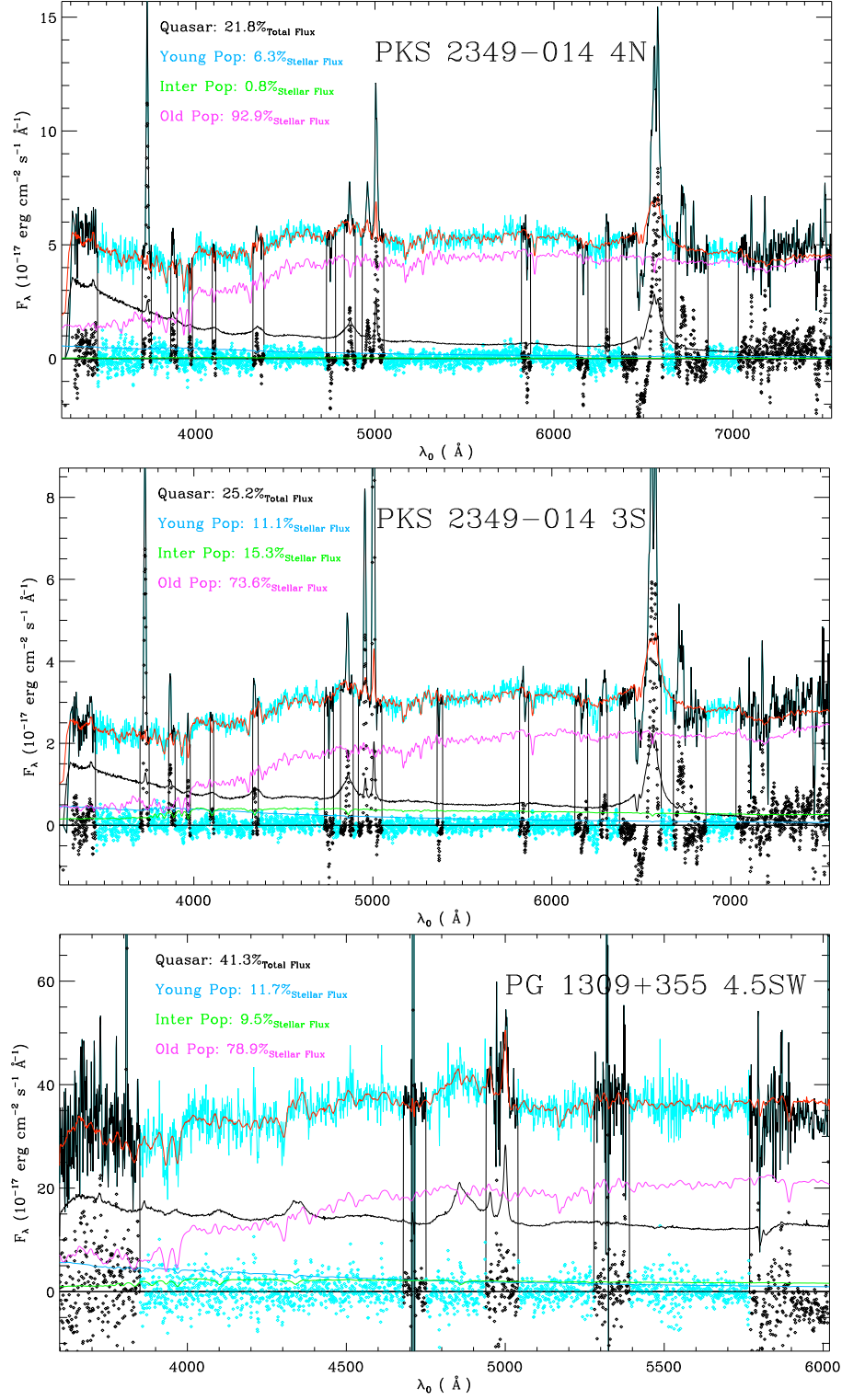


Fig. 2.A1. — : Continued

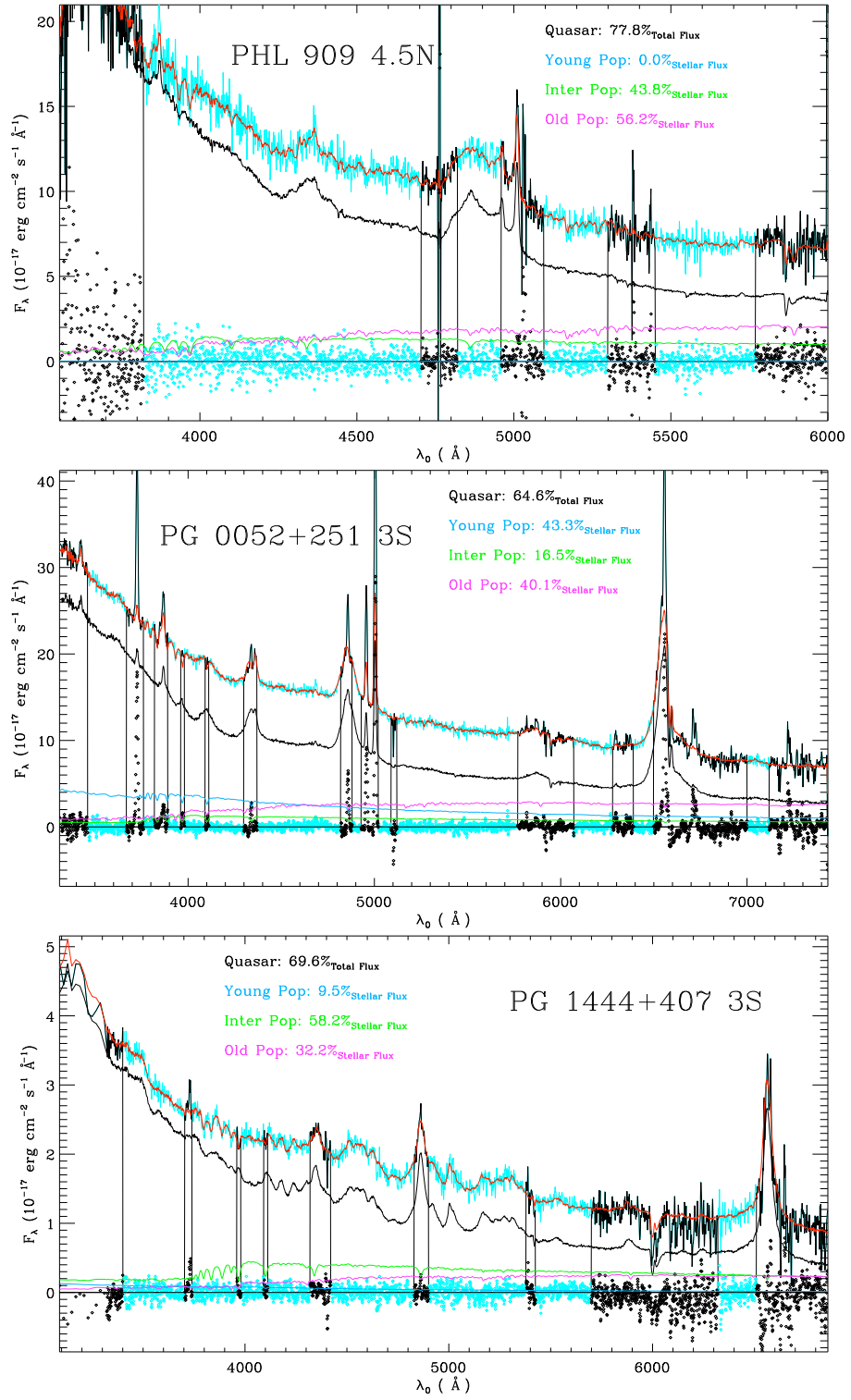


Fig. 2.A1. — : Continued

has been classified as a disturbed elliptical by various studies (Hutchings & Neff 1992; Bahcall et al. 1997; Hamilton et al. 2002; Guyon et al. 2006). Jahnke et al. (2007) and Letawe et al. (2007) have found evidence from on-axis spectroscopy for a young spiral-like stellar population. Jahnke et al. (2007) note that there are almost no stellar absorption lines with the exception of a weak Ca *II* K and Mg *I* line. This is not the case in our observed off-axis spectrum; Ca *II* K λ 3933 and H λ 3969 are prominent with clear Mg *I* b λ 5175 and Na D λ 5895 absorption features. The stellar component is found to be best fit by a $88.9 \pm 14.8\%$ old population with a statistically insignificant intermediate population. Jahnke et al. (2007) and Letawe et al. (2007) analyze the stellar content with on-axis spectra, potentially probing much closer in to the central SMBH. Thus a plausible explanation for this disagreement is the different effective radii probed by our studies; however, other systematics are not ruled out. In our observed off-axis spectrum, scattered light from the central quasar is significant $\sim 68.4\%$, effectively decreasing the signal-to-noise of the stellar component. Additionally, the Balmer decrement has been masked due to nebular emission, potentially removing important spectral information. On the other hand, we estimate the nucleus-to-host ratio to be 13.5, which is relatively close to the stated upper limit of ~ 15 to reliably detect absorption features with the on-axis method (L07). Regardless, the observed prominent Ca H and K absorption lines support the claim that a significant old population is present at the radius probed ~ 13 Kpc. Residual OII and OIII narrow line emission is noted.

PKS 0736+017 – The host galaxy has been classified as elliptical (Wright, McHardy & Abraham 1998 McLure et al. 1999; Falomo & Ulrich 2000; Hamilton et al. 2002). Others describe the host as a disturbed elliptical based on near-infrared

imaging (Dunlop et al. 1993) and deep HST imaging (Bennert et al. 2008). Off-axis spectroscopic studies have found a stellar component indicative of a 12 Gyr population (Hughes et al. 2000; Nolan et al. 2001). Canalizo & Stockton (in preparation) find a 2.2 Gyr starburst in this host (Bennert et al. 2008) which falls in our 'old' age bin. Our results indicate $100 \pm 12.4\%$ flux contribution due to an old population. No narrow line emission is found for this object.

PKS 2135-147 – The host galaxy of this radio loud quasar has been classified as elliptical by Bahcall et al. (1997) and Hamilton et al. (2002). Our results are consistent with the expected stellar population of an elliptical galaxy. We find $100 \pm 12.0\%$ old stellar population at a radius of approximately 12.5 Kpc. Multiple residual narrow emission lines are noted for this object.

PKS 2349-014 – The host galaxy of this radio loud quasar has been classified as a highly disturbed elliptical by many imaging studies (Bahcall et al. 1997; Guyon et al. 2006). An off-axis spectroscopic study by Nolan et al. (2001) found a dominant old stellar population of 12 Gyr with a low level young population. Off-axis studies (Miller & Sheinis 2003; Wolf & Sheinis 2008), utilizing the same data analysed in this paper, have also found evidence for a predominately old stellar population with a lesser young population. Our results are consistent with a predominantly old population by flux. The northern pointing (14.12 kpc), probing large tidal arms, is consistent with an entirely old stellar population; whereas the closer-in Southern pointing (9.47 kpc) we find evidence for a small intermediate population ($16.1 \pm 13.2\%$). Multiple residual narrow emission lines are noted for this object.

PG 1309+355 – HST imaging studies classify this object as a spiral (Bahcall et al. 1997; Hamilton et al. 2002), while the near-infrared study of Guyon et al. (2006)

classifies the host as an elongated elliptical. If this object is truly a spiral, then this is a very rare object displaying a large radio luminosity, just below our radio-loud threshold. Our results indicate a predominantly old population. No significant narrow emission lines are noted.

PHL 909 (0054+144) – The host is an elliptical galaxy as classified by the imaging studies of Bahcall et al. (1997) and Hamilton et al. (2002). The near-infrared imaging of Dunlop et al. (1993) detects extended emission toward a companion. Recent deep HST imaging (Bennert et al. 2008) detects tidal tails and shells. Barthel (2006), analysing the far-infrared / radio correlation, finds evidence of recent or on going star formation. Off-axis spectroscopic studies have either classified the stellar population as old (Nolan et al. 2001) or have reported ambiguous results (Hughes et al. 2000). Canalizo & Stockton (in prep.), analysing ~ 2 hr exposure Keck LRIS data, find a 12 Gyr population combined with a 2.2 Gyr starburst (as reported in Canalizo et al. 2006). This would correspond to a 100% old population given our adopted age bins; however our results indicate $59.6 \pm 12.4\%$ old and $48.7 \pm 20.0\%$ intermediate by flux. This pointing has the highest scattered quasar component at 77.8% by flux. The scattered light contamination is highest at the blue end of the spectrum where the 4000Å break and various stellar absorption features are located. Thus our Monte-Carlo error simulations, which normally are not constrained to have steep blue scattering efficiency curves, may be under estimating the actual error. To test this scenario, we performed Monte-Carlo simulations with input parameters indicative of PHL 909 and constrained to have a steep scattering efficiency curve, as found by the best fit model output. The error estimates and offsets were not significantly

affected by this alteration⁸. If our observations are co-spatial with those of Canalizo & Stockton, then the difference in the results may simply be a 3σ outlier arising from separate observations and different analysis methods. Regardless, construction of a solar BC03 stellar spectrum consistent with the findings of Canalizo et al. (2006) results in values for the mean light-weighted age and $B-V$ color that are consistent (within 1σ) of our findings. Therefore, we believe that the main discussion regarding the more reliably recovered parameters, color and $\langle \log t_\star \rangle_L$, are robust.

PG 0052+251 – The host galaxy associated with this radio quiet quasar is a spiral as classified by various imaging studies (Bahcall et al. 1997; Hamilton et al. 2002). Our results are consistent with a significant young population of $35.3 \pm 19.2\%$ by flux and an old population of $43.7 \pm 11.5\%$. Multiple residual narrow emission lines are noted for this object.

PG 1444+407 – The host of this radio quiet quasar is classified as a spiral by Hamilton et al. (2002). Bahcall et al. (1997) note that the host has the appearance of an elliptical; however the light profile is best fit by an exponential disc model. Additionally, Ho (2005) estimate a significant star formation rate ($19.4 M_\odot \text{yr}^{-1}$) based on the [O II] luminosity. Our results indicate a $60.8 \pm 27.6\%$ intermediate population, a $37.4 \pm 17.7\%$ old population and a statistically insignificant young population. Multiple residual narrow emission lines are noted for this object.

⁸As listed in Table 2.1 and Table 2.2, the original error simulations found the following offsets and $\pm 1\sigma$ errors: $-8.3 \pm 18.4\%$ for young, $+4.9 \pm 20.0\%$ for intermediate, $+3.4 \pm 12.4\%$ for old, $+0.02 \pm 0.10$ for $B-V$ color, and $+0.14 \pm 0.45$ for $\langle \log t_\star \rangle_L$. The steep blue scattering simulations found: $-3.1 \pm 22.0\%$ for young, $-1.8 \pm 22.5\%$ for intermediate, $+4.9 \pm 11.9\%$ for old, $+0.01 \pm 0.08$ for $B-V$ color, and $+0.03 \pm 0.45$ for $\langle \log t_\star \rangle_L$.

Chapter 3

VLA 1.4 GHz Catalogs of the Abell 370 and Abell 2390 Cluster Fields

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I. G. B. Wold, F. N. Owen, W. Wei-Hao, A. J. Barger, R. C. Keenan, 2012, vol.
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Abstract

We present 1.4 GHz catalogs for the cluster fields Abell 370 and Abell 2390 observed with the Very Large Array. These are two of the deepest radio images of cluster fields ever taken. The Abell 370 image covers an area of $40' \times 40'$ with a synthesized beam of $\sim 1.7''$ and a noise level of $\sim 5.7 \mu\text{Jy}$ near field center. The Abell 2390 image covers an area of $34' \times 34'$ with a synthesized beam of $\sim 1.4''$ and a noise level of $\sim 5.6 \mu\text{Jy}$ near field center. We catalog 200 redshifts for the Abell 370 field. We construct differential number counts for the central regions (radius $< 16'$) of both clusters. We find that the faint ($S_{1.4\text{ GHz}} < 3 \text{ mJy}$) counts of Abell 370 are roughly consistent with the highest blank field number counts, while the faint number counts of Abell 2390 are roughly consistent with the lowest blank field number counts. Our analyses indicate that the number counts are primarily from field radio galaxies. We suggest that the disagreement of our number counts can be largely attributed to cosmic variance.

3.1 Introduction

Radio surveys probe active galactic nuclei (AGNs) and star-forming (SF) galaxies. SF galaxies produce non-thermal radio continuum through synchrotron emission from supernova remnants. For these sources, the 1.4 GHz luminosity is found to be an accurate indicator of the star formation rate (Condon 1992). AGNs also emit synchrotron radiation, which is ultimately powered by accretion onto supermassive black holes (SMBHs). Observed tight correlations between SMBH mass and bulge properties (Kormendy & Richstone 1995; Ferrarese & Merritt 2000; Tremaine et al. 2002) plus various theoretical considerations (Granato et al. 2004; Croton et al. 2006; Bower et al. 2006) have led to the hypothesis that AGNs regulate star formation. Thus, radio surveys are an important tool to constrain how stars and SMBHs evolve and interact as a function of cosmic time.

There is still debate over the faint radio population, especially regarding the differential source counts. AGNs are found to dominate the counts at high flux densities, while SF galaxies are thought to emerge at lower flux densities (Condon 1989). However, the exact composition — and the counts themselves — are debated below $S_{1.4\text{ GHz}} = 100\text{ }\mu\text{Jy}$. The disagreement in faint radio counts from one survey to the next has been attributed mostly to instrumental and analysis effects, not to cosmic variance (Condon 2007). For example, for the heavily studied Hubble Deep Field-North (HDF-N), three different groups have derived faint-end number counts, with each subsequent study finding them to be incrementally higher (Richards 2000; Biggs & Ivison 2006; Morrison et al. 2010). However, studies such as Biggs & Ivison

(2006), which present catalogs for three deep radio fields, have shown that similar instrument configurations and analysis methods still result in faint counts that are inconsistent with merely Poisson variation. It is important to obtain as many deep radio images as possible to help resolve this issue, especially since cosmic variance could be an important factor.

In this paper, we present deep radio observations of two heavily-studied cluster fields. Radio surveys of cluster fields have been vital to many areas of study. For example, they have improved our understanding of cluster members by finding evidence for a population of dust-obscured SF cluster galaxies that were previously classified as post-starburst galaxies based on optical spectra. With the help of high-resolution near-infrared (NIR) and optical imaging, Smail et al. (1999) interpreted radio emission from these objects as an indication of ongoing star formation.

Radio surveys of cluster fields have also been useful in the study of cluster evolution. For example, Morrison (1999) found that the population of low-luminosity radio sources in clusters rapidly increases with redshift ($0.02 \leq z \leq 0.41$). This can be interpreted as an extension of the Butcher-Oemler effect (Butcher & Oemler 1984), since the majority of low-luminosity radio sources are found to be blue SF galaxies (Morrison & Owen 2003).

Radio data are key to multiwavelength studies. Radio emission is unobstructed by dust, which avoids a major source of bias found in UV and optical studies. With the addition of far-infrared (FIR) data, radio data can be used to indicate the dominant emission mechanism. The radio luminosity is observationally found to be tightly correlated with the FIR power for SF galaxies locally (Helou et al. 1985; Condon 1992) and at high redshift (Appleton et al. 2004; Ivison et al. 2010; Mao et al. 2011).

Any significant departure from the FIR-radio correlation is an indication of AGN activity.

In addition, the positional accuracy of radio surveys can be used to pinpoint counterparts at other wavebands. In the submillimeter, single dish telescopes have very poor resolution, and the unambiguous identification of counterparts is not possible without additional information. From the FIR-radio correlation, we know that FIR luminous SF galaxies, such as submillimeter galaxies (SMGs), are correspondingly luminous in radio emission. Thus, radio data can be used to identify SMG counterparts. Barger et al. (2000), Ivison et al. (2002), and Chapman et al. (2003) found that $\sim 60\%$ of bright (>2 mJy) SMGs had radio counterparts. This feature allowed Chapman et al. (2005) to use radio positions to target spectroscopically a large sample of bright SMGs, establishing the redshift distribution for this population. Bright SMGs are predominantly massive, dust-obscured, SF galaxies at a median redshift of ~ 2.2 (Chapman et al. 2005; Alexander et al. 2005).

Submillimeter observations are a redshift independent probe (due to a negative K -correction: $1 < z < 8$) of dust-reprocessed UV light. However, the positive K -correction of the radio synchrotron emission results in faint observed 1.4 GHz fluxes for high-redshift objects. Thus, a high submillimeter-to-radio flux measurement is an indication of a high-redshift source (Wang et al. 2007, 2009; Dannerbauer et al. 2008; Capak et al. 2008, 2011; Schinnerer et al. 2008; Daddi et al. 2009a,b; Coppin et al. 2009, 2010; Riechers et al. 2010; Knudsen et al. 2010). This extreme population of very massive sources at very high redshifts has been the topic of intense study and has led many authors to suggest the need for significant modifications to models of galaxy evolution (e.g., Granato et al. 2004; Baugh et al. 2005; Hopkins et al.

2005; Lukić et al. 2007). Deep radio surveys continue to be an important tool in the discovery of these objects.

Blank-field submillimeter surveys with the Submillimeter Common-User Bolometer Array (SCUBA; Holland et al. 1999) first resolved the bright SMGs that account for $\sim 20\% - 30\%$ of the $850\ \mu\text{m}$ extragalactic background light (e.g., Barger et al. 1998; Hughes et al. 1998; Barger et al. 1999; Eales et al. 1999). These surveys cannot reach the sensitivities required to detect directly the dominant population of $< 2\ \text{mJy}$ sources because of confusion noise resulting from the coarse resolution of SCUBA. In order to detect this population, one must observe fields with massive cluster lenses to take advantage of both gravitational amplification by the lens and reduced confusion noise (Smail et al. 1997; Cowie et al. 2002; Knudsen et al. 2008). Deep radio images of cluster fields are therefore valuable for identifying the counterparts and determining the properties of this important faint SMG population. Such data will also be very useful for helping to interpret *Herschel* (Egami et al. 2010) and SCUBA2 (Chen et al. 2013) observations.

In this paper, we construct deep radio catalogs of the cluster fields Abell 370 (A370) and Abell 2390 (A2390), which we have reduced and analyzed in a similar fashion. We derive the number counts for the two fields, and we discuss the influence of the cluster and the importance of cosmic variance on these counts. In our A370 catalog we include redshifts for 200 radio sources that we obtained from the literature, from unpublished work, and from our own observations. We note that, in addition to copious ancillary data, these clusters also have excellent lens models (Kneib et al. 1993; Kneib 2002; Richard et al. 2010). Our radio catalogs in combination with the public data already available for these extensively studied fields will aid in both

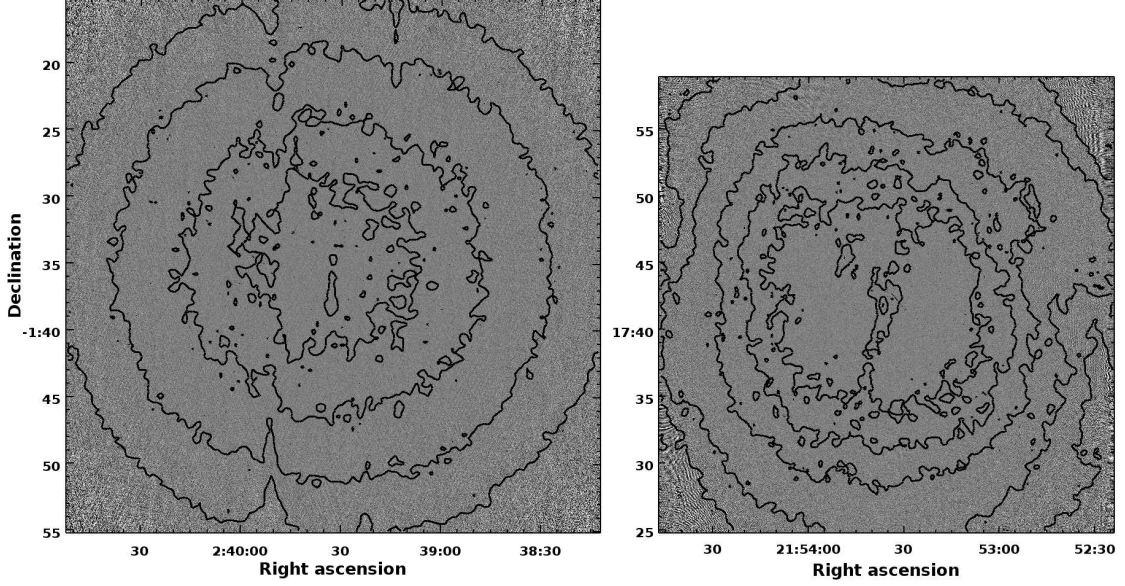


Fig. 3.1. — : **Left**: Contours of constant rms noise overlaid on the $40' \times 40'$ A370 image. Contours levels are 6.5, 8.0, 12.0, and $20.0 \mu\text{Jy}$ and are located approximately $6'$, $11'$, $16'$, and $20'$ from field center. The image has a 1σ rms noise level of $\sim 5.7 \mu\text{Jy}$ near field center and a $1.8'' \times 1.6''$ synthesized beam. **Right**: Contours of constant rms noise overlaid on the $34' \times 34'$ A2390 image. Contours levels are 5.5, 6.5, 8.0, 12.0, and $20.0 \mu\text{Jy}$ and are located approximately $8'$, $10'$, $12'$, $16'$, and $19'$ from field center. The image has a 1σ rms noise level of $\sim 5.6 \mu\text{Jy}$ near field center and a $1.4'' \times 1.3''$ synthesized beam.

cluster and field galaxy studies.

We describe our observations and data reduction in Section 3.2. In Section 3.3, we describe our source extraction and cataloging. In Section 3.4, we compare our catalog to large-area survey results for bright sources. In Section 3.5, we construct differential number counts for the central regions (radius $< 16'$) of both clusters. We discuss the derived counts in Section 3.6 and summarize the paper in Section 3.7. Throughout this paper, our adopted cosmology is $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

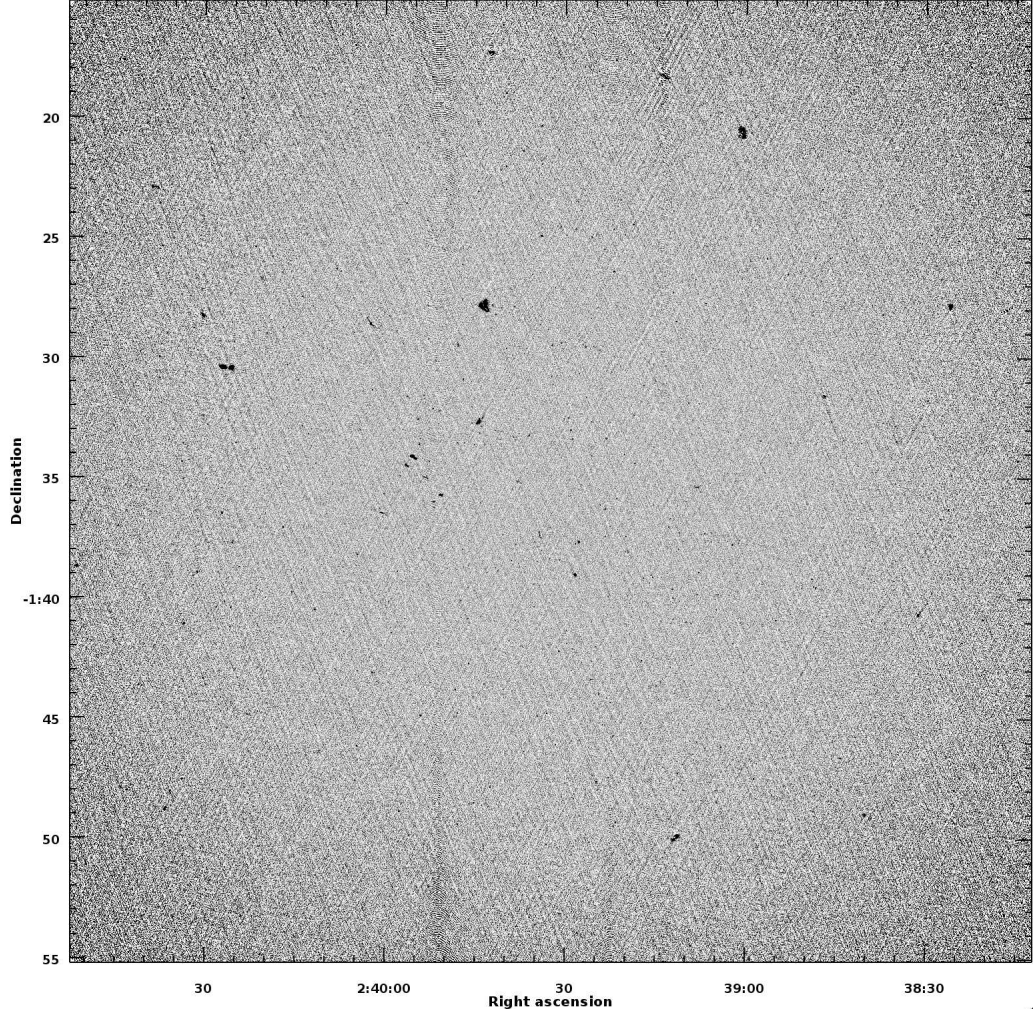


Fig. 3.2. — : The $40' \times 40'$ A370 image. Field center is located at $02^h 39^m 32^s$, $-01^\circ 35' 07''$ in J2000 coordinates. This is offset by $\sim 5'$ from the cluster center at $02^h 39^m 50.5^s$, $-01^\circ 35' 08''$. We observe no radio halos or relics; however, smaller array configurations would be more sensitive to these large structures.

3.2 Observations and Data Reduction

3.2.1 A370 VLA Observations and Data Reduction

We observed the A370 cluster field with the VLA in the A configuration for ~ 42.4 hr on-source during August and September 1999. K. S. Dwarkanath observed A370 in the B configuration for ~ 18.4 hr on-source during August and September

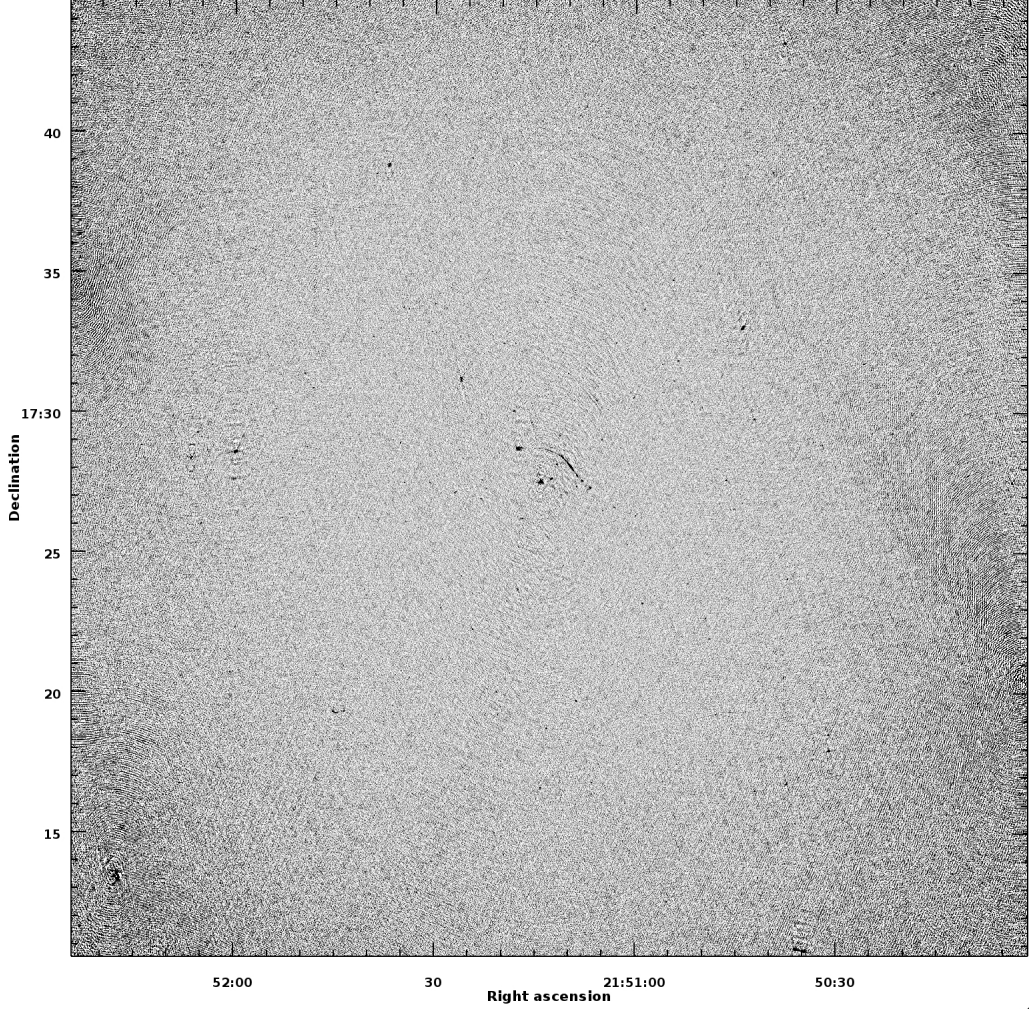


Fig. 3.3. — : The $34' \times 34'$ A2390 image. Field center is located at $21^h53^m36^s$, $+17^\circ41'52''$ in J2000 coordinates. This is only offset by $20''$ from the cluster's central cD galaxy at $21^h53^m37^s$, $+17^\circ41'44''$. We observe no radio halos or relics; however, smaller array configurations would be more sensitive to these large structures.

1994. In Table 3.1, we summarize the parameters of the observing runs. In both configurations, the data were taken in spectral line mode 4, which records seven 3.125 MHz channels in each of the two intermediate frequencies (IFs) centered at 1.365 and 1.435 GHz, and each of the two polarizations. Five and ten second integration times were utilized for the A and B configurations, respectively. Field center is located at $02^h39^m32^s$, $-01^\circ35'07''$ in J2000 coordinates. This is offset by approximately 5

arcmins from the cluster center at $02^h39^m50.5^s$, $-01^\circ35'08''$.

Since we reduced both the A and B configuration data in a similar fashion, we only describe our reduction of the B configuration data. When necessary, we indicate any significant alterations needed for the A configuration data reduction. Once we completed our initial reduction, we combined the two configuration data sets and performed a final round of calibration. Our data reduction techniques follow the procedures described by Owen & Morrison (2008, hereafter OM08) and Owen et al. (2009). We exclusively used the AIPS package to reduce these data.

We reduced the data obtained during the first day of the observations in the following manner. We edited the phase and flux calibrators for obvious amplitude anomalies using TVFLG. Then, we split the flux calibrator from the raw database and applied a phase self-calibration. At this point, we determined the bandpass correction using the BPASS task applied to the flux calibrator. To account for the effects of the sloping spectral response, we applied this bandpass correction by copying the table generated by BPASS to the raw database. We then scaled the primary flux calibrator, 3C 48, using the Baars flux density values (Baars et al. 1977).

We imaged these data using the AIPS task IMAGR and the three dimensional multifacet options. To image 0.9° from field center and include all bright NVSS

Table 3.1. : Observing Summary

Field	Config.	Start Date	End Date	On Source Hrs
A370	A	1999 Aug 24	1999 Sep 20	42.4
A370	B	1994 Aug 01	1994 Sep 03	18.4
A2390	A	2008 Oct 20	2008 Oct 28	31.4

objects within a 2.5° radius required 211 facets, each with 512^2 $1.5''$ pixels. The A configuration required 384 facets (each with 1024^2 $0.5''$ pixels) to image 0.8° from field center and include all strong B configuration sources. After initial imaging, we limited cleaning to real features by designating detected sources with clean boxes. We performed phase self-calibration followed by phase and amplitude self-calibration. Thus, we generated clean images which were then used as fiducial models for each subsequent day.

We employed the VLA pipeline as recommended by AIPS Memo 112 (Lorant Sjouwerma 2007) to perform initial calibration on subsequent days. Then, we calibrated these data to images produced from the day one observations. We used the AIPS procedure STUFR to combine and compress data from all days of the observing run, producing one master visibility file (for each configuration).

We then split this combined visibility data set by IF and further self-calibrated. As discussed in Owen et al. (2009), we used UVSUB to subtract the bright off-axis sources from the visibility data. We then imaged the facets known to contain bright, outlying sources as a data cube. We subtracted the generated clean components from the original visibility data channel by channel. We conducted this residual spectral subtraction procedure to compensate for frequency-dependent artifacts which produce radial smearing for very bright sources far from field center.

We then combined the like components of the A and B array with DBCON and further split the data into 2 polarizations, thus producing 4 visibility files (2 polarizations and 2 IFs). We further calibrated these data, including another iteration of the residual spectral subtraction procedure. As a final calibration step, we employed PEELR to account for local gain variations produced by bright sources in the out-

skirts of the field. Final images were made using robust weighting (ROBUST=0 in IMAGR) and using IMAGR's UVTAPER empirically set to 100,100. We combined the facet images into 4 composite images using FLATN. Then, we combined these 4 images, weighted by rms^{-2} . Finally, we flattened the image composite using MWF (as performed in OM08, but with a 41×41 pixel support window). This final image has a noise level of $\sim 5.7 \mu\text{Jy rms}$ near field center, with a $1.8'' \times 1.6''$ synthesized beam at a position angle of 166° . In Figure 3.1(a), we show the $40 \times 40 \text{ arcmin}^2$ A370 radio field with rms noise contours overlaid. Residual sidelobes from bright outlying sources are still clearly present on either side of the field center, offset by approximately $6'$ from center with a North-South orientation. In Figure 3.2, we show a larger image of the A370 radio field without noise contours to allow for inspection of individual radio sources. We observe no radio halos or relics; however, smaller array configurations would be more sensitive to these large structures.

3.2.2 A2390 VLA Observations and Data Reduction

We observed the A2390 cluster field with the VLA in the A configuration for ~ 31.4 hr on-source during October 2008. We obtained the data in spectral line mode 4, and we sampled the data every 3.3 seconds. Field center is located at $21^h 53^m 36^s$, $+17^\circ 41' 52''$ in J2000 coordinates.

As described above for the A370 field, we followed the data reduction techniques outlined by OM08 and Owen et al. (2009). The primary flux calibrator was 3C 48. We used 102 facets to cover the primary beam. Each facet consisted of 1024^2 $0.5''$ pixels. We carried out the reductions as described above, producing a master visibility file for all A configuration data. After an initial pass of self calibration, we split the visibility file into the 28 parts that come from the 7 channels, 2 IFs,

and 2 polarizations. We self-calibrated, imaged, cleaned, and PEELRed the 28 data sets independently. We carried out a few self-calibration/imaging/PEELR cycles to obtain a converging solution for each of the 28 data sets. We then made 28 images with the AIPS task IMAGR. This procedure, which further splits the visibility files by channel, was necessary to minimize the sidelobes from the bright sources around the edges of the field and from the central cD galaxy.

We combined the 28 images using IDL. For each pixel in the 28 images, we first measured the local background fluctuation in a $32'' \times 32''$ region around it. Such background fluctuations come from both noise and weak residual sidelobes from bright sources that cannot be perfectly calibrated with the above procedure. We then merged the 28 images using an error-weighted mean according to the above measured background fluctuation. Very weak residual sidelobes can still be seen in the final merged image in certain regions, especially along the North-South side of the central cD galaxy. However, we obtained an excellent overall $5.6 \mu\text{Jy}$ rms in the central part of the image. The synthesized beam is $1.4'' \times 1.3''$ with a position angle of 72° . In Figure 3.1(b), we show the $34 \times 34 \text{ arcmin}^2$ A2390 radio field with rms noise contours overlaid. In Figure 3.3, we show a larger image of the A2390 radio field without noise contours to allow for inspection of individual radio sources. We observe no radio halos or relics; however, smaller array configurations would be more sensitive to these large structures.

Table 3.2. Sample of Radio Source Catalog

Abell Field	Number	R.A. (J2000) hms $\pm$ e(s)	Dec. d ' ' ' $\pm$ e('')	PNR	S _{1.4} $\pm$ e μ Jy	Maj	Size Min	P.A.	Upper "	Beam "	Redshift	Ref.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
370	0	02 38 13.15 0.439	-01 46 26.57 0.55	25.4	1422.9 $\pm$ 74.3	5.8	3.9	59	...	1.8	...	...
370	1	02 38 13.83 0.095	-01 17 30.36 0.12	5.3	705.1 $\pm$ 134.5	...	...	...	0.5	3.0	...	...
370	2	02 38 14.64 0.070	-01 34 15.05 0.06	23.5	610.7 $\pm$ 31.8	...	...	...	1.6	1.8	...	...
370	3	02 38 15.07 0.192	-01 51 24.19 0.22	7.9	575.6 $\pm$ 75.1	...	...	...	3.2	3.0	...	...
370	4	02 38 15.50 0.110	-01 55 2.76 0.10	5.3	1005.1 $\pm$ 190.3	...	...	...	1.8	1.8	...	...
370	5	02 38 16.61 0.292	-01 33 0.89 0.21	13.0	207.8 $\pm$ 25.6	7.2	0.0	60	...	1.8	...	...
370	6	02 38 16.62 0.400	-01 27 58.24 0.53	934.8	31519.4 $\pm$ 946.3	6.7	3.8	103	...	1.8	...	...
370	7	02 38 16.89 0.416	-01 53 6.26 0.54	39.4	4367.0 $\pm$ 177.2	6.7	3.9	42	...	1.8	...	...
370	8	02 38 17.26 0.421	-01 50 41.28 0.54	32.2	3195.5 $\pm$ 145.4	6.0	3.2	48	...	1.8	...	...
370	9	02 38 17.35 0.221	-01 52 46.70 0.37	5.3	390.1 $\pm$ 73.9	...	...	...	4.2	1.8	...	...

Note. — Table 2 is published in its entirety in the electronic edition of *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content.

3.2.3 A370 Spectroscopic Observations and Reductions

We targeted 58 radio sources without existing spectral data using the Hydra fiber spectrograph on the Wisconsin-Indiana-Yale-NOAO (WIYN) telescope. We preferentially targeted optically bright galaxies. We observed these data with a single two hour pointing on 2012 January 20. Seeing was approximately $0.8''$. We configured the spectrograph using the “red” fiber bundle and the 316@7.0 grating at first order with the GG-420 filter to provide a spectral window of $\sim 4500 - 9500$ Å with a pixel scale of 2.6 Å per pixel. The Hydra “red” fibers are $2''$ in diameter and have a positional accuracy of $0.3''$, which ensured that the majority of light from our target galaxies was observed with little contamination from the sky and neighboring sources. We employed the IRAF task *dohydra*¹ in the reduction of our spectra. This task is specifically designed for reduction of data from the Hydra spectrograph and includes steps for dark and bias subtraction, flatfielding, dispersion calibration, and sky subtraction. As described in Keenan et al. (2012), we used the IRAF task *xciao* within the *rvsao* package (Kurtz & Mink 1998) to determine redshifts for our observed spectra. Of the 58 targets, we obtained high-confidence redshifts for 36.

3.3 Source Extraction and Cataloging

For the A370 image, we extracted sources from the central 40×40 arcmin² region. For the A2390 image, we extracted sources from the central 34×34 arcmin² region. To help account for instrumental and intrinsic image broadening effects, we also analyzed our images at lower resolutions. For each field, we created two

¹<http://iraf.noao.edu/tutorials/dohydra/dohydra.html>

complementary low resolution images by convolving the final images with Gaussians with FWHM equal to 3'' and 6''. We extracted sources from the full, 3'', and 6'' resolution images independently. We then compared and collated the results. This procedure has been shown to assist in the detection of low surface brightness sources (Morrison et al. 2010).

We generated noise maps using the AIPS routine RMSD (IMSIZE=71,-1; OP-
TYPE='HIST') for each of the three resolutions. When extracting sources using the AIPS routine SAD, we used the output of RMSD to estimate the background noise. SAD searches an image for sources above some peak flux threshold and then uses a Gaussian fitting routine to estimate flux density. For each resolution, we extracted sources with peak signal-to-noise ratios (PNRs) greater than 4. For sources with $\text{PNR} \leq 5.5$ or for residual sources found manually, we used JMFIT to determine source properties. The final catalog contains sources with PNRs greater than 5. We accounted for bandwidth smearing and primary beam attenuation in both the SAD and JMFIT procedures.

We considered a source resolved if the lower limit for the major axis is greater than zero and the integrated flux minus 1σ error exceeds the peak flux. For unresolved sources, we recorded the upper limit of the major axis and the total flux (best estimated by the peak flux, OM08). For resolved sources, we recorded the integrated flux and the best fit deconvolved major axis, minor axis, and position angle (P.A.).

For extended sources, it is more accurate to estimate the flux densities using TVSTAT, which sums the total signal in a user-defined area, rather than using the summation of the SAD Gaussians. As prescribed by Morrison et al. (2010), we used IMEAN to determine the peak flux and its location. Using the noise map, we then

measured the 1σ noise level at this position. We adopted the ratio of these values, peak flux / 1σ noise level, as the PNRs for extended sources.

For each field, we compared the three catalogs extracted from the three images with different resolutions. We adopted the $3''$ resolution source only if the PNR was more than 10% higher than its higher resolution counterpart. Similarly, we adopted the $6''$ resolution source only if the PNR was more than 10% higher than its $3''$ resolution counterpart. Thus, we generated a catalog for the A370 and A2390 fields.

We compared an intermediate image constructed just after combination of the A and B configurations to our final A370 image. We found that the extracted source flux is underestimated by a factor of 1.1. We attribute this discrepancy to calibration errors from combining the A and B configuration data. In our data reduction routine, we performed self calibration of the combined data without constraining the mean gain modulus to unity. In the presented A370 catalog, we have corrected for this systematic offset.

We present the first ten lines of our combined A370 and A2390 catalog in Table 3.2.2. In Column 1, we indicate the Abell field, either Abell 370 or 2390. In Column 2, we indicate the radio source number. There are a total of 699 galaxies in the A370 catalog and 524 galaxies in the A2390 catalog. In Columns 3 and 4, we give the (J2000) right ascension and declination with error estimates. We report the peak signal-to-noise ratio in Column 5. In Column 6, we indicate the total 1.4 GHz flux and uncertainty in μJy . For resolved sources, we list the best-fit deconvolved size characteristics in Columns 7–9, reporting the major and minor FWHM sizes in arcsec. For unresolved sources, we indicate the major axis upper limit size in Column 10. We list the resolution of the image used in the source extraction in Column 11.

Only the A370 field contains data in Columns 11 and 12. In these columns, we list 200 A370 redshifts and their references. To identify redshift - radio matches, we visually inspected all spectroscopic data lying within $10''$ of a radio source position by overlaying radio contours and the spectral position on deep broadband optical images. We adopted this technique, because extended and double-lobe radio sources often have peak radio brightness offset from their optical center. Although these redshifts have been utilized in previous studies, the vast majority are published for the first time. Reference 1 designates redshifts obtained via an ongoing spectroscopic campaign using the DEep Imaging Multi-object Spectrograph (DEIMOS) on the Keck telescope (L. Cowie, private communication). Reference 2 denotes a campaign by F. Owen using Hydra on WIYN (F. Owen, private communication). Reference 3 designates additional WIYN Hydra redshifts obtained in a $z \sim 0.2$ NIR follow-up survey (Keenan et al. 2012). Reference 4 denotes an archival redshift obtained from Dunlop et al. (1989). Reference 5 designates the new WIYN Hydra redshifts that we obtained (see Section 3.2.3) to supplement the existing data. We determine the redshift false identification rate by shifting the radio image by $70''$ and re-identifying redshift - radio matches. We estimate that 4% of our redshift identifications are false.

3.4 Comparison with NVSS and FIRST

We compare our work to the Faint Image of the Radio Sky at Twenty-cm (FIRST) (White et al. 1997) and the NRAO VLA Sky Survey (NVSS) (Condon et al. 1998) catalogs. The FIRST survey is a VLA program which produced images with 0.75 mJy sensitivity and a resolution of $\sim 5''$ in the vicinity of A370. This survey has 50 sources coincident with our 40×40 arcmin² A370 field. Of these 50

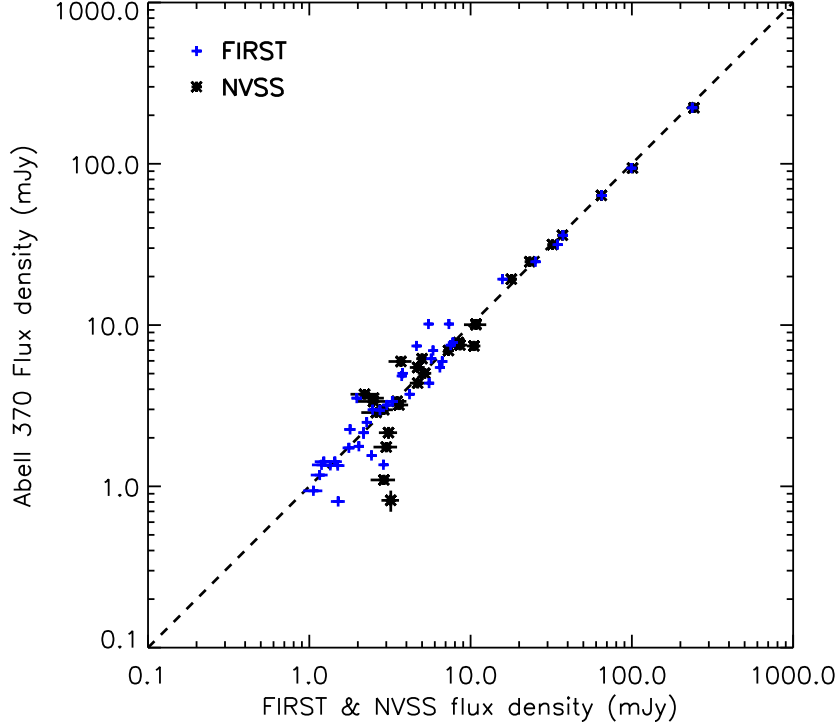


Fig. 3.4. — : A370 flux densities compared to those from the FIRST and NVSS catalog. 41 out of 50 FIRST objects (blue crosses) and 29 out of 30 NVSS objects (black asterisks) are found to have counterparts. The dashed line indicates the ideal case, equality of flux densities.

objects, 41 have counterparts in our catalog. NVSS provides ~ 2.5 mJy sensitivity and a resolution of $45''$. There are 30 NVSS sources in our A370 field. Twenty-nine of these have counterparts in our radio catalog.

Based on all 41 FIRST sources with counterparts in our radio catalog, the $\text{mean}(S_{1.4\text{ GHz}}^{\text{FIRST}}/S_{1.4\text{ GHz}}^{\text{A370}}) = 1.01 \pm 0.05$. Based on the 25 sources brighter than the ~ 2.5 mJy NVSS sensitivity limit that also have counterparts, the $\text{mean}(S_{1.4\text{ GHz}}^{\text{NVSS}}/S_{1.4\text{ GHz}}^{\text{A370}}) = 0.98 \pm 0.04$. Figure 3.4 compares our flux density measurements with those of NVSS and FIRST. We find no systematic offset between our flux densities and the FIRST and NVSS flux densities.

The FIRST survey does not cover the A2390 cluster field. The NVSS cat-

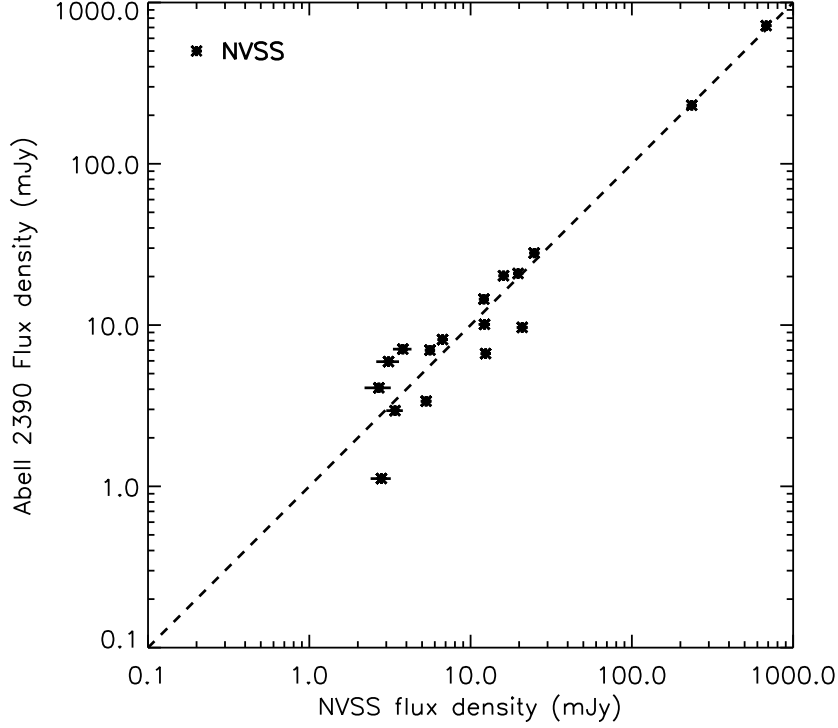


Fig. 3.5. — : A2390 flux densities compared to those from the NVSS catalog. Of the 18 NVSS objects in our survey area, 17 (black asterisks) are found to have counterparts. The dashed line indicates the ideal case, equality of flux densities.

alog contains 18 objects within our A2390 field. Seventeen of these objects have counterparts in our catalog. Based on the 16 sources brighter than the ~ 2.5 mJy NVSS sensitivity limit that also have counterparts, the $\text{mean}(S_{1.4\text{ GHz}}^{\text{NVSS}}/S_{1.4\text{ GHz}}^{\text{A2390}}) = 1.05 \pm 0.12$. Figure 3.5 compares our flux density measurements with those of NVSS. We find no systematic offset between our flux densities and the NVSS flux densities.

We believe that most, if not all, non-overlapping NVSS and FIRST sources are false detections. Inspection of our images reveals no viable counterparts. The two NVSS sources without counterparts have cataloged flux densities of 2.7 mJy (A370 field) and 2.8 mJy (A2390 field), which are very close to the NVSS sensitivity limit. The non-overlapping object in the A370 field also has no FIRST counterpart.

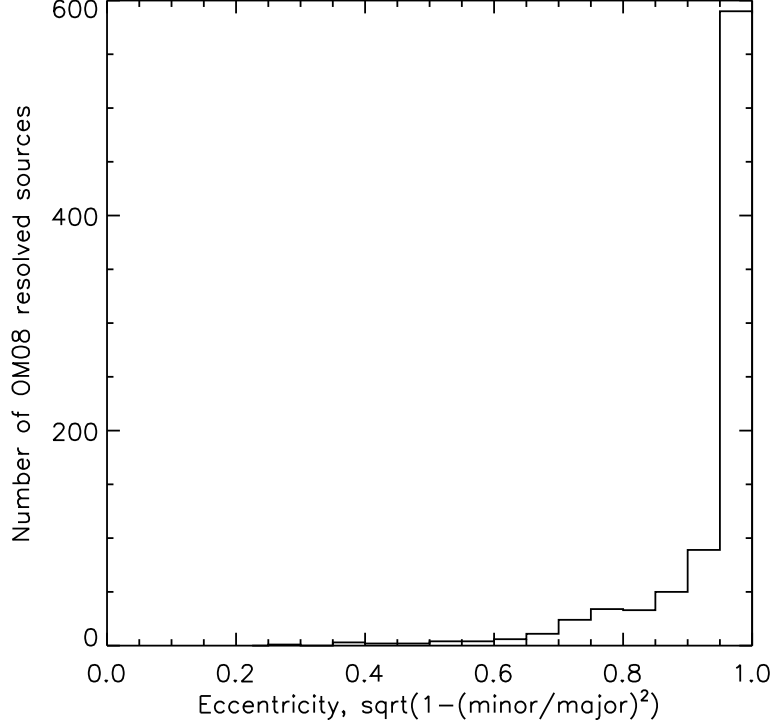


Fig. 3.6. — : Eccentricity distribution of resolved OM08 radio sources. The high level of observed eccentricity is the motivation behind our one-dimensional simulated sources. These sources modified by instrumental effects are used to assess the completeness of our catalog.

The NVSS catalog only gives upper limits for the major and minor deconvolved sizes, indicating that these objects should be relatively compact. The nine non-overlapping FIRST objects may be judged based on their reported sidelobe probability values, which give the likelihood that a source is spurious. Spurious sources are commonly due to artifacts created by nearby bright sources (White 2008). We find that there is a 60% mean probability that these 9 sources are spurious. Approximately 95% of FIRST sources have sidelobe probabilities that are lower than this mean value.

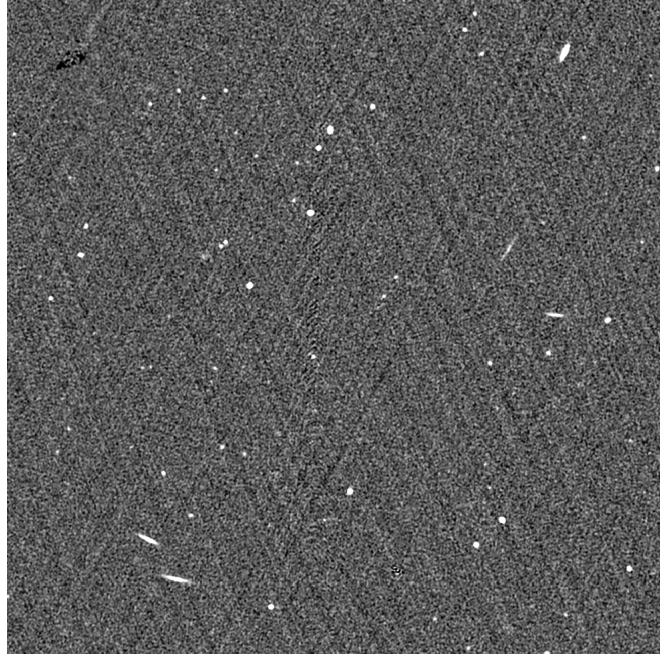


Fig. 3.7. — : $8' \times 8'$ cutout of a simulated image. The recovery rate of the simulated sources determines the correction factors applied to our number counts. The background template is a residual, source extracted, SAD image of the cluster field. SAD poorly extracts extended sources, leaving a non-representative background. We prevent simulated sources from populating these regions. The area affected is less than 1% of the total field area. We show a region with a poorly extracted extended source in the upper left corner. See Section 3.5 for details.

3.5 Source Counts

We constructed the differential source counts for the central region (radius $< 16'$) of each fields. These areas allow for the 5σ detection of all point sources above $\sim 60 \mu\text{Jy}$ (see Figure 3.1). The A370 and A2390 catalogs contain 529 and 380 objects, respectively, with $37 < S_{1.4\text{GHz}} < 3000 \mu\text{Jy}$ that lie within the areas of interest. In the first three columns of Tables 3.3 and 3.4, we list the the 1.4 GHz flux bins, the flux bin centers in log space, and the number of sources found per bin.

We assess the significance of false detections (5σ noise spikes) by performing an identical source extraction procedure on the inverted radio image (see Ibar et al.

2009 for a similar procedure). We generate the inverted image by multiplying all pixel values by -1. This analysis assumes that positive noise spikes are as likely as negative noise spikes. Overall, we find that $\sim 8\%$ of our cataloged sources are likely to be false detections (see Column 4 of Tables 3.3 and 3.4 for the number of false sources found per flux bin). We subtract the false detections per bin from our raw counts. We show the small effect of this correction on our final results in Figure 3.11.

To determine the completeness of our catalog, we developed a simple Monte Carlo simulation that accounts for major instrumental and extraction inefficiencies. For the background template, we used a residual, source extracted, SAD image (see Biggs & Ivison 2006 for a similar setup). We removed all detections above 4.5σ from this background image. We randomly positioned one thousand sources within the area of interest, a $16'$ radius circle. However, we prevented sources from populating areas with poorly extracted extended sources. This affected less than 1% of the total area. We randomly sampled the object's flux from a Euclidean power law distribution with a minimum flux threshold of 4.5σ . We randomly selected the object's major axis from the OM08 distribution, shown in their Figure 3.8 and assign a random position angle. Based on the observed eccentricity of faint radio sources (e.g. see our Figure 3.6 for the OM08 eccentricity distribution), we assumed an unresolved minor axis. All sources initially had a Gaussian flux profile. We convolved the object with the beam and then radially convolved the object with a Gaussian, with $\text{FWHM} = (\text{distance from field center}) \times (\text{channel bandwidth}) / (\text{central frequency})$. The later convolution accounted for bandwidth smearing. Finally, we modified the gain to account for primary beam attenuation. The simulation did not account for finite time-average smearing, which we estimate would to broaden sources by a few percent.

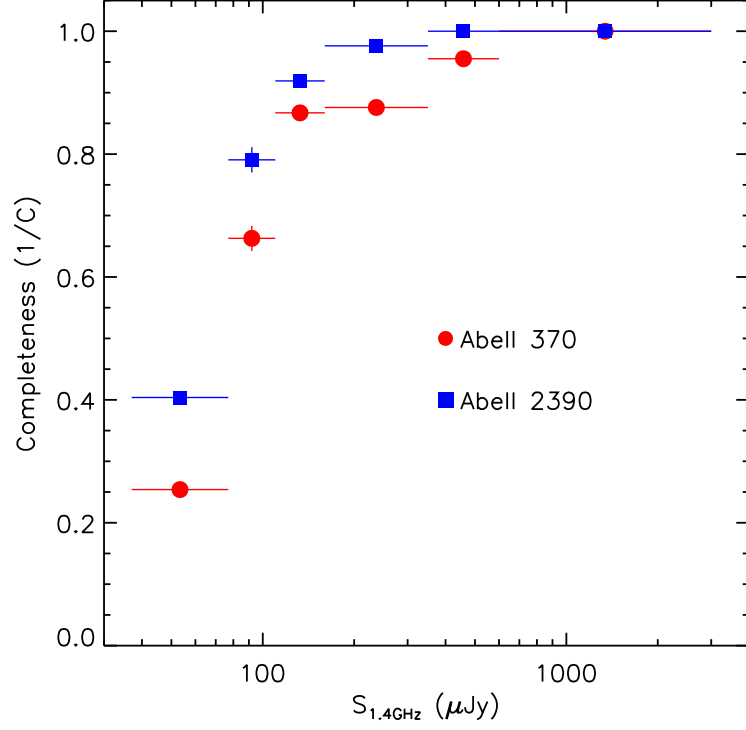


Fig. 3.8. — : Monte Carlo simulation results. The completeness, or number of recovered sources per number of input sources, as a function of flux density.

We show an $8' \times 8'$ cutout of a simulated image in Figure 3.7.

Table 3.3. : A370 1.4 GHz Radio Source Counts.

S bin (μJy)	S (μJy)	N	N_{false}	C	$S^{2.5}dN/dS$ ($\text{Jy}^{1.5}\text{sr}^{-1}$)
37 - 77	53	189	20	3.9	5.1 ± 0.5
77 - 110	92	113	14	1.5	5.4 ± 0.6
110 - 160	133	89	3	1.2	5.9 ± 0.7
160 - 350	237	91	0	1.1	6.9 ± 0.7
350 - 600	458	23	0	1.0	6.4 ± 1.3
600 - 3000	1342	24	0	1.0	9.7 ± 2.0

We perform the extraction technique described in Section 3.3 on the simulated image. We complete this procedure 5 times, providing a total of 5000 simulated

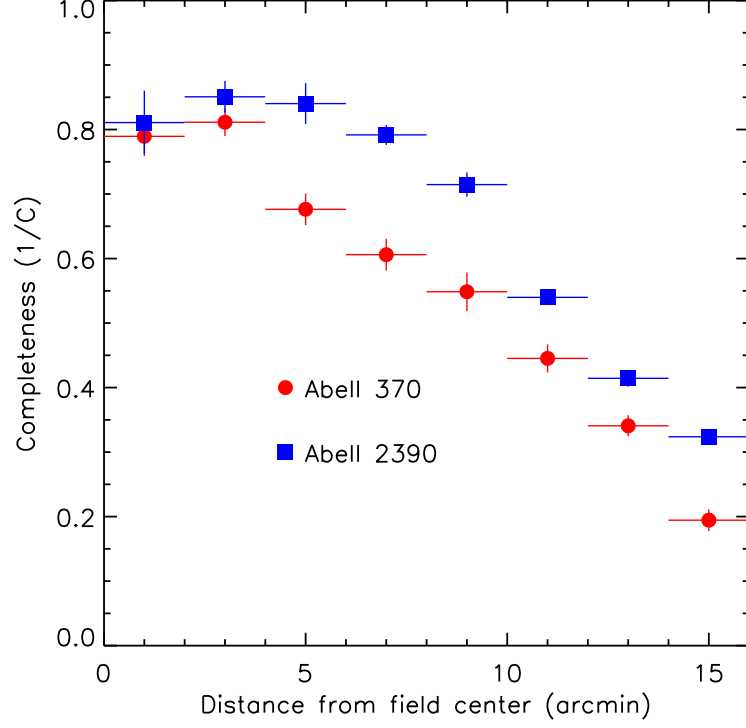


Fig. 3.9. — : Monte Carlo simulation results. The completeness, or number of recovered sources per number of input sources, as a function of radius from field center.

Table 3.4. : A2390 1.4 GHz Radio Source Counts.

S bin (μJy)	S (μJy)	N	N_{false}	C	$S^{2.5}dN/dS$ ($\text{Jy}^{1.5}\text{sr}^{-1}$)
37 - 77	53	210	22	2.5	3.6 ± 0.3
77 - 110	92	74	5	1.3	3.2 ± 0.4
110 - 160	133	29	0	1.1	1.9 ± 0.3
160 - 350	237	33	1	1.0	2.2 ± 0.4
350 - 600	458	14	0	1.0	3.7 ± 1.0
600 - 3000	1342	20	0	1.0	8.1 ± 1.8

sources per field. The recovery rate between the known input and the extracted output gives the correction factors, C , listed in Column 5 of Tables 3.3 and 3.4 and displayed in Figures 3.8 and 3.9. In Figure 3.10, we show how the variation of the

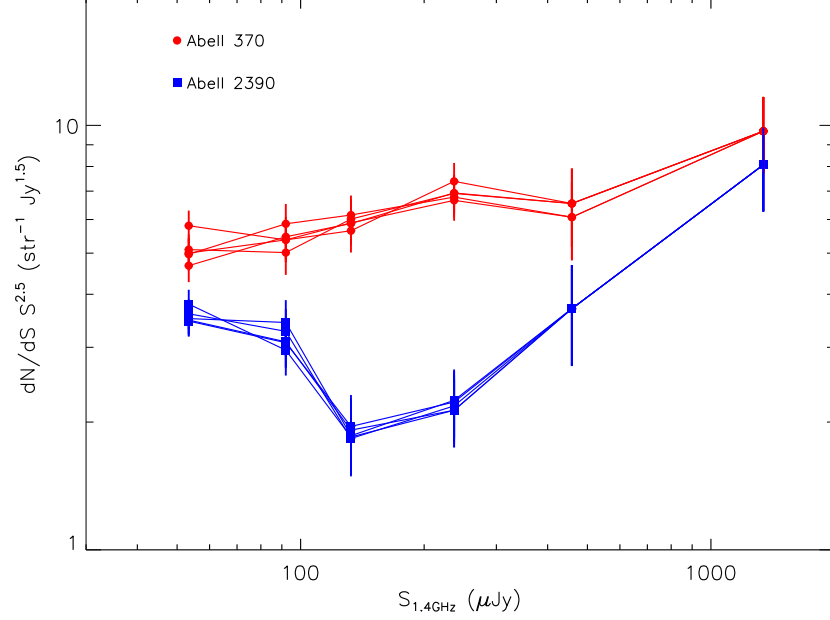


Fig. 3.10. — : Five Monte Carlo completeness results per field applied to our A370 and A2390 counts. We use the variation of the Monte Carlo results to estimate the error in the derived correction factors. This error is less than or approximately equivalent to the Poisson error (displayed error bars).

5 Monte Carlo simulations affects our derived counts. We calculate the corrected counts using the following equation:

$$N_{corr} = (N - N_{false}) \times C.$$

We then divide N_{corr} by the survey area and the bin width. We normalize these values by the Euclidean slope $S^{-2.5}$, where S is bin center in log space. We summarize the final results in Column 6 of Tables 3.3 and 3.4. In Figure 3.11, we show the A370 (*red circles*) and A2390 (*blue squares*) number counts with error bars indicative of Poisson uncertainty and Monte Carlo variation. We use dotted lines to indicate the effect on our derived counts of not correcting for false detections. We use open black circles to show number counts constructed from a VLA Coma cluster survey (Miller et al.

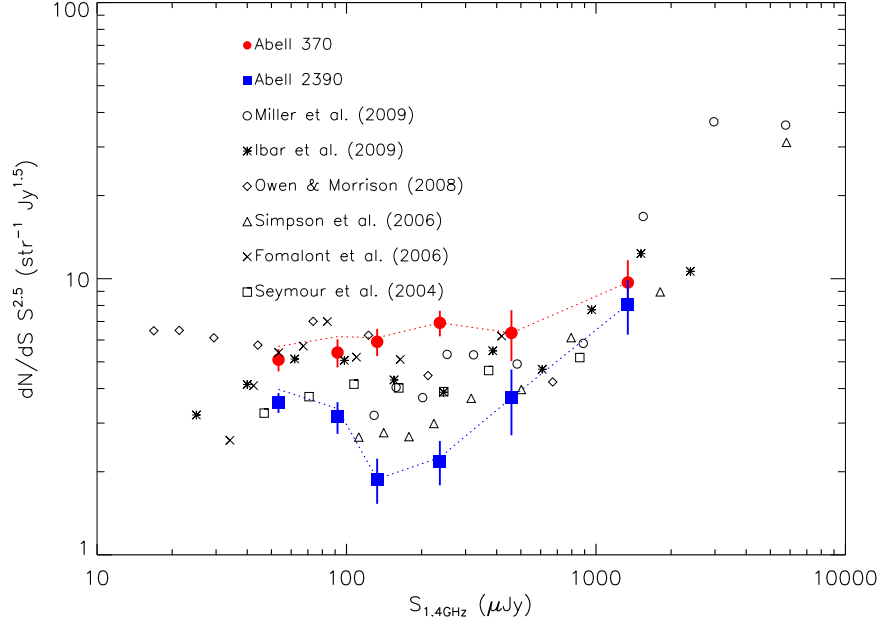


Fig. 3.11. — : A370 and A2390 differential source counts compared to blank field counts and Coma cluster counts (Miller et al. 2009). The dotted lines indicate the effect on our derived counts of not correcting for false detections.

2009). We also show various blank field counts (*black: asterisks, diamonds, triangles, crosses, and squares*) for comparison to our A370 and A2390 number counts.

3.6 Discussion

The A370 number counts form an upper envelope to the blank field number counts. This could potentially be explained by an over-density of cluster galaxies superimposed on the $z \sim 1$ field galaxies. In addition to the galaxy cluster at $z = 0.375$, Keenan et al. (2012) found galaxy over-densities at $z \sim 0.18$ and $z \sim 0.25$. We clearly see evidence for the $z \sim 0.25$ over-density in the redshift distribution (see Figure 3.12).

The A2390 number counts form a lower envelope to the blank field number counts, which is more surprising. This might indicate that the galaxy cluster at

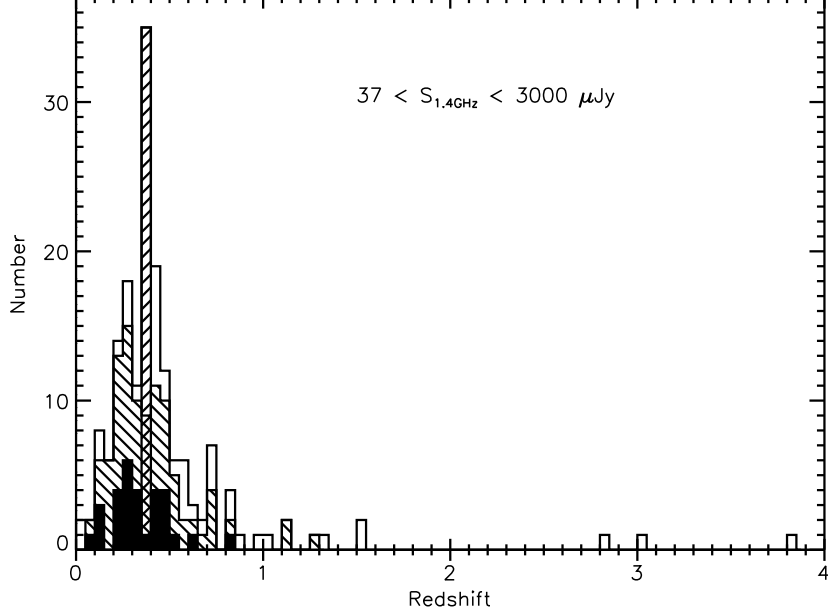


Fig. 3.12. — : A histogram of the 167 redshifts in our A370 number counts sample. The outer outline of the histogram indicates the redshift distribution of the entire 167 objects. The three interior filled histograms display the effect of applying cluster masks. The histogram filled with positive-slope diagonal lines designates the 35 cluster members that were excluded in our $z_{A370} \pm 0.025$ mask. The histogram filled with negative-slope diagonal lines designates the spectroscopically identified sources that lie beyond a $6'$ radius from the cluster center. Our $6'$ radius cluster mask excludes 26 (74%) of the spectroscopically identified cluster members. The filled histogram designates the spectroscopically identified sources that lie beyond $12'$ radius from the cluster center. Our $12'$ radius cluster mask excludes 34 (97%) of the spectroscopically identified cluster members.

$z=0.228$ does not significantly contribute to a sparsely populated field of $37 < S_{1.4 \text{ GHz}} < 3000 \mu\text{Jy}$ galaxies.

In the following, we investigate disentangling the cluster galaxy population from the field galaxy population using two techniques. 1) *Redshift mask*: For the A370 field, we re-derive the number counts with all the spectroscopically confirmed cluster members excluded. We lack sufficient spectroscopic data to perform a similar analysis on A2390. 2) *Radial masks*: We re-derive the number counts for both fields

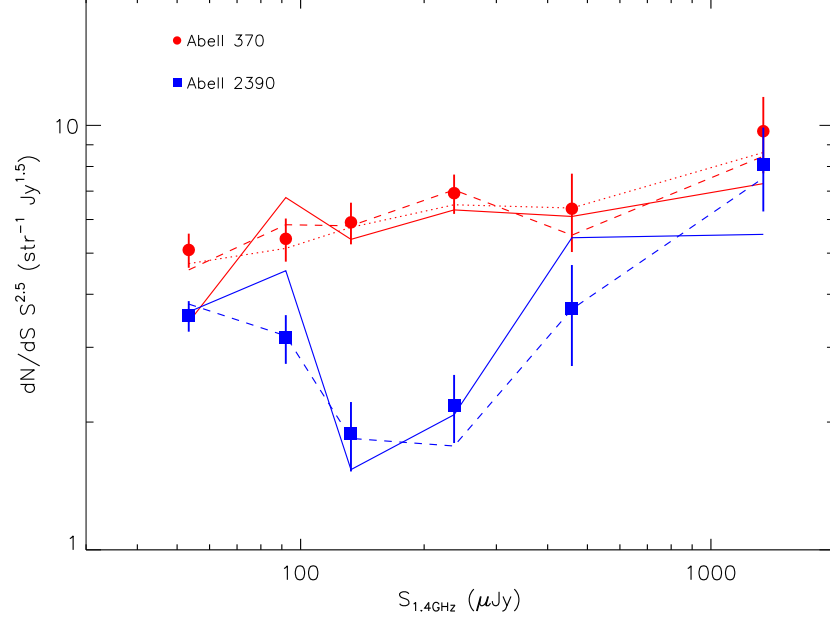


Fig. 3.13. — : Illustration of the effect on our derived number counts of applying radial cluster masks. Symbols with error bars indicate the cluster counts with no mask applied (full $16'$ radius field). The dashed lines indicate the counts with a radial area of $6'$ from the cluster centers masked. The solid lines indicate the counts with a radial area of $12'$ from the cluster centers masked. The red dotted line indicates the counts with spectroscopically confirmed A370 cluster members excluded. On average, the A370 counts are reduced, bringing them in closer agreement to blank field results. The A2390 counts are consistently low. Even taking into account the greater Poisson error of the more restrictive masks, the counts in the two cluster fields are found to be inconsistent with one another in the $110 - 350 \mu\text{Jy}$ flux range.

with the cluster center masked. In other words, we re-derive the number counts within a range of annuli to eliminate the majority of cluster objects. As we reduce the influence of the cluster, we note the effect that has on the number counts.

3.6.1 Redshift Mask

Our large sample of A370 redshifts allows us to re-derive the number counts after excluding known cluster members. To construct the A370 number counts, we used the 529 sources with $37 < S_{1.4\text{GHz}} < 3000 \mu\text{Jy}$ that lie within $16'$ of the

field center. Of these, 167 (32%) have known redshifts. In Figure 3.12, we show the distribution of these redshifts. We define cluster members as any object with $z_{A370} \pm 0.025$. Rather than a physical cluster scale, we base the redshift range on a conservative estimate of the redshift error. Using this criterion, we identify 35 objects as cluster members, and we exclude them from the re-derived counts. In Figure 3.12, we use positive-slope diagonal lines to denote the cluster members. We note that our spectroscopic completeness declines as the 1.4 GHz flux decreases and as the projected distance from the cluster center increases. Given these biases and the proximity of the cluster members compared to the average field galaxy at $\langle z \rangle \sim 1$, we expect to have succeeded in excluding more than 32% of the cluster members.

We show the re-derived number counts in Figure 3.13 as a red dotted line. We find that the A370 counts are lowered by a weighted average of $5.7\% \pm 6.5\%$. The estimated error in our weighted average calculation (6.5%) results from propagating the Poisson error of our measured counts. Although not corrected for, excluding spectroscopic cluster members will also remove the cluster’s effective volume. This will reduce the survey’s effective area and therefore increase the re-derived counts. This effect is small (estimated to be on the order of a few percent), since the effective volume of our radio field is large when compared to the effective volume of the cluster. Given our spectroscopic completeness of 32%, we expect the systematic uncertainty in our estimate of cluster influence to be dominated by any unidentified cluster members. Thus, we regard the reported $5.7\% \pm 6.5\%$ reduction in our re-derived counts as a lower limit.

3.6.2 Radial Masks

We also re-derive the number counts with cluster center radial masks. We apply masks to eliminate all galaxies within $2'$, $4'$, $6'$, $8'$, $10'$, and $12'$ from the cluster center. We obtain an estimate of the effectiveness of removing cluster members from both fields using radial masks by considering the cluster evolution study of Morrison (1999, hereafter M99). M99 investigated the radial distribution of low-luminosity ($10^{22.3} < L_{1.4 \text{ GHz}} < 10^{23} \text{ W Hz}^{-1}$) radio galaxies (LLRGs) for a $z < 0.25$ and a $z \sim 0.4$ cluster sample. The low-redshift sample was composed of 76 cluster LLRGs, while the $z \sim 0.4$ sample was composed of 43 cluster LLRGs.

From M99's derived cumulative radial density profile (his Figure 6.18), we see that a 1.9 Mpc ($6'$ radius) A370 mask should exclude $\sim 82\%$ of the cluster's LLRG population, while a 3.7 Mpc ($12'$ radius) mask should exclude $> 97\%$. The 1.3 Mpc ($6'$) and 2.6 Mpc ($12'$) A2390 masks should exclude $\sim 82\%$ and $\sim 97\%$ of the cluster's LLRGs, respectively. LLRGs correspond to galaxies with flux densities between 41 - 206 μJy for the A370 cluster and 129 - 648 μJy for the A2390 cluster. The radial distributions of higher luminosity radio sources are found to be more centrally compact. Thus, we expect our masks to reduce significantly the population of all $S_{1.4 \text{ GHz}} > 129 \text{ } \mu\text{Jy}$ ($> 41 \text{ } \mu\text{Jy}$ for A370) cluster sources. There are uncertainties in this estimate, since individual clusters will have deviations from this averaged radial profile. Additionally, the M99 study notes a lack of confirmed outer cluster members in the $z \sim 0.4$ sample, which may bias this radial profile. As a check on these percentages, we note how many spectroscopically confirmed cluster members remain after applying the A370 radial masks. Figure 3.12 shows the redshift histogram before and after the application of the $6'$ (histogram filled with negative-slope diagonal

lines) and the 12' (filled histogram) masks. Our 6' and 12' cluster masks remove 74% and 97% of the spectroscopically identified cluster members, respectively. This estimate, while roughly consistent with the M99 result, suffers from our spectroscopic incompleteness, which gets worse with increasing radius and decreasing flux. We conclude that our 6' radial masks should significantly reduce cluster influence on the derived number counts. We adopt the 12' mask result as our best estimate of the total cluster influence.

In Figure 3.13, we show the number counts after excluding radial areas of 6' (*dashed*) and 12' (*solid*) from the cluster centers. These angular radii, respectively, correspond to 1.9 and 3.7 Mpc at $z_{A370} = 0.375$ and 1.3 and 2.6 Mpc at $z_{A2390} = 0.228$. The A370 field has a 5.0 Mpc (16') radial extent, while the A2390 field has a 3.5 Mpc (16') radial extent. Excluding radial areas of 6' and 12' from the A370 cluster center reduces the number counts by a weighted average of $3.5\% \pm 7.4\%$ and $7.6\% \pm 10.7\%$. If we also exclude any additional spectroscopically identified cluster members not in the masked regions, then these percentages increase by 1%. Excluding radial areas of 6' and 12' from the A2390 cluster center reduces the number counts by an average of $0.7\% \pm 8.8\%$ and $1.1\% \pm 15.1\%$. In Figure 3.13, we can see that the re-derived number counts in A2390 are consistently low in the 110 to 350 μJy range, even when compared to the lowest blank field results.

Our best estimate indicates that the A370 cluster influences the derived number counts on the 10% level. The A2390 cluster does not appear to alter significantly the derived number counts. However, the large Poisson error of our measurements weakens this conclusion.

3.6.3 Comparison to Coma Cluster Counts

Coma is a local ($z=0.0231$) cluster of galaxies, while our clusters are at redshifts of $z=0.228$ and $z=0.375$. In cluster environments, the fraction of LLRGs decreases with decreasing redshift (M99). Thus, evolution effects may be significant and no direct comparison is possible. However, we may compare our results with the Coma cluster counts merely to check for consistency given this known evolution with redshift. Specifically, our finding that $z\sim 0.3$ cluster LLRGs are not a major component in the derived number counts would be at odds with a local measurement showing a significant LLRG contribution.

Miller et al. (2009) surveyed two ~ 0.5 deg² 1.4 GHz VLA observations covering the core and southwest region of the Coma cluster. They presented number counts from 0.110 mJy (their 5σ limit) to 100 mJy. Their counts have only been corrected for areal coverage. Thus, their faint counts ($\lesssim 0.230$ mJy) should be regarded as lower limits. At the Coma cluster's redshift LLRGs would correspond to the flux density range 16-82 mJy. No overdensity is noted in this range. Moreover, they find that their cluster counts are consistent with blank field counts (we also show this in Figure 3.11). The only excess of sources is in the ~ 1 -5 mJy range, and this is not attributed to a cluster effect. We conclude that our result, indicating that field galaxies make up the vast majority of sources in our cluster fields, is consistent with the local counts found in the Coma cluster field.

3.6.4 Gravitational Lensing Bias

Gravitational lensing affects number counts by boosting observed source flux and by magnifying the source plane. This lensing bias occurs over a relatively small

area compared to our $r = 16'$ fields. Given reasonable estimates for the cluster masses and background source redshifts, we estimate that beyond 2 Mpc there is no significant lensing bias. We believe our estimate of cluster influence does not require any modifications due to lensing considerations.

3.6.5 Cosmic Variance

Our results are consistent with the faint number counts being primarily determined by field radio galaxies. We performed similar reduction and extraction procedures on both cluster fields. Further, the lack of A2390 sources is already seen in the bright radio flux bins, and these should not suffer significantly from incompleteness. For these reasons, we investigate the significance of cosmic variance.

We estimate the effect of cosmic variance with the method of Somerville et al. (2004). Assuming a correlation length of 5 Mpc (consistent with the values given by Overzier et al. (2003) for NVSS mJy sources) and a redshift interval of $z = 1 \pm 0.5$, we estimate $\sim 12\%$ rms variance due to large-scale structure (see Simpson et al. 2006 for a similar calculation).

Since there is no clear consensus on the ‘true’ faint number counts, we choose to determine if our derived cluster number counts for the two fields can be brought into agreement given reasonable assumptions. This avoids having to develop some ad hoc method of averaging together faint number counts from radio surveys that have different analysis methods. An accurate comparison of our derived number counts depends on the accuracy of our derived error bars. While the estimated error does take into account Poisson error and the variance of our Monte Carlo simulations, it does not account for uncertainties inherent to the completeness simulations. For example, we determined a simulated object’s major axis by randomly sampling from

OM08’s size distribution. Any inaccuracy in this distribution could alter our derived completeness corrections and thus, our derived number counts. We adopt 1.5σ error bars to account for these additional concerns. Assuming a 10% reduction in the A370 number counts to account for the cluster’s influence, we find that our counts can be brought to within 1 - 2 sigma of each other. This suggests that cosmic variance can explain the disagreement seen in our derived number counts.

3.7 Summary

We presented 1.4 GHz catalogs for the cluster fields A370 and A2390 observed with the Very Large Array. These are two of the deepest radio images of cluster fields ever taken and will be useful for both cluster and field studies. The A370 image covers an area of $40' \times 40'$ with a synthesized beam of $\sim 1.7''$ and a noise level of $\sim 5.7 \mu\text{Jy}$ near field center. The A2390 image covers an area of $\sim 34' \times 34'$ with a synthesized beam of $\sim 1.4''$ and a noise level of $\sim 5.6 \mu\text{Jy}$ near field center. We cataloged 200 redshifts for the A370 field. For the region within $16'$ of field center, we derived differential number counts for both fields. We found that the faint ($37 < S_{1.4\text{ GHz}} < 3000 \mu\text{Jy}$) number counts of A370 are roughly consistent with the highest blank field counts, while the faint number counts of A2390 are roughly consistent with the lowest blank field counts. For the A370 field, we found that cluster members increase our derived number counts by $\sim 10\%$, while the A2390 cluster does not appear to contribute significantly to the presented faint number counts.

We suggest that the disagreement between our faint number counts can be primarily attributed to cosmic variance. We note that our observed fields, consisting of single pointings with nonuniform sensitivity and contaminated by foreground clus-

ters, are not ideal to resolve definitively the debate over the importance of cosmic variance on faint radio sources. Further progress awaits a large area survey that probes the micro-Jansky population.

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Chapter 4

$z \sim 1$ Ly α Emitters I. The Luminosity Function

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Abstract

We construct a flux-limited sample of 135 candidate $z \sim 1$ Ly α emitters (LAEs) from *Galaxy Evolution Explorer* (*GALEX*) grism data using a new data cube search method. These LAEs have luminosities comparable to those at high redshifts and lie within a 7 Gyr gap present in existing LAE samples. We use archival and newly obtained optical spectra to verify the UV redshifts of these LAEs. We use the combination of the *GALEX* UV spectra, optical spectra, and X-ray imaging data to estimate the active galactic nucleus (AGN) fraction and its dependence on Ly α luminosity. We remove the AGNs and compute the luminosity function (LF) from 60 $z \sim 1$ LAE galaxies. We find that the best fit LF implies a luminosity density increase by a factor of ~ 1.5 from $z \sim 0.3$ to $z \sim 1$ and ~ 20 from $z \sim 1$ to $z \sim 2$. We find a $z \sim 1$ volumetric Ly α escape fraction of $0.7 \pm 0.4\%$.

4.1 Introduction

$\text{Ly}\alpha$ emitters (LAEs) have the potential to be a powerful cosmological probe. The evolution of their number density at $z \gtrsim 7$ offers the opportunity to constrain the opacity of the intergalactic medium (IGM) and the timing of cosmic reionization (e.g., Stark et al. 2011). Their clustering properties may be able to constrain efficiently the expansion history of the universe (e.g., Hill et al. 2008; Greig et al. 2013). Furthermore, at the highest redshifts ($z > 6$) $\text{Ly}\alpha$ is the only emission line that we can detect from the ground, making it the only probe of the internal structure of these galaxies. However, to use LAEs as probes of the high-redshift universe, we must first understand their physical properties.

The $\text{Ly}\alpha$ line is resonantly scattered by neutral hydrogen, making its flux and line profile notoriously hard to interpret (e.g., Neufeld 1991; Kunth et al. 2003; Finkelstein et al. 2007; Schaerer & Verhamme 2008; Östlin et al. 2009). For example, unlike rest-frame UV continuum observations, one cannot merely apply a dust extinction correction to obtain an estimate of the star formation rate (SFR). Thus, constraints on the $\text{Ly}\alpha$ escape fraction must be empirically measured. Furthermore, observational studies are required to determine which physical properties facilitate the escape of $\text{Ly}\alpha$ emission.

Due to the limited resources in the UV, most observational studies have focused on constraining the physical properties of $z \sim 2 - 3$ LAEs, where the $\text{Ly}\alpha$ line moves into the optical. Detailed analysis of the host galaxies is difficult at these high redshifts, and different groups have come to drastically different conclusions

about them (e.g., compare Hu et al. 1998; Nilsson et al. 2007; Gawiser et al. 2007 to Lai et al. 2008; Kornei et al. 2010). Furthermore, at these redshifts Ly α emission may be significantly altered by the intervening IGM. For example, based on hydro-simulations, Laursen et al. (2011) find that only $\sim 70\%$, 26% , and 20% of Ly α photons are transmitted through the IGM at $z \sim 3.5$, 5.8 , and 6.5 , respectively. To make progress, we need to study lower-redshift samples where LAEs are bright due to smaller luminosity distances and where LAEs can be integrated into comprehensive studies of galaxies at the same redshifts to understand how LAEs are drawn from the general galaxy population.

Recently, a $z \sim 0.3$ LAE sample has been found by searching for emission-line objects in *Galaxy Evolution Explorer* (*GALEX*; Martin et al. 2005) FUV pipeline spectra. Since the *GALEX* grism pipeline only includes objects whose UV continuum magnitudes are bright enough to generate measurable continuum spectra, only a fraction of the emission-line objects are extracted. Thus, this sample's selection process is most analogous to locating LAEs in the high-redshift Lyman break galaxy (LBG) population via spectroscopy (e.g., Shapley et al. 2003). However, the procedure enables the selection of a substantial sample of $z \sim 0.3$ sources, and many papers have investigated their properties (e.g., Deharveng et al. 2008; Finkelstein et al. 2009; Atek et al. 2009; Scarlata et al. 2009; Cowie et al. 2010, 2011). The picture that emerged from the optical follow-up of the $z \sim 0.3$ *GALEX* sample is that LAEs, when compared to UV-continuum selected galaxies, are relatively young, compact, metal poor, star-forming galaxies (Cowie et al. 2010, 2011).

However, it is not clear that the properties of these low-redshift ($z \sim 0.3$) sources are representative of high-redshift LAEs. In particular, LAEs are consider-

ably fainter and much less common at $z \sim 0.3$ than they were in the past, with only about 5% of $z \sim 0.3$ UV-continuum selected galaxies having rest-frame Ly α equivalent widths ($\text{EW}_r(\text{Ly}\alpha)$) greater than 20 Å, compared with 20% – 25% at $z \sim 3$ (Shapley et al. 2003). The $\text{EW}_r(\text{Ly}\alpha) \geq 20\text{\AA}$ requirement is typically used to define high-redshift samples (e.g., Hu et al. 1998). The first redshift where LAEs are seen that are comparable in luminosity to high-redshift LAEs is at $z \sim 1$. However, only a handful of $z \sim 1$ LAEs have *GALEX* detectable continuum spectra. Thus, we need to remove the pipeline’s continuum selection requirement ($\text{NUV} < 22$) in order to study a large sample of $z \sim 1$ LAEs. This has the additional virtue of producing a purely flux-limited sample that is straightforward to analyze.

Table 4.1. *GALEX* Field Exposure Time, 80% Completeness Flux Threshold,
Number of LAE Candidates, and Number of Confirmed LAE Galaxies

<i>GALEX</i> Field (1)	α (J2000.0) (2)	δ (J2000.0) (3)	Exp. time (4)	$f_{\text{Ly}\alpha}$ (erg cm $^{-2}$ s $^{-1}$) (5)	Num. LAE candidates (6)	Num. confirmed LAEs (7)
CDFS	3 ^h 30 ^m 40 ^s	-27°27'43''	353 ks	1.8×10 $^{-15}$	40	24
GROTH	14 ^h 19 ^m 58 ^s	52°46'54''	291 ks	2.0×10 $^{-15}$	41	19
NGPDWS	14 ^h 36 ^m 37 ^s	35°10'17''	165 ks	2.3×10 $^{-15}$	35	11
COSMOS	10 ^h 00 ^m 29 ^s	+2°12'21''	140 ks	3.2×10 $^{-15}$	19	4

In Barger, Cowie, & Wold (2012, hereafter, BCW12), we solved the problem of obtaining a flux-limited sample of $z \sim 1$ LAEs for the *Chandra* Deep Field-South (CDFS). To do this, we converted the multiple *GALEX* grism images into a three-dimensional (two spatial axes and one wavelength axis) data cube. We then treated the wavelength “slices” as narrowband images in which we searched for emission-line galaxies. Through simulations, we showed that we could recover more than 80% of the sources with $f(\text{Ly}\alpha) \gtrsim 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$, which corresponds to $L(\text{Ly}\alpha) \gtrsim 10^{42.5} \text{ erg s}^{-1}$ at $z \sim 1$. By comparing our sample to X-ray data, existing optical spectroscopy, and deep *U*-band imaging, we determined that nearly all of our 28 new LAEs are real and that the UV spectroscopic redshifts based on the $\text{Ly}\alpha$ identifications are reliable. We also determined the fraction of active galactic nuclei (AGNs) in the sample relative to star formers.

In this chapter, we apply the data cube search method to all of the deepest *GALEX* grism fields (CDFS-00, 353 ks; GROTH-00, 291 ks; NGPDWS-00, 165 ks; COSMOS-00, 140 ks), which correspond to some of the most intensively studied regions in the sky. This work provides the first large sample of $z = 0.67 - 1.16$ LAEs ($N=60$) that can be used to investigate the physical properties of these galaxies. There are relatively large samples of known LAEs at redshifts of $z \sim 0.3$ and $z \sim 2$. Thus, a sample of $z \sim 1$ LAEs is needed to map the evolution of LAEs over a ~ 7 Gyr gap. This redshift regime is where the star-forming properties of galaxies change very rapidly and where the star formation begins to decline. It is a key area for connecting to the high-redshift universe.

In Chapter 5, we will leverage existing archival spectra and followup optical spectra to constrain their physical properties. In particular, we will study which

properties facilitate the escape of Ly α emission and how LAEs are drawn from the overall galaxy population. This will help us understand how the Ly α emission properties of galaxies evolve as we move to higher redshifts and higher Ly α luminosities.

Here we catalog our candidate $z \sim 1$ LAE samples in each field and give optical redshifts from both archival and newly obtained observations. With X-ray, UV, and optical data, we determine the false detection rate (cases where the emission line is either not confirmed or is not Ly α) and the AGN contamination rate of our sample. With the remaining LAEs, we compute the LAE galaxy luminosity function (LF) at $z \sim 1$ and use this to investigate the evolution of the Ly α LF and the Ly α escape fraction over the redshift range from $z \sim 0.3$ to $z \sim 2$. Unless otherwise noted, we give all magnitudes in the AB magnitude system ($m_{\text{AB}} = 23.9 - 2.5 \log_{10} f_{\nu}$ with f_{ν} in units of μJy). We use a standard $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ cosmology.

4.2 Choice of Fields

We study the four deepest NUV grism observations: CDFS-00, GROTH-00, NGPDWS-00, and COSMOS-00. The *GALEX* fields are large ($\sim 1 \text{ deg}^2$), but in subregions of the fields, there are many objects with optical spectra (CDFS, Vanzella et al. 2008, Popesso et al. 2009; GROTH, Newman et al. 2012; COSMOS, Lilly et al. 2007, Trump et al. 2009). In subregions, there are also multi-color observations from the *HST* GOODS (Giavalisco et al. 2004), CANDELS (Grogin et al. 2011; Koekemoer et al. 2011), COSMOS (Leauthaud et al. 2007), and GEMS (Rix et al. 2004) programs that provide the galaxy morphologies and spectral energy distributions from the rest-frame far-UV to the mid-infrared. When corrected for the emission-line contributions

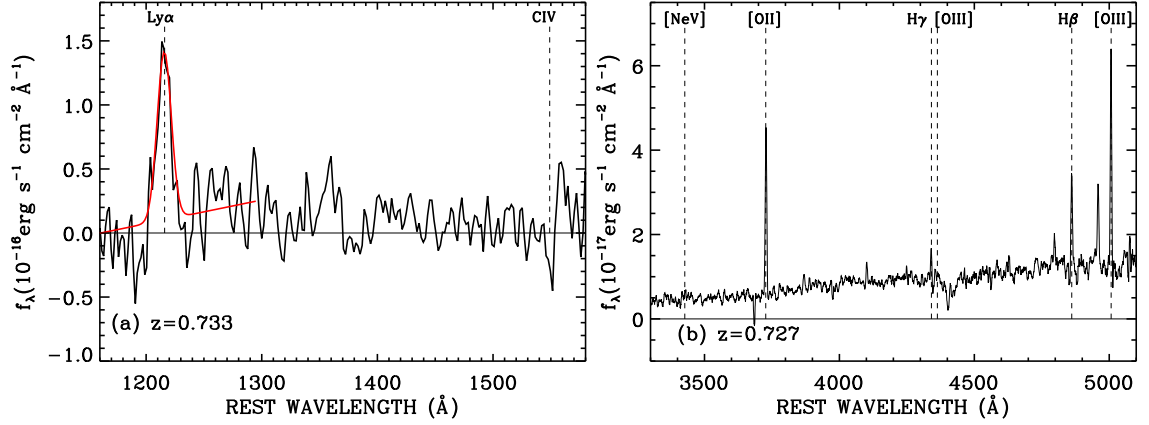


Fig. 4.1. — : **(a)** LAE galaxy UV spectrum GALEX033100-273020. The redshift ($z = 0.733$) and Ly α flux is measured from the Gaussian fit (red profile). The lack of detected CIV λ 1549 is consistent with this source being star-forming galaxy rather than AGN. **(b)** Keck-DEIMOS spectrum for the same source. The optical redshift ($z = 0.727$) is found to be consistent with the UV redshift. The lack of detected [NeV] λ 3426 or broad Balmer lines is consistent with this source being star-forming galaxy rather than AGN.

using the spectra (Schaerer & de Barros 2009; Atek et al. 2011; Cowie et al. 2011), the spectral energy densities can be used to compute the ages and extinctions of the galaxies.

Finally, the 4 Ms *Chandra* image of the CDFS (Alexander et al. 2003; Luo et al. 2008) region, along with shallower X-ray observations in the Extended CDFS (Lehmer et al. 2005; Virani et al. 2006), COSMOS (Elvis et al. 2009), GROTH (Laird et al. 2009), and NGPDWS (Kenter et al. 2005) fields, can be used to identify AGNs. AGNs may also be identified using the UV grism spectra obtained with *GALEX* and the optical spectra, but the X-rays provide a valuable cross-check, where they are available.

4.3 *GALEX* NUV LAEs

4.3.1 Catalog Extraction

As described in BCW12, we converted multiple *GALEX* NUV grism images into a three-dimensional (two spatial axes and one wavelength axis) data cube. Each background subtracted data cube consists of thirty 20 Å narrowband slices covering a wavelength range of 2030 to 2630 Å and a 50'×50' field of view. We used SExtractor (Bertin & Arnouts 1996) to identify all 4σ sources within the cube and then visually inspected each source and its spectrum (1-D and 2-D) to eliminate objects that were artifacts. Applying the data cube search produced 40 CDFS, 41 GROTH, 35 NGPDWS, and 19 COSMOS objects for a full Ly α selected candidate sample of 135 (see Table 4.1). In Figure 4.1(a), we show the extracted 1-D spectrum for GALEX033100-273020 to illustrate the quality of our *GALEX* spectra. BCW12 performed this routine on the deepest NUV grism field (CDFS-00). To verify the BCW12 sample of 28 LAE candidates, we have independently searched the CDFS cube for emission-line sources. We found 27 of the 28 objects that were identified by BCW12, and we found 12 new objects. Approximately half of these new LAE candidates are close to the field's 80% completeness flux threshold (see Section 4.3.3) and were probably missed due to their faintness. The other half are relatively bright and were probably mis-classified as data cube artifacts, such as the remaining edge effects from brighter objects. The BCW12 LAE candidate missed by this search (GALEX033124-275625) is real and has a consistent optical redshift. This LAE was eliminated in the visual inspection phase of our search due to its proximity to a UV-bright star. We include this missed LAE in all subsequent analysis. To date,

we have confirmed the UV redshifts of 92% (11 out of 12) of the newly discovered CDFS LAEs with optical follow-up spectra.

4.3.2 Optical Spectroscopic Followup

Spectroscopic observations were primarily obtained with the DEep Imaging Multi-Object Spectrograph (DEIMOS; Faber et al. 2003) on Keck II in a series of runs in 2012 to 2013. The observations were made with the ZD600 line mm^{-1} grating blazed at $7500 \text{ \AA}$. This gives a resolution of $\sim 5 \text{ \AA}$ with a $1''$ slit and a wavelength coverage of $5300 \text{ \AA}$. The high spectral resolution is necessary to distinguish the $[\text{OII}]\lambda 3727$ doublet structure. The observations were not generally taken at parallactic angle, since the position angle was determined by the mask orientation. Each ~ 30 min exposure was broken into three subsets, with the objects stepped along the slit by $1.5''$ in each direction. The raw two-dimensional spectra were reduced and extracted using the procedure described in Cowie et al. (1996). In Figure 4.1(b), we show the optical spectrum for GALEX033100-273020 to illustrate the quality of our DEIMOS spectra. We used the remaining space available in our MOS masks to observe a control sample, a UV-continuum selected sample without detected $\text{Ly}\alpha$ that have the same luminosities and are expected, based on their colors, to lie in the same redshift interval as our primary LAE sample. In Chapter 5, we will use the control sample to determine how the LAE galaxies are drawn from the general galaxy population.

Table 4.2. Emission-Line Sample: CDFS-00

Name	R.A.	Decl.	NUV	FUV	z_{galex}	$\log L(\text{Ly}\alpha)$	$\text{EW}_r(\text{Ly}\alpha)$	$\log f_{2-8\text{ keV}}^a$	Type(UV)	R.A.(opt)	Decl.(opt)	Offset	z_{opt}	Type(opt)
(1)	(J2000.0)	(J2000.0)	(AB)	(AB)	(6)	(erg s ⁻¹)	(Å)	(erg cm ⁻² s ⁻¹)	(10)	(J2000.0)	(J2000.0)	(arcsec)	(14)	(15)
GALEX033111-281725 ⁱ	52.796374	-28.290444	23.55	27.50	1.168	43.61	281±17	...	...	52.796253	-28.290321	0.6	1.164 ^b	AGN
GALEX033112-281517	52.800377	-28.254936	23.02	28.01	1.162	43.31	87±5	...	...	52.800663	-28.255022	1.0	1.161 ^{b,c}	...
GALEX033359-275326	53.499160	-27.890792	22.04	24.13	1.143	43.53	63±2	...	AGN	53.499096	-27.890846	0.3	1.133 ^b	AGN
GALEX033301-273227	53.255196	-27.540939	23.45	-27.75	1.135	43.08	82±7	...	...	53.255268	-27.540880	0.3	1.136 ^b	...
GALEX033146-272942	52.942574	-27.495223	22.73	25.44	1.137			...	...	52.942543	-27.495167	0.3	(0.629) ^{b,g}	...
GALEX033348-280216	53.453649	-28.038008	23.40	25.53	1.128	43.09	82±8	...	...	53.453671	-28.038050	0.2	1.130 ^b	...
GALEX033230-280804	53.125683	-28.134514	22.34	23.83	1.124	43.27	47±3	...	AGN	...	...	...	...	...
GALEX033120-274917	52.837504	-27.821383	22.82	32.73	1.116	42.91	30±5	...	...	52.837444	-27.821638	0.9	1.113 ^b	...
GALEX033255-281320	53.231551	-28.222466	22.46	-27.50	1.087	42.95	28±3	...	...	53.231567	-28.222486	0.1	1.085 ^b	...
GALEX033112-281442 ⁱ	52.803095	-28.245108	22.19	-28.20	1.055	42.85	19±3	...	AGN	52.801987	-28.244835	3.6	1.042 ^b	...
GALEX033413-275940 ⁱ	53.555847	-27.994665	24.21	26.59	1.052	42.78	118±12	...	...	53.555477	-27.994663	1.2	1.051 ^b	AGN
GALEX033212-274913 ⁱ	53.051599	-27.820316	22.68	27.04	1.053	42.89	33±4	...	...	53.051613	-27.820168	0.5	1.048 ^b	...
GALEX033200-274319	53.001430	-27.722033	22.40	24.39	1.042	43.25	59±4	-14.2	...	53.001520	-27.722071	0.3	1.041 ^d	AGN
GALEX033228-273614	53.121022	-27.604317	23.62	26.66	1.036	42.77	59±9	...	...	53.118469	-27.604019	8.2	1.046 ^b	...
GALEX033113-274949	52.807630	-27.830242	22.45	31.95	1.031	42.81	24±3	...	...	52.807545	-27.830231	0.3	1.026 ^b	...
GALEX033331-280625 ⁱ	53.382523	-28.107164	24.41	27.66	1.029	42.80	141±14	...	...	53.382084	-28.106623	2.4	1.026 ^b	AGN
GALEX033202-280320	53.010734	-28.055702	23.44	25.22	1.018	42.94	81±6	-13.7	AGN	53.010658	-28.055834	0.5	1.015 ^b	AGN
GALEX033111-275506	52.798577	-27.918436	23.81	-27.52	1.010	43.12	168±17	...	...	52.798473	-27.918442	0.3	1.023 ^b	...
GALEX033336-274224	53.402806	-27.706674	23.02	26.37	0.977	43.22	119±6	-14.8	AGN	53.402771	-27.706703	0.2	0.976 ^b	...
GALEX033204-273725	53.017064	-27.623785	22.78	24.25	0.977	43.36	133±8	-13.6	AGN	53.016788	-27.623751	0.9	0.970 ^e	AGN
GALEX033246-274154	53.195680	-27.698408	23.17	26.61	0.976	43.20	128±10	...	...	53.196271	-27.698547	2.1	no z	...
GALEX033342-274035 ⁱ	53.425620	-27.676525	24.73	26.03	0.956	42.59	146±15	...	...	53.425163	-27.676567	1.5	0.948 ^b	...
GALEX033335-273934	53.398183	-27.659591	22.54	23.31	0.949			-14.3	...	53.398163	-27.659760	0.6	(0.622) ^b	...
GALEX033329-280127	53.373274	-28.024282	23.16	25.95	0.942	42.62	37±6	...	...	53.373272	-28.024244	0.1	0.940 ^b	...
GALEX033206-281408	53.026465	-28.235703	21.79	25.75	0.913	43.30	56±3	...	...	53.026493	-28.235905	0.7	0.909 ^b	...

Table 4.2. (Continued)

Name	R.A.	Decl.	NUV	FUV	z_{galax}	$\log L(\text{Ly}\alpha)$	$\text{EW}_{\text{r}}(\text{Ly}\alpha)$	$\log f_{2-8}^a$	Type(UV)	R.A.(opt)	Decl.(opt)	Offset	z_{opt}	Type(opt)
(1)	(J2000.0)	(J2000.0)	(AB)	(AB)	(6)	(erg s ⁻¹)	(Å)	(erg cm ⁻² s ⁻¹)	(10)	(J2000.0)	(J2000.0)	(arcsec)	(14)	(15)
GALEX033044-280237	52.686897	-28.043707	23.25	26.58	0.869	42.82	116±13	...	...	52.686813	-28.043819	0.5	0.859 ^{b,c}	...
GALEX033042-274215 ⁱ	52.679011	-27.704257	23.03	25.18	0.861	42.57	38±4	...	...	52.678730	-27.704462	1.2	0.856 ^b	...
GALEX033409-280129 ⁱ	53.541285	-28.024923	23.34	26.40	0.857	42.63	60±6	...	...	53.540737	-28.024443	2.5	0.854 ^b	...
GALEX033251-280809	53.214351	-28.135966	22.70	26.17	0.838	42.71	43±4	...	...	53.214489	-28.136051	0.5	0.832 ^b	...
GALEX033314-274834	53.310626	-27.809526	24.23	25.48	0.830	42.65	155±21	...	...	53.310975	-27.809095	1.9	0.826 ^d	...
GALEX033045-274506	52.689797	-27.751818	23.04	25.67	0.832	42.74	63±6	...	...	52.689950	-27.752197	1.4	no z^h	...
GALEX033405-275023 ⁱ	53.521292	-27.839993	23.13	25.03	0.825	42.56	47±9	...	...	53.520832	-27.839972	1.5	0.821 ^b	...
GALEX033057-273316	52.739776	-27.554542	22.37	24.09	0.794	42.73	38±3	...	...	52.739708	-27.554583	0.3	0.790 ^b	...
GALEX033124-275625	52.851698	-27.940441	22.69	25.82	0.778	42.57	36±4	...	...	52.851761	-27.940475	0.2	0.773 ^b	...
GALEX033235-274059	53.148932	-27.683184	23.67	25.70	0.745	42.79	182±15	...	...	53.149258	-27.683273	1.1	0.735 ^b	...
GALEX033146-274846	52.942503	-27.812779	22.98	25.88	0.742	42.75	86±6	...	...	52.942345	-27.812771	0.5	0.736 ^b	...
GALEX033100-273020 ⁱ	52.751186	-27.505665	22.52	24.80	0.733	42.68	51±5	...	...	52.750877	-27.505367	1.5	0.727 ^b	...
GALEX033131-273429	52.880399	-27.574774	22.56	25.77	0.695	43.28	280±11	-14.1	...	52.880260	-27.574841	0.5	0.688 ^f	AGN
GALEX033321-275031 ⁱ	53.341285	-27.842052	23.16	25.06	0.691	42.59	90±9	...	AGN	...	...	...	...	...
GALEX033150-274116 ⁱ	52.962287	-27.687773	22.28	23.15	0.673	42.70	54±5	-14.2	AGN	52.962346	-27.687700	0.3	0.667 ^d	...

Note. —

^aX-ray data from Lehmer et al. (2005)^bOur DEIMOS spectra^cOur SALT spectra^dRedshifts from Cooper et al. (2012)^eTreister et al. (2009); Szokoly et al. (2004) give $z = 0.977$ ^fSilverman et al. (2010)^g[alt] Alternative counterpart at 52.942825, -27.494650, 2.2, (1.191)^b(R.A., Decl., Offset, z_{opt})^h[alt] Two untargated counterparts $\sim 2''$ from NUV positionⁱLAE candidate not listed in BCW12

Table 4.3. Emission-Line Sample: GROTH-00

Name	R.A.	Decl.	NUV	FUV	z_{galex}	$\log L(\text{Ly}\alpha)$	$\text{EW}_r(\text{Ly}\alpha)$	$\log f_{2-10}^a$	Type(UV)	R.A.(opt)	Decl.(opt)	Offset	z_{opt}	Type(opt)
(1)	(J2000.0)	(J2000.0)	(AB)	(AB)	(6)	(erg s^{-1})	($\text{\AA}$)	($\text{erg cm}^{-2}\text{s}^{-1}$)	(10)	(J2000.0)	(J2000.0)	(arcsec)	(14)	(15)
GALEX142028+524640	215.11946	52.777836	23.41	26.75	1.131	42.57	25 $\pm$ 4	...	...	215.11989	52.777527	1.5	1.134 ^b	...
GALEX141814+524415	214.56075	52.737531	23.97	-27.83	1.128	43.10	144 $\pm$ 14	...	...	214.56084	52.737473	0.3	1.123 ^b	...
GALEX141950+522542	214.96249	52.428532	24.09	26.34	1.114	42.97	124 $\pm$ 12	...	...	214.96179	52.427998	2.5	1.111 ^b	...
GALEX142013+524008	215.05510	52.669118	25.11	29.17	1.100	43.05	380 $\pm$ 49	...	...	215.05558	52.669342	1.2	no z^d	...
GALEX141842+522919	214.67858	52.488791	22.69	23.68	1.084	42.98	37 $\pm$ 5	-14.3	...	214.67863	52.488586	0.7	1.084 ^b	AGN
GALEX141824+522329	214.60416	52.391463	23.51	24.99	1.083	43.12	110 $\pm$ 12	-13.6	...	214.60379	52.391666	1.1	1.081 ^b	AGN
GALEX141718+525521	214.32734	52.922402	22.47	24.41	1.067	43.58	127 $\pm$ 4	...	AGN	214.32666	52.922764	2.0	1.064 ^b	AGN
GALEX142028+522516	215.12077	52.421360	23.00	26.88	1.052	42.94	51 $\pm$ 4	...	...	215.12045	52.421455	0.8	1.045 ^b	AGN
GALEX141842+523735	214.67549	52.626454	23.07	25.43	1.038	43.17	93 $\pm$ 14	...	...	214.67545	52.625916	1.9	1.035 ^b	AGN
GALEX141737+524236	214.40603	52.709992	22.20	26.33	1.027	43.53	99 $\pm$ 6	-13.3	...	214.40543	52.710182	1.5	1.025 ^c	AGN
GALEX141815+530452	214.56554	53.081148	22.36	23.26	1.028	43.07	41 $\pm$ 3	...	...	214.56442	53.081223	2.4	1.020 ^b	AGN
GALEX142015+525024	215.06357	52.840222	24.04	-28.66	1.021	43.13	223 $\pm$ 20	...	...	215.06401	52.840656	1.8	1.014 ^b	...
GALEX142144+523627	215.43607	52.607699	21.83	24.66	1.011	43.32	46 $\pm$ 3	...	...	215.43503	52.607677	2.3	1.006 ^b	AGN
GALEX142027+530455	215.11514	53.081989	23.18	-27.68	1.002	42.82	54 $\pm$ 6	-13.1	...	215.11458	53.081806	1.4	0.994 ^b	AGN
GALEX141851+523600	214.71624	52.600051	23.54	26.00	1.000	43.00	112 $\pm$ 14	-14.1	...	214.71530	52.599945	2.1	0.986 ^b	AGN
GALEX142242+525245	215.67896	52.879323	22.07	-26.74	1.003	42.65	12 $\pm$ 3	...	...	215.67851	52.879360	1.0	0.999 ^b	...
GALEX142033+530617	215.14121	53.104797	23.62	25.29	0.999	42.80	75 $\pm$ 8	-14.5	...	215.14162	53.105114	1.5	0.994 ^b	...
GALEX141902+525637	214.76161	52.943789	22.47	24.55	0.984	42.56	21 $\pm$ 4	...	...	214.76091	52.943871	1.6	0.980 ^b	...
GALEX142207+525411	215.52938	52.903111	23.07	25.35	0.996	43.16	104 $\pm$ 5	...	...	215.52910	52.902931	0.9	0.994 ^b	AGN
GALEX142148+522902	215.45007	52.484033	23.04	27.40	0.961	43.23	131 $\pm$ 13	...	...	215.44913	52.484470	2.6	0.961 ^b	...
GALEX142244+525442	215.68588	52.911824	23.85	26.89	0.958	43.26	300 $\pm$ 22	...	...	215.68564	52.911930	0.6	0.954 ^b	...
GALEX141746+525259	214.44522	52.882997	24.17	-27.28	0.957	42.58	87 $\pm$ 10	...	...	214.44400	52.884399	5.7	0.957 ^b	...
GALEX141946+524755	214.94289	52.798752	22.23	28.91	0.928	42.21	6 $\pm$ 3	...	...	214.94319	52.798855	0.7	0.914 ^b	...
GALEX141935+524127	214.89632	52.690888	22.13	24.21	0.920	42.72	20 $\pm$ 3	...	...	214.89662	52.690529	1.4	0.917 ^b	...
GALEX141733+530403	214.39094	53.067620	23.21	24.87	0.918	43.07	120 $\pm$ 10	...	...	214.39050	53.067913	1.4	0.915 ^b	AGN

Table 4.3. (Continued)

Name	R.A.	Decl.	NUV	FUV	z_{galex}	$\log L(\text{Ly}\alpha)$	$\text{EW}_{\text{r}}(\text{Ly}\alpha)$	$\log f_{2-10}^a$	Type(UV)	R.A.(opt)	Decl.(opt)	Offset	z_{opt}	Type(opt)
(1)	(J2000.0)	(J2000.0)	(AB)	(AB)	(6)	(erg s ⁻¹)	(Å)	(erg cm ⁻² s ⁻¹)	(10)	(J2000.0)	(J2000.0)	(arcsec)	(14)	(15)
GALEX141833+525525	214.64107	52.923739	23.46	26.32	0.916	42.74	72±7	...	...	214.64212	52.924011	2.5	0.912 ^b	...
GALEX142201+530637	215.50453	53.110604	24.13	25.62	0.912	43.19	398±53	-13.3	...	215.50462	53.110195	1.5	0.898 ^b	AGN
GALEX142202+530823	215.50844	53.139988	22.85	24.75	0.872			...	...	215.50819	53.140114	1.3	(0.572) ^b	...
GALEX142028+525839	215.11758	52.977690	23.30	-27.77	0.870	42.81	83±8	-13.9	...	215.11682	52.978155	2.3	0.871 ^c	...
GALEX141800+522514	214.50369	52.420519	22.59	25.99	0.838	42.89	60±5	...	...	214.50280	52.419863	3.1	0.833 ^c	...
GALEX141722+524209	214.34177	52.702458	22.26	26.40	0.838	43.07	65±5	...	...	214.34238	52.702278	1.5	0.838 ^c	...
GALEX142202+522931	215.50918	52.492172	24.88	28.45	0.812	42.66	307±52	...	...	215.51004	52.493038	3.6	0.807 ^b	...
GALEX142223+525642	215.59777	52.945235	23.55	26.86	0.770	42.90	187±21	...	...	215.59738	52.944958	1.3	0.763 ^b	...
GALEX141858+523209	214.74578	52.535948	21.76	22.67	0.762	43.11	57±4	-14.4	...	214.74509	52.536110	1.6	0.758 ^b	AGN
GALEX142049+523203	215.20764	52.534438	23.62	28.61	0.754	43.03	273±21	...	...	215.20830	52.534378	1.5	0.758 ^b	...
GALEX142212+522634	215.55384	52.443058	23.67	27.45	0.762	42.47	79±11	...	...	215.55397	52.443161	0.5	0.759 ^b	...
GALEX142057+525642	215.24117	52.945171	22.54	24.98	0.756	43.00	101±6	...	...	215.24106	52.944958	0.8	0.747 ^b	...
GALEX141746+525646	214.44476	52.946049	23.28	25.21	0.750	42.97	191±22	...	...	214.44504	52.946918	3.2	0.746 ^b	AGN
GALEX141842+522256	214.67524	52.382180	23.65	26.29	0.750	42.49	85±16	...	...	214.67545	52.381447	2.7	0.747 ^b	...
GALEX141842+530140	214.67697	53.027806	23.03	25.01	0.748	42.59	62±9	...	...	214.67871	53.028191	4.0	0.741 ^b	...
GALEX142139+523401	215.41400	52.567205	23.82	26.24	0.741			...	AGN	215.41359	52.568192	3.8	(0.692) ^b	...

Note. —

^aX-ray data from Laird et al. (2009)^bOur DEIMOS spectra^cArchival DEIMOS DEEP2 spectra (Newman et al. 2012)^d[alt] Alternative counterpart at 215.05445, 52.667969, 4.4, no z (R.A., Decl., Offset, z_{opt})

Table 4.4. Emission-Line Sample: NGPDWS-00

Name	R.A.	Decl.	NUV	FUV	z_{galex}	$\log L(\text{Ly}\alpha)$	$\text{EW}_r(\text{Ly}\alpha)$	$\log f_{2-7}^a_{\text{keV}}$	Type(UV)	R.A.(opt)	Decl.(opt)	Offset	z_{opt}	Type(opt)
(1)	(J2000.0) (2)	(J2000.0) (3)	(AB) (4)	(AB) (5)	(6)	(erg s^{-1}) (7)	($\text{\AA}$) (8)	($\text{erg cm}^{-2}\text{s}^{-1}$) (9)	(10)	(J2000.0) (11)	(J2000.0) (12)	(arcsec) (13)	(14)	(15)
GALEX143557+350702	218.98764	35.117445	23.82	-28.46	1.158	43.27	169 $\pm$ 26	...	...	218.98735	35.116795	2.5	1.152 ^b	...
GALEX143539+351001	218.91250	35.167233	22.20	25.99	1.083	43.40	63 $\pm$ 6	...	...	218.91272	35.167511	1.2	1.082 ^b	...
GALEX143545+350039	218.93744	35.011330	24.17	26.63	1.063			...	AGN	218.93967	35.010777	5.9	(0.722) ^b	...
GALEX143520+350414	218.83421	35.070876	21.55	22.69	1.055	43.32	31 $\pm$ 3	-14.5	...	218.83405	35.070351	2.0	1.052 ^b	AGN
GALEX143824+352325	219.60174	35.390787	21.92	24.92	1.039	42.92	18 $\pm$ 3	...	AGN	219.60257	35.390755	2.4	1.031 ^b	...
GALEX143512+352338	218.80005	35.394162	24.84	-31.03	1.037			...	...	218.80109	35.392956	4.2	(1.080) ^{b,c}	...
GALEX143726+351448	219.36103	35.247140	22.44	24.39	1.034	43.13	47 $\pm$ 6	-15.1 ^e	...	...	...	...	...	...
GALEX143443+353037	218.68009	35.510756	23.39	28.50	1.034	42.85	61 $\pm$ 8	...	...	218.68036	35.510929	1.0	1.025 ^b	...
GALEX143750+350645	219.45954	35.112962	22.22	23.70	1.010			-15.0	...	219.46024	35.113098	1.9	(0.577) ^b	...
GALEX143449+350248	218.70428	35.046988	23.21	29.53	1.009	43.60	303 $\pm$ 9	-15.3	...	...	...	...	...	...
GALEX143810+350424	219.54441	35.073741	23.73	26.81	1.006	43.15	177 $\pm$ 14	...	...	219.54455	35.073328	0.7	no z	...
GALEX143450+352520	218.70844	35.422650	22.85	26.74	0.967	43.29	122 $\pm$ 7	-14.2	...	218.70876	35.422508	1.1	0.964 ^b	AGN
GALEX143512+345907	218.79986	34.985750	24.58	28.79	0.963			...	...	218.80116	34.984894	3.8	(0.884) ^b	...
GALEX143510+351602	218.79406	35.267619	23.42	26.28	0.941			...	...	218.79521	35.267330	2.5	(0.478) ^{b,d}	...
GALEX143639+350557	219.16252	35.099672	22.31	23.43	0.937	42.87	32 $\pm$ 3	...	...	219.16257	35.099346	1.2	0.932 ^b	...
GALEX143702+350155	219.26169	35.032282	22.94	24.99	0.933	43.34	149 $\pm$ 10	-14.6	...	219.26167	35.032078	0.7	0.927 ^b	AGN
GALEX143531+351415	218.88092	35.237743	23.09	27.50	0.934	42.96	78 $\pm$ 11	...	...	218.88094	35.238354	2.2	0.930 ^b	...

Table 4.4. (Continued)

Name	R.A.	Decl.	NUV	FUV	z_{galex}	$\log L(\text{Ly}\alpha)$	$\text{EW}_r(\text{Ly}\alpha)$	$\log f_{2-7}^a$	Type(UV)	R.A.(opt)	Decl.(opt)	Offset	z_{opt}	Type(opt)
(1)	(J2000.0)	(J2000.0)	(AB)	(AB)	(6)	(erg s ⁻¹)	(Å)	(erg cm ⁻² s ⁻¹)	(10)	(J2000.0)	(J2000.0)	(arcsec)	(14)	(15)
GALEX143730+352016	219.37524	35.338103	22.51	24.34	0.907	42.90	46±5	...	...	219.37563	35.337757	1.7	0.904 ^b	AGN
GALEX143521+350509	218.83940	35.086214	21.89	26.57	0.901			...	...	218.83961	35.085414	2.1	star	star
GALEX143819+351542	219.58154	35.262070	23.01	26.70	0.889	42.63	39±9	...	...	219.58224	35.261349	3.3	0.889 ^b	...
GALEX143652+350537	219.21699	35.093944	21.90	23.03	0.870	43.25	63±5	-15.0	...	219.21677	35.093887	0.7	0.866 ^b	AGN
GALEX143729+350732	219.37419	35.125830	22.68	24.16	0.868	43.31	151±11	-15.0	...	219.37398	35.126053	1.0	0.860 ^b	AGN
GALEX143457+353213	218.73762	35.537287	21.75	23.02	0.865	42.82	21±3	-14.9	...	218.73782	35.537319	0.6	0.857 ^b	AGN
GALEX143715+353355	219.31319	35.565674	22.38	23.84	0.854	43.27	127±11	-15.1 ^e	...	219.31288	35.565460	1.2	0.846 ^b	AGN
GALEX143459+352504	218.74643	35.418085	22.48	-28.10	0.848			...	...	218.74582	35.417044	4.0	star	star
GALEX143800+352206	219.50182	35.368824	22.24	24.81	0.829	42.81	35±5	-15.4	...	...	...	...	...	...
GALEX143642+345027	219.17868	34.841281	24.09	27.73	0.823	42.91	254±49	...	...	219.17896	34.841167	0.9	0.818 ^b	...
GALEX143655+344610	219.23087	34.769857	24.20	28.61	0.820	42.88	269±30	...	...	219.23146	34.769501	2.2	0.813 ^b	...
GALEX143801+352533	219.50452	35.426310	21.62	22.75	0.806	43.09	42±3	-14.7	...	...	...	...	...	...
GALEX143700+353132	219.25323	35.525830	22.50	24.40	0.791	42.96	75±7	...	...	219.25333	35.525555	1.0	0.784 ^b	AGN
GALEX143515+353203	218.81441	35.534506	21.77	23.47	0.789			...	...	218.81459	35.534233	0.5	(0.410) ^b	...
GALEX143821+350707	219.59055	35.118996	21.62	23.15	0.741	43.23	75±5	-14.8	AGN	219.59068	35.119396	1.5	0.728 ^b	...
GALEX143829+352308	219.62144	35.385905	22.19	24.26	0.720	42.49	25±4	...	...	219.62173	35.385715	1.1	0.710 ^b	...
GALEX143716+352324	219.32011	35.390438	24.61	27.67	0.716	42.61	365±65	...	...	219.31993	35.391083	2.4	0.699 ^b	...
GALEX143813+351121	219.55694	35.189666	24.20	27.14	0.710	42.67	199±53	...	...	219.55760	35.190166	2.6	0.717 ^b	...

Note. —

^aX-ray data from Kenter et al. (2005)^bOur DEIMOS spectra^c[alt] Alternative counterpart at 218.98737, 35.115852, 5.8, (1.096)^b(R.A., Decl., Offset, z_{opt})^d[alt] Alternative counterpart at 218.79877, 35.394573, 4.0, (0.977)^b(R.A., Decl., Offset, z_{opt})^eSource not detected in X-ray hard band but detected in the soft 0.5-2 keV flux band

Table 4.5. Emission-Line Sample: COSMOS-00

Name	R.A.	Decl.	NUV	FUV	z_{galax}	$\log L(\text{Ly}\alpha)$	$\text{EW}_r(\text{Ly}\alpha)$	$\log f_{2-10 \text{ keV}}^a$	Type(UV)	R.A.(opt)	Decl.(opt)	Offset	z_{opt}	Type(opt)
(1)	(J2000.0) (2)	(J2000.0) (3)	(AB) (4)	(AB) (5)	(6)	(erg s ⁻¹) (7)	(Å) (8)	(erg cm ⁻² s ⁻¹) (9)	(10)	(J2000.0) (11)	(J2000.0) (12)	(arcsec) (13)	(14)	(15)
GALEX095954+021707	149.97779	2.2852787	22.17	23.93	1.163	43.24	30±4	-14.7	...	...	...	...	...	...
GALEX100145+023237	150.43904	2.5436927	23.59	24.84	1.154	43.35	158±13	...	...	150.43942	2.5435109	1.5	1.149 ^b	AGN
GALEX100016+015104	150.06776	1.8512265	21.74	23.40	1.140	43.63	57±4	-13.6	AGN	150.06784	1.8513390	0.5	1.134 ^b	AGN
GALEX100031+023012	150.13260	2.5034525	22.72	25.38	1.103	43.21	59±6	...	...	150.13235	2.5033109	1.0	1.099 ^{b,c}	...
GALEX095918+014933	149.82753	1.8260336	22.89	25.11	1.070	43.38	109±10	...	...	149.82774	1.8258640	1.0	1.069 ^{b,c}	...
GALEX095916+015048	149.81704	1.8467845	21.94	24.30	1.034	43.20	33±4	-14.0	AGN	149.81688	1.8467280	0.6	1.034 ^b	AGN
GALEX100141+021029	150.42197	2.1748164	21.83	23.00	0.989	43.47	65±5	-13.5	AGN	150.42221	2.1754150	2.3	0.982 ^d	AGN
GALEX100150+020936	150.45907	2.1598448	22.75	25.61	0.927	43.11	79±7	...	...	150.45946	2.1603360	2.3	0.926 ^{b,c}	AGN
GALEX100124+021447	150.34970	2.2463910	22.34	23.46	0.900	43.23	77±8	-13.8	...	150.34988	2.2461319	1.1	0.894 ^d	...
GALEX100202+020145	150.51078	2.0290676	22.95	24.72	0.894	43.20	124±9	-13.6	...	150.51064	2.0292540	0.8	0.898 ^d	AGN
GALEX100049+021707	150.20630	2.2852412	23.88	24.96	0.877	42.96	181±30	-13.7	...	150.20627	2.2857921	2.0	0.874 ^d	AGN
GALEX100136+020653	150.40266	2.1148013	22.28	25.06	0.853	42.92	42±5	...	...	150.40346	2.1155031	3.8	0.849 ^{b,c}	...
GALEX100133+015451	150.39033	1.9141639	21.85	24.96	0.848	43.02	37±3	...	...	150.39020	1.9144530	1.1	0.844 ^{b,c}	...
GALEX100002+021628	150.00988	2.2746592	21.90	23.78	0.847	42.99	34±4	-13.5	...	150.00922	2.2755051	3.9	0.850 ^d	AGN
GALEX100207+021119	150.53190	2.1886307	22.31	22.60	0.838	43.25	101±19	-14.0	...	150.53186	2.1889460	1.1	0.830 ^d	...
GALEX100113+022548	150.30739	2.4301342	22.76	23.40	0.757			-13.6	...	150.30808	2.4300640	2.5	(0.374) ^e	AGN
GALEX100029+022129	150.12442	2.3581919	22.26	23.42	0.739	42.93	66±9	-13.6	AGN	150.12370	2.3582580	2.6	0.728 ^e	AGN
GALEX095910+020732	149.79323	2.1258027	22.12	22.22	0.730			-14.8 ^f	...	149.79295	2.1256490	1.1	(0.353) ^d	...
GALEX100017+020013	150.07274	2.0037061	22.69	23.04	0.729			-13.6	...	150.07301	2.0035551	1.1	(0.350) ^d	AGN

Note. —

^aX-ray data from Elvis et al. (2009)^bOur DEIMOS spectra^cOur SALT spectra^dArchival Magellan spectra from Trump et al. (2009)^eArchival VLT spectra from Lilly et al. (2007)^fSource not detected in X-ray hard band but detected in the soft 0.5-2 keV flux band

We observed our southern and equatorial fields (COSMOS and CDFS) with the Robert Stobie Spectrograph (RSS; Burgh et al. 2003) on SALT from 2011 to 2013. The observations were made with the pg1300 grating with the grating angle adjusted to ensure spectral coverage of lines redward of [NeV]. This gives a resolution of $\sim 4 \text{ \AA}$ with a $1.5''$ slit and a wavelength coverage of $2000 \text{ \AA}$. We observed each target for ~ 30 min. The raw two-dimensional spectra were reduced and extracted using the IRAF packages LONGSLIT and APEXTRACT.

4.3.3 Catalog Completeness

To determine the limitations of our multi-field catalogs and to compute the LAE galaxy LF, we have developed a simulation to determine the completeness of recovery versus flux. For each field, we added 1000 simulated emitters uniformly within the field's data cube. We did not model morphology or size difference, since nearly all emitters are unresolved at the spatial ($\sim 6''$) and spectral resolution ($\sim 25 \text{ \AA}$) of the *GALEX* grism data. We then ran our standard selection procedure and found the number of recovered objects. We independently performed the above procedure ten times, giving a total of 10,000 input sources. In Table 4.1, we list the flux threshold above which each field is greater than 80% complete. As expected, the completeness limit scales as the inverse square root of the exposure time. Below this threshold, the completeness of our sample rapidly declines (see Figure 4.2).

4.3.4 Catalogs of LAE Candidates by Field

In Tables 4.2-4.5, we list all of the LAE candidates in the CDFS, GROTH, NGPDWS, and COSMOS fields ordered by redshift. In Column 1, we give the *GALEX* name; in Columns 2 and 3, the J2000 right ascension and declination based

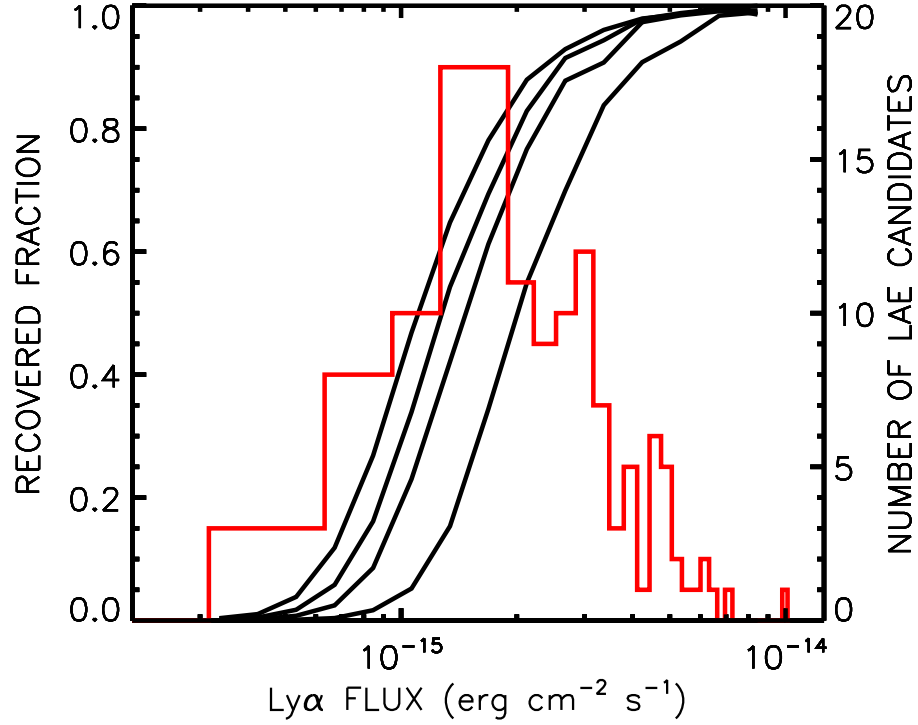


Fig. 4.2. — : Fraction of simulated sources recovered as a function of the emission-line flux. From left to right the black curves show recovered fractions from CDFS, GROTH, NGPDWS, and COSMOS fields (also see Table 4.1). The red histogram shows the number of LAE candidates as a function of flux for all four *GALEX* fields.

on NUV position; in Columns 4 and 5, the NUV and FUV AB magnitudes; in Column 6, the redshift from the *GALEX* UV spectrum; in Column 7, the logarithm of the Ly α luminosity; in Column 8, the rest-frame EW_r(Ly α) with 1σ errors; in Column 9, the logarithm of the X-ray flux; in Column 10, the UV classified AGNs; in Columns 11 and 12, the J2000 right ascension and declination based on optical position; in Column 13, the offset between the optical to UV positions; in Column 14, the optical redshift; and in Column 15 the optically classified AGNs.

We measured NUV and FUV AB magnitudes from the archival *GALEX* background subtracted intensity maps (Morrissey et al. 2007). We first determined the magnitudes within 8'' diameter apertures centered on each of the emitter positions.

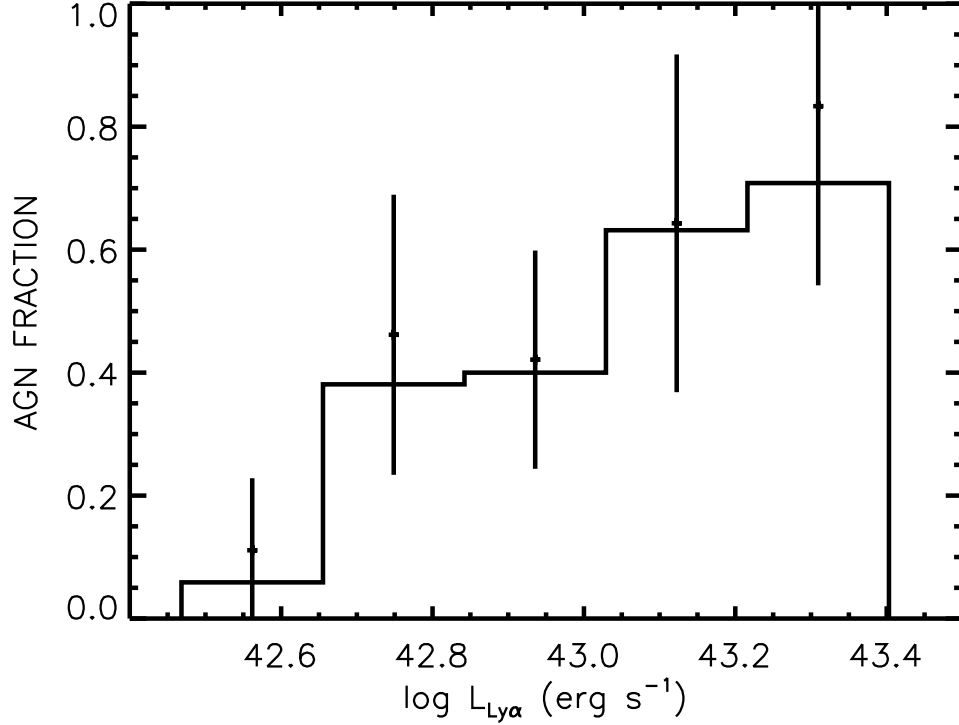


Fig. 4.3. — : AGN fraction per $\text{Ly}\alpha$ luminosity bin for the $\text{EW}_r(\text{Ly}\alpha) \geq 20 \text{ \AA}$ LAE data cube sample. The histogram shows the sample wide AGN fractions, while the points with error bars show the AGN fractions for regions with deep X-ray data.

To correct for flux that falls outside our apertures, we measured the offset between $8''$ aperture magnitudes and *GALEX* pipeline total magnitudes for all bright cataloged objects (20-23 mag range) within our fields. We determined the median offset for each field and applied these to the magnitudes listed in Columns 4 and 5. All objects are bright in the NUV when compared to their FUV magnitudes. In some cases, we measure negative FUV fluxes. For these cases, we list the magnitude corresponding to the absolute value of the flux with a minus sign in front to indicate that the flux was negative.

We corrected our one-dimensional NUV spectra for Galactic extinction assuming a Fitzpatrick (1999) reddening law with $R_V=3.1$. We obtained A_V values from

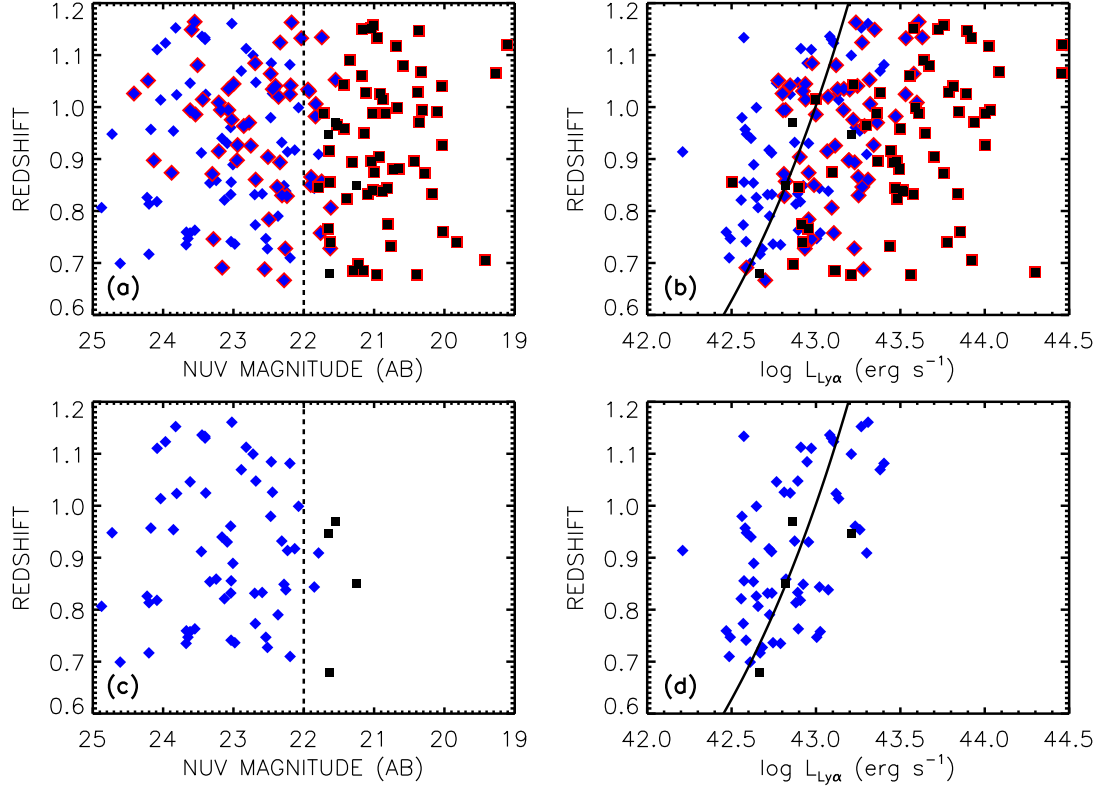


Fig. 4.4. — : **(a)** LAE redshift vs. $\text{Ly}\alpha$ luminosity. Black squares show the pipeline LAEs found by Cowie et al. (2010, 2011) constrained to the data cubes’ $50' \times 50'$ FOVs and redshift range ($z = 0.67 - 1.16$). Blue diamonds show our data cube LAEs. Objects classified as AGNs in any way are surrounded by red. The dashed line shows the *GALEX* pipeline’s magnitude limit $\text{NUV} \sim 22$. **(b)** LAE redshift vs. $\text{Ly}\alpha$ luminosity. The solid line indicates the data cube’s $\sim 80\%$ flux completeness limit. **(c)** The same as Figure 4.4(a), but with all AGNs removed. **(d)** The same as Figure 4.4(b), but with all AGNs removed.

the Schlafly & Finkbeiner (2011) recalibration of the Cardelli et al. (1989) extinction map as listed in the NASA/IPAC Extragalactic Database (NED). Galactic extinction modifies the $\text{Ly}\alpha$ flux by $\sim 11\%$ for the COSMOS LAEs, $\sim 4\%$ for the GROTH LAEs, and $\sim 6\%$ for the CDFS and NGPDWS LAEs.

From these extinction corrected spectra, we measured the redshifts, the $\text{Ly}\alpha$ fluxes, and the line widths using a two step process. First, we fit a $140 \text{ \AA}$ rest-frame region around the $\text{Ly}\alpha$ line with a Gaussian and a sloped continuum (see

Figure 4.1(a)). A downhill simplex optimization routine was used to χ^2 fit the five free parameters (continuum level and slope plus Gaussian center, width, and area). We used the results of this fitting process to eliminate the two continuum parameters and as a starting point for the second step. In the second step, we used the IDL MPFIT procedures of Markwardt (2009) to χ^2 fit the remaining three Gaussian parameters. We also employed the same fitting routine but with only a flat continuum (one continuum free parameter instead of two). We find that our results are not significantly affected by this model assumption. With the best-fit redshifts and Ly α fluxes, we calculated Ly α luminosities. When available, we used the more precise optical redshift rather than the UV redshift to calculate the Ly α luminosities. We list the UV redshifts and Ly α luminosities in Columns 6 and 7.

The rest-frame EW_r(Ly α) measured on the spectra are quite uncertain due to the very faint UV continuum. We obtained a more accurate rest-frame EW by dividing the measured Ly α flux by the continuum flux measured from the broadband NUV image. It is these rest-frame EWs that are given in Column 8. In Section 4.5, we investigate the $z \sim 1$ rest-frame EW distribution.

We made a classification of whether the emitter was an AGN based on the presence of either broad or high-excitation emission lines in its UV or optical spectra or on the presence of an X-ray counterpart. Candidate X-ray counterparts were identified by matching all X-ray sources within a 6'' radius from the data cube position. We then manually inspected the matches to reject false counterparts. We list the X-ray flux of each identified counterpart in Column 9. The X-ray luminosity threshold of 10^{42} erg s⁻¹ that is usually used to define AGN activity (Hornschemeier et al. 2001; Barger et al. 2002; Szokoly et al. 2004) corresponds to an X-ray flux of

$\gtrsim 10^{-15.3}$ erg cm $^{-2}$ s $^{-1}$ for our $z > 0.67$ sample. All X-ray detected sources exceed this luminosity threshold, and we hereafter consider these sources to be AGNs. In Column 10, we list sources classified as AGNs based on the presence of broad or high-excitation emission lines in their UV spectrum (see, e.g., Cowie et al. 2010). Our candidate star-forming galaxy sample will still contain some remaining AGNs, so we used the optical spectra to make a final determination of whether a galaxy is, in fact, star-forming. In Column 15, we identify optical AGNs based on the presence of either detectable [NeV] or broad Balmer or MgII λ 2798 emission lines in the optical spectra.

We obtained optical redshifts for 122 of our 135 candidate LAEs. We found that 15 optical redshifts did not match the measured UV redshifts. For these objects, the Ly α luminosity and the rest-frame EW $_{\text{r}}(\text{Ly}\alpha)$ fields are left blank in Columns 7 and 8. These sources are either spurious, stars, or strong CIV λ 1549 emitters. For example, we found three LAE candidates in our COSMOS-00 field to be $z \sim 0.35$ CIV λ 1549 emitters. We indicate these objects by showing their optical redshift in parentheses or by setting their optical redshift and type to ‘star’ in Columns 14 and 15. Additionally, we observed 4 candidate LAEs with Keck DEIMOS without recovering an optical redshift. We indicate these objects by setting their optical redshifts to ‘no z’ in Column 14. For the purpose of computing the LF, we retain the NUV brightest ‘no z’ source (GALEX033045-274506), which has two nearby untargeted potential optical counterparts. The remaining ‘no z’ candidate LAEs have relatively faint NUV counterparts and may be spurious. Given the spatial resolution of our data cubes ($\sim 6''$), we find that a total of five ‘no z’ and non-matching redshift sources have potential alternative optical counterparts. We list these ‘[alt]’ sources in the

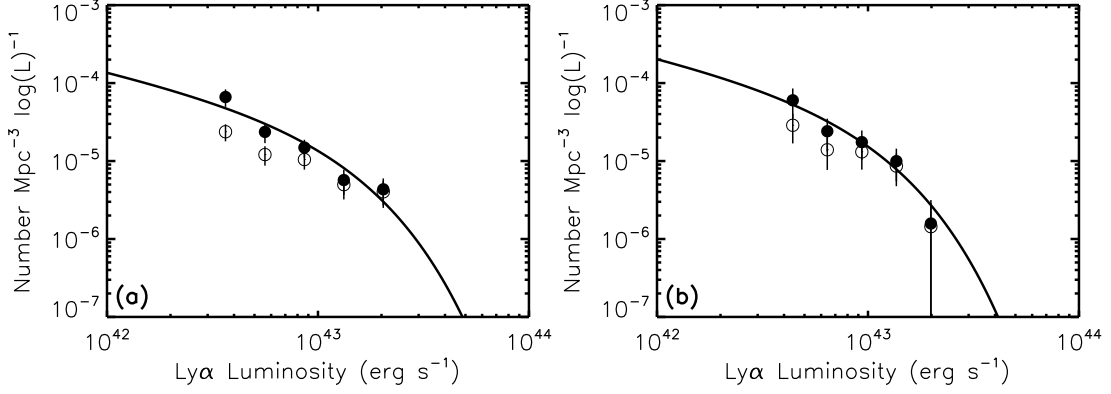


Fig. 4.5. — : **(a)** Derived $\text{Ly}\alpha$ luminosity function at $z = 0.67 - 1.16$ for the LAE galaxies in deep *GALEX* grism fields (CDFs, GROTH, NGPDWS, and COSMOS) with $\text{EW}_r(\text{Ly}\alpha) \geq 20 \text{ \AA}$ from both the *GALEX* pipeline and the data cube samples (black circles: open—raw data; solid—corrected for the effects of incompleteness using the results from our Monte Carlo simulations). The black curve indicates the best fit Schechter function assuming a fixed slope of $\alpha = -1.6$. We find best fit parameters $\log L_\star = 43.0 \pm 0.2$ and $\log \phi_\star = -4.8 \pm 0.3$. **(b)** Same as Figure 4.5(a), but with the LAE survey limited to regions with deep X-ray data to ensure a robust AGN classification. Assuming a fixed slope of $\alpha = -1.6$, we find best fit Schechter parameters $\log L_\star = 42.8 \pm 0.2$ and $\log \phi_\star = -4.5 \pm 0.3$.

Table 4.2-4.5 notes. Overall, we exclude 18 optically unconfirmed LAE candidates in the following discussion and in the construction of the $z \sim 1$ $\text{Ly}\alpha$ LF.

Excluding these 18, we are left with a sample of 117 LAEs. We classified 57 of these sources as UV, X-ray, or optical AGN. This establishes an AGN fraction (f_{AGN}) of $49\% \pm 8\%$ for our sample. After we exclude UV identified AGNs, our f_{AGN} drops to $41\% \pm 8\%$. When performing the optical spectroscopic followup, we preferentially targeted LAEs that were not classified as UV or X-ray AGNs. With this policy, we obtained optical redshifts for 98% (59 out of 60) of our LAE galaxies but only 89% (51 out of 57) of our AGNs. We found that 9 of the 37 LAEs classified as X-ray AGNs were already classified as AGNs based on their UV spectra. We observed 19 LAEs classified as X-ray AGNs with Keck DEIMOS. Only 3 of these X-ray AGNs

were not classified as optical AGNs.

As a cross check to our sample’s AGN fraction of $49\% \pm 8\%$, we only consider LAEs within deep X-ray fields and re-compute the AGN fraction. There are 79 candidate LAEs within deep X-ray fields; we classified 44 (or $56\% \pm 10\%$) as AGNs. This is not significantly different our sample-wide AGN contamination. In Figure 4.3, we show that the AGN fraction increases with $\text{Ly}\alpha$ luminosity (similar trends have been noted by Cowie et al. 2010 and Nilsson & Møller 2011). Breaking each sample into 5 luminosity bins from $\log L_{\text{Ly}\alpha} = 42.5$ to 43.4 (used below in the $\text{Ly}\alpha$ LF computation) and requiring $\text{EW}_r(\text{Ly}\alpha) \geq 20\text{\AA}$, we find that the AGN fraction increases from 6% to 71% for the full *GALEX* data cube sample and from 13% to 83% for the deep X-ray subsample. Given this small but systematic difference, we derive the $\text{Ly}\alpha$ LF for our full LAE galaxy sample and for the subsample limited to regions with deep X-ray data to determine the effect, if any, on our results.

In common with other low-redshift samples, our AGN fraction is high compared to the AGN fractions quoted for higher redshift samples. (Note that many of the low-redshift samples quote AGN fractions that exclude sources known to be AGNs based on the UV spectra; our AGN fraction includes these sources.) However, it is essential to emphasize that the AGN fraction is strongly dependent on the luminosity range. Our LAEs have $\text{Ly}\alpha$ luminosities from $10^{42.2}$ to $10^{43.6} \text{ erg s}^{-1}$. As shown in Nilsson & Møller (2011), the AGN fraction rapidly increases over this range and approaches 100% at $\text{Ly}\alpha$ luminosities above $10^{43.6} \text{ erg s}^{-1}$.

The high-luminosity LAEs are primarily AGNs, and it is these objects that are included in the *GALEX* pipeline extractions. Only with the increased sensitivity of the data cube search do we probe faint enough to develop large samples of

star-forming LAEs. In Figure 4.4(a), we show the LAE redshift versus the NUV magnitudes for our LAE data cube sample (blue diamonds) and for the pipeline LAE sample found by Cowie et al. (2010, 2011, black squares) constrained to the data cubes' $50' \times 50'$ FOVs and redshift range ($z = 0.67 - 1.16$). We note that there are seven pipeline LAE galaxies listed within the CDFS, GROTH, NGPDWS, and COSMOS fields (see Table 2 in Cowie et al. 2011). We excluded one pipeline LAE galaxy due to its low redshift $z = 0.65$, and we excluded two pipeline LAE galaxies because they do not fall within our data cubes' $50' \times 50'$ FOVs. Although not excluded for the purposes of this discussion, if we also require $\text{EW}_r(\text{Ly}\alpha) \geq 20\text{\AA}$, then there are only two LAE galaxies that remain in the pipeline sample. By construction, the *GALEX* pipeline extractions miss all LAEs fainter than the pipeline magnitude limit of $\text{NUV} \sim 22$ (dashed line in Figure 4.4(a)). Objects classified as AGNs in any way have their symbols outlined in red. In Figure 4.4(b), we show the LAE redshift versus the $\text{Ly}\alpha$ luminosity. Directly below Figures 4.4(a) and 4.4(b), we show these Figures again but with all AGNs removed. We find that the AGN fraction reaches 100% at a $\text{Ly}\alpha$ luminosity of $\sim 10^{43.5} \text{ erg s}^{-1}$. This is also the $\text{Ly}\alpha$ luminosity where the pipeline extraction begins to miss sources. While there is some luminosity overlap between the data cube and pipeline samples, we find that our data cube search is necessary to obtain a large LAE galaxy sample.

4.4 Luminosity Function

We computed the $\text{Ly}\alpha$ LF of the combined CDFS, GROTH, NGPDWS, and COSMOS LAE galaxy samples in the redshift range $z = 0.67 - 1.16$ using the $1/V$ technique (Felten 1976). We only included sources that were not classified as AGN

in any way and that have $\text{EW}_r(\text{Ly}\alpha) \geq 20 \text{ \AA}$. With these criteria, the sample includes two LAE galaxies, which appeared in the pipeline sample of Cowie et al. (2011, see their Table 2). The rest (58) come from our data cube sample and are not found in the *GALEX* pipeline extractions.

To compute the LF, we divided our $\text{Ly}\alpha$ survey into 20 samples (5 samples per field), where the sample j covers a $\text{Ly}\alpha$ flux range $f_{1j} \leq f \leq f_{2j}$ and a solid angle area ω_j (the masking of bright sources alters ω_j from one *GALEX* $50' \times 50'$ field to another). For each field, we took the difference between the minimum and maximum observed $\text{Ly}\alpha$ flux and divided this into 5 flux bins of equal size (see Table 4.6 for minimum $\text{Ly}\alpha$ flux values and corresponding completeness limits). The sampling rate S_j (the fraction of LAE galaxies in the given flux range that were observed) was estimated with our completeness simulations. The effective area of a sample is $\Omega_j = \omega_j S_j$. The accessible volume of the i^{th} LAE galaxy in sample j is

$$V_{ij} = \Omega_j \left(V(z_{max}^{ij}) - V(z_{min}^{ij}) \right),$$

where the comoving volume is calculated at the highest and lowest redshifts at which

Table 4.6. Luminosity Function Minimum $\text{Ly}\alpha$ Flux and Corresponding Completeness Limit

<i>GALEX</i> Field (1)	$f_{\text{Ly}\alpha}$ (erg cm ⁻² s ⁻¹) (2)	Completeness (3)
CDFS	8.5×10^{-16}	26.4%
GROTH	5.2×10^{-16}	1.6%
NGPDWS	10.9×10^{-16}	24.6%
COSMOS	24.1×10^{-16}	62.3%

the i^{th} LAE galaxy remains both within sample j 's Ly α flux range $f_{1j} \leq f \leq f_{2j}$ and within the redshift range $z = 0.67 - 1.16$. The total accessible volume of the i^{th} LAE galaxy is

$$V_i = \sum_{j=1}^{20} V_{ij} ,$$

and the Ly α LF in the luminosity range $L_1 \leq L_i \leq L_2$ and redshift range $z = 0.67 - 1.16$ is

$$LF = (\log(L_2) - \log(L_1))^{-1} \sum_{\{i: L_1 \leq L_i \leq L_2\}} 1/V_i .$$

In Figure 4.5(a), we show our raw LF (black open circles) along with our LF corrected for incompleteness (black solid circles). Error bars are $\pm 1\sigma$ Poisson errors. In Table 4.7 Columns 1, 2, and 3, we list the luminosity bins, the number of LAE galaxies per bin, and the computed luminosity function values corrected for incompleteness. We have tested that these results are not dependent on our method of constructing flux bins. Alternatively, for each field, we generated 5 flux bins of equal size within the range of f_{thres} to the maximum observed Ly α flux, where f_{thres} is the Ly α flux corresponding to 50% completeness (see Figure 4.2). This method reduces the dependence on our completeness simulations but does not significantly change our results.

We may correct for any remaining AGNs in our sample by restricting our field to regions with deep X-ray data. This removes the NGPDWS field and restricts the area of the remaining $50' \times 50'$ *GALEX* fields but ensures a robust AGN classification. In Figure 4.5(b), we show our X-ray data limited LF (black circles). Comparing this LF to the LF computed from the full LAE galaxy sample, we find that all points are

consistent within 1σ error bars.

We find that our LAE galaxy LF is consistent with the $z \sim 1$ LAE galaxy LF computed in BCW12. BCW12 based their LF on ~ 20 LAE galaxies found in one of the four *GALEX* fields contained in this study. We have increased the sample size by a factor of three. Furthermore, we have searched for AGNs in the BCW12 LAE galaxy sample (none found) and removed spurious sources (3 BCW12 LAE candidates) with our newly obtained optical spectroscopic data.

4.5 Distribution of Equivalent Widths

In Figure 4.6, we show our rest-frame EWs versus redshift. Because we have a flux-limited sample, the distribution of these EWs should be directly comparable to narrowband Ly α selected samples at higher redshifts. In Figure 4.7(a), we show the distribution of these EWs for the full sample.

The rest-frame EW distribution is normally fit with an exponential function. For the LAE samples, which are truncated below 20 Å, the maximum likelihood estimate of the scale length is the mean of the rest-frame EW values minus 20 Å.

Table 4.7. Cumulative Luminosity Function

$\log(L)$ bin (erg s $^{-1}$) (1)	N (2)	$\frac{1}{\Delta \log(L)} \sum 1/V$ (Mpc $^{-3}$ log(L) $^{-1}$) (3)
42.468 - 42.655	17	$66.3 \pm 16.8 \times 10^{-6}$
42.655 - 42.842	13	$23.6 \pm 6.7 \times 10^{-6}$
42.842 - 43.029	15	$14.9 \pm 3.9 \times 10^{-6}$
43.029 - 43.216	8	$5.7 \pm 2.0 \times 10^{-6}$
43.216 - 43.403	7	$4.3 \pm 1.6 \times 10^{-6}$

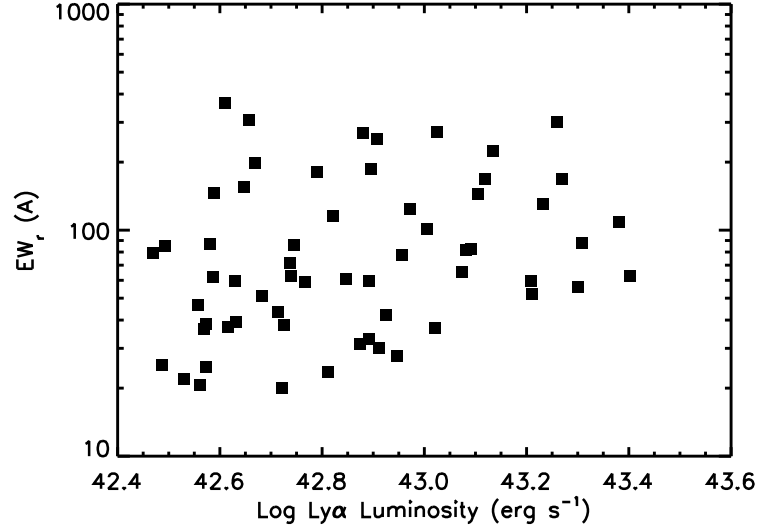


Fig. 4.6. — : Rest-frame EWs vs. log $\text{Ly}\alpha$ luminosity for the full sample.

We find a scale length of $80 \pm 10 \text{ \AA}$ for the full sample, where we computed the error using the parameterized bootstrap method. Separating the sample by luminosity gives a scale length of $91 \pm 14 \text{ \AA}$ for sources with logarithmic $\text{Ly}\alpha$ luminosities above 42.8 and $68 \pm 10 \text{ \AA}$ for those with lower luminosities. This is consistent with the distribution being invariant as a function of $\text{Ly}\alpha$ luminosity, as has been found in the higher redshift samples (Ciardullo et al. 2012).

We compare our sample at $z \sim 1$ with a sample at $z = 2.25$ from Nilsson et al. (2009) (Figure 4.7(b)) and a sample at $z = 3.1$ from Ciardullo et al. (2012) (Figure 4.7(c)). The Nilsson et al. sample has a logarithmic luminosity limit of 42.4 erg s^{-1} , which is very similar to that of the present sample, while the Ciardullo et al. sample covers 42 erg s^{-1} to just above 43 erg s^{-1} , making it slightly fainter, on average. The Nilsson et al. and Ciardullo et al. maximum likelihood estimates of the rest-frame EW scale length are both $56 \pm 7 \text{ \AA}$. Nilsson et al. also give a least squares fit value of $56 \pm 7 \text{ \AA}$, which is consistent within the errors.

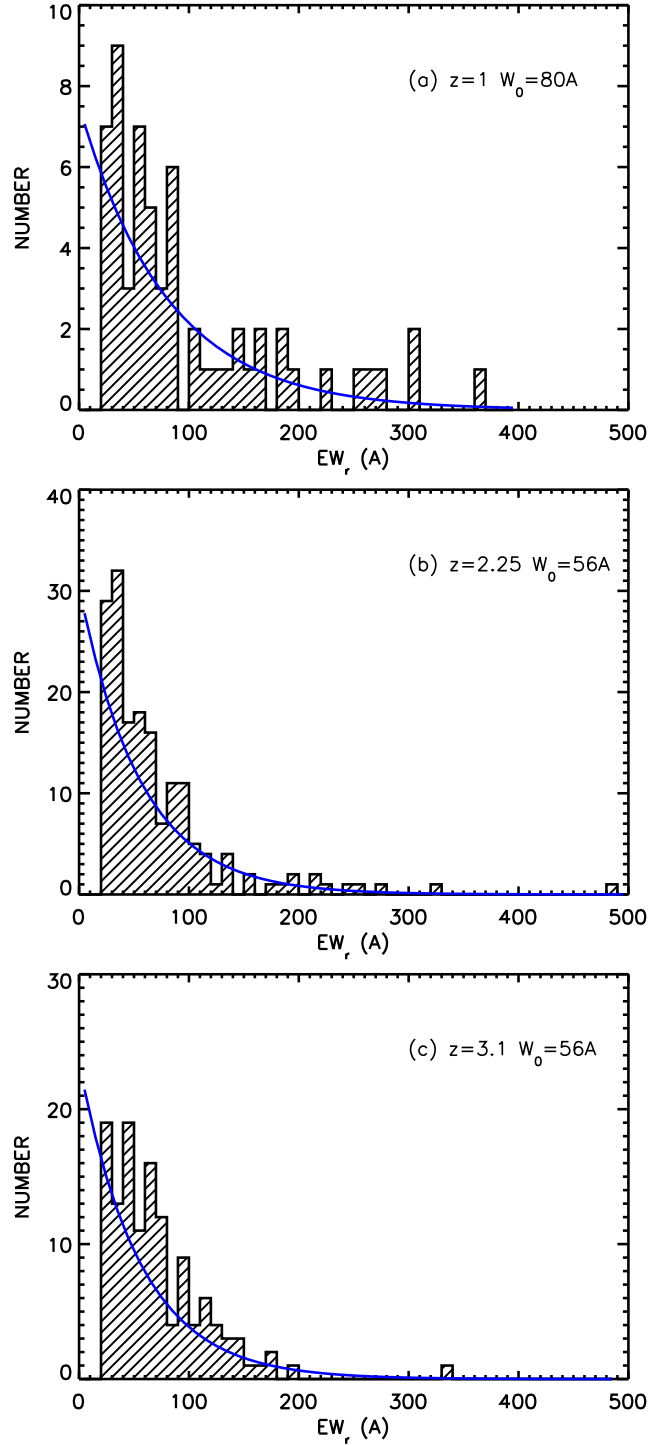


Fig. 4.7. — : Histograms of the rest-frame EWs in 10 $\text{\AA}$ bins. (a) The present sample at $z \sim 1$. (b) The Nilsson et al. (2009) sample at $z = 2.25$. (c) The Ciardullo et al. (2012) sample at $z = 3.1$. In each case, the blue curve shows the exponential distribution computed using a maximum likelihood procedure. The rest-frame scale length is $80 \pm 10 \text{\AA}$ for $z \sim 1$, $56 \pm 7 \text{\AA}$ for $z = 2.25$, and $56 \pm 7 \text{\AA}$ for $z = 3.1$.

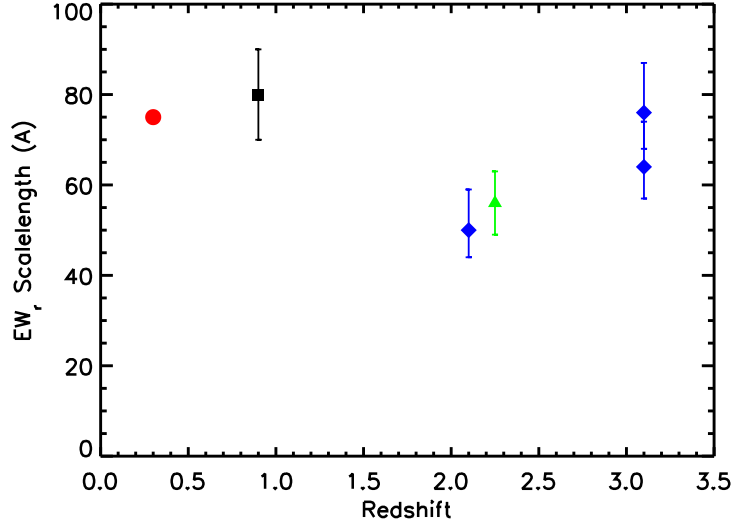


Fig. 4.8. — : Maximum likelihood estimates of the rest-frame EW scale length from the present $z \sim 1$ sample (black square), the $z = 2.25$ Nilsson et al. (2009) sample (green triangle), and the $z = 2.1$ Guaita et al. (2010), $z = 3.1$ Gronwall et al. (2007), and $z = 3.1$ Ciardullo et al. (2012) samples (blue diamonds; values quoted from Ciardullo et al.) vs. redshift. The red circle shows the scale length from the $z = 0.3$ *GALEX* LAE sample of Cowie et al. (2010) after correction for their continuum selection, as described in their Section 5.4.

However, when Ciardullo et al. (2012) allowed for biases in their sample, such as those introduced by the filter shape, then their rest-frame EW scale length rose to 64^{+10}_{-7} Å. When Ciardullo et al. analyzed an alternate sample at $z = 3.1$ from Gronwall et al. (2007) in the same way, they found 76^{+11}_{-8} Å. From the combined samples, they found 70^{+7}_{-5} Å. Ciardullo et al. also reanalyzed the $z = 2.1$ sample from Guaita et al. (2010) in a self-consistent way and found 50^{+9}_{-6} Å. The Ciardullo et al. $z = 2.1$ value is consistent with the Nilsson et al. (2009) $z = 2.25$ value. Based on an Anderson-Darling test, they concluded that there is a significant difference between the $z = 3.1$ and $z = 2.1$ samples.

The Ciardullo et al. (2012) analysis emphasizes that differences inherent in the methodology and fitting procedure are important. In particular, comparisons

between the present sample, where the line fluxes are computed from the spectra and the continua from the broadband magnitudes, and samples such as the Ciardullo et al. sample, which are based purely on imaging data, can be tricky (e.g., Zheng et al. 2013). Nevertheless, the present sample appears to indicate that, if there is indeed a narrowing of the rest-frame EW distribution from $z = 3$ to $z = 2$, then it has reversed by $z = 1$.

In Figure 4.8, we show the rest-frame EW scale lengths measured from the maximum likelihood procedures for the present sample (black square), the $z = 2.25$ Nilsson et al. (2009) sample (green triangle), and the $z = 2.1$ Guaita et al. (2010), $z = 3.1$ Ciardullo et al. (2012), and $z = 3.1$ Gronwall et al. (2007) samples (blue diamonds; values quoted from Ciardullo et al.) While there may be a drop at $z \sim 2$, overall the scale length shows little variation with redshift. This is in sharp contrast to the analysis of Zheng et al. (2013), who found a redshift evolution of $(1 + z)^{1.7}$. The Zheng et al. result appears to be due primarily to their misinterpretation of the scale length given by Cowie et al. (2010) for their $z = 0.3$ *GALEX* LAE sample. Zheng et al. used 23.7 ± 2.2 , which was what Cowie et al. gave for their continuum selected sample. However, as Cowie et al. emphasized in their Section 5.4, this needs to be corrected for missing high EW sources before it can be compared with Ly α luminosity selected samples. In Figure 4.8, we show the Cowie et al. corrected scale length of 75 Å (red circle). (Because of the large systematic errors, we do not show an error bar.) This is fully consistent with there being a constant value of the scale length with redshift.

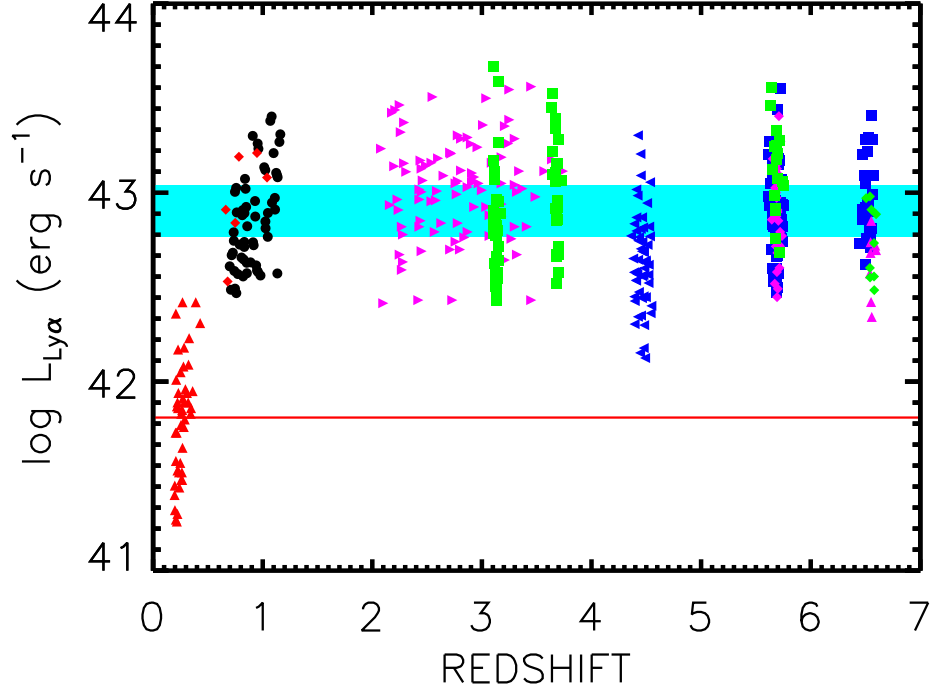


Fig. 4.9. — : Observed $\text{Ly}\alpha$ luminosity vs. redshift for LAE galaxies with $\text{EW}_r(\text{Ly}\alpha) \geq 20 \text{ \AA}$. We show pipeline *GALEX* LAEs from Cowie et al. (2011, red triangles and red diamonds), data cube *GALEX* LAEs from this study (black circles), $z = 1.9 - 3.8$ HETDEX LAEs from Blanc et al. (2011, magenta right pointing triangles), $z = (3.1, 3.7, 5.7)$ LAEs from Ouchi et al. (2008, green squares), $z = 4.5$ LAEs from Dawson et al. (2007, blue left pointing triangles), $z = (5.7, 6.5)$ LAEs from Hu et al. (2010, blue squares), $z = 5.7$ LAEs from Shimasaku et al. (2006, magenta diamonds), and $z = 6.5$ LAEs from Taniguchi et al. (2005, green diamonds) and Kashikawa et al. (2006, magenta triangles). The red line shows the $L_\star$ derived for the $z \sim 0.3$ LF assuming a slope of $\alpha = -1.6$. The cyan area shows the range of $L_\star$ values derived for the $z = 2.85 - 5.7$ LFs.

4.6 Discussion

In Figure 4.9, we show the dramatic increase in the observed $\text{Ly}\alpha$ luminosities to a redshift of $z \sim 1$ followed by relatively no luminosity evolution from $z \sim 1$ to $z \sim 6$. This large luminosity boost was previously noted by Cowie et al. (2011) with a sample of ~ 5 LAEs at a redshift of $z \sim 1$ (see Figure 4.9, red diamonds). We have now increased the sample size of $z \sim 1$ LAEs to 60 galaxies (see Figure 4.9,

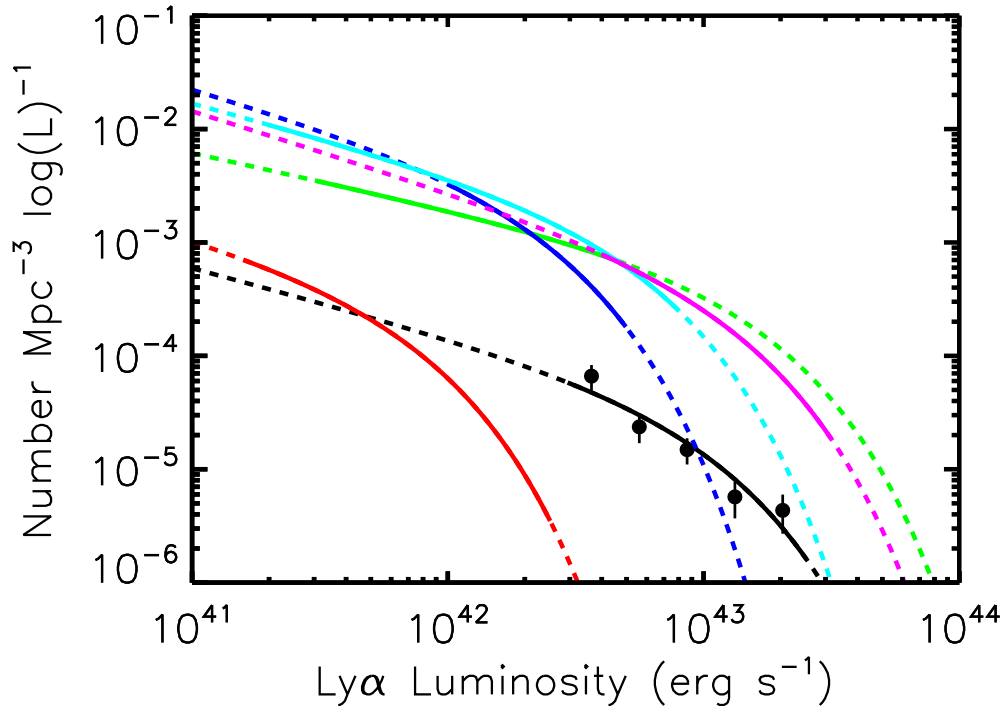


Fig. 4.10. — : Derived $\text{Ly}\alpha$ luminosity function at $z = 0.67 - 1.16$ for the LAE galaxies in deep *GALEX* grism fields (black circles from Figure 4.5(a)) compared to other $\text{Ly}\alpha$ luminosity functions in close redshift proximity. The fitted Schechter functions are shown as solid curves over the extent of their observed data points. The black curve indicates our best fit Schechter function assuming a fixed slope of $\alpha = -1.6$. The red curve indicates the $z = 0.194 - 0.44$ Cowie et al. (2010) LF. The blue curve indicates the $z = 2.1$ Ciardullo et al. (2012) LF. The green curve indicates the $z = 2.2$ Hayes et al. (2010) LF. The cyan curve indicates the $z = 1.95 - 3$ Cassata et al. (2011) LF. The magenta curve indicates the $z = 1.9 - 3.8$ Blanc et al. (2011) LF.

black circles). Our relatively nearby $z \sim 1$ sample will facilitate the study of LAEs with luminosities analogous to high-redshift LAEs. In Chapter 5, we will use the available spectroscopic and imaging data to constrain the properties of our sample and to serve as a baseline for studies of higher redshift LAEs.

In order to quantify the evolution in L_* , we have held the slope α fixed and found the best Schechter (1976) function fit to our data. We assume a slope of $\alpha = -1.6$, which allows us to compare directly our results to the LAE galaxy LF at

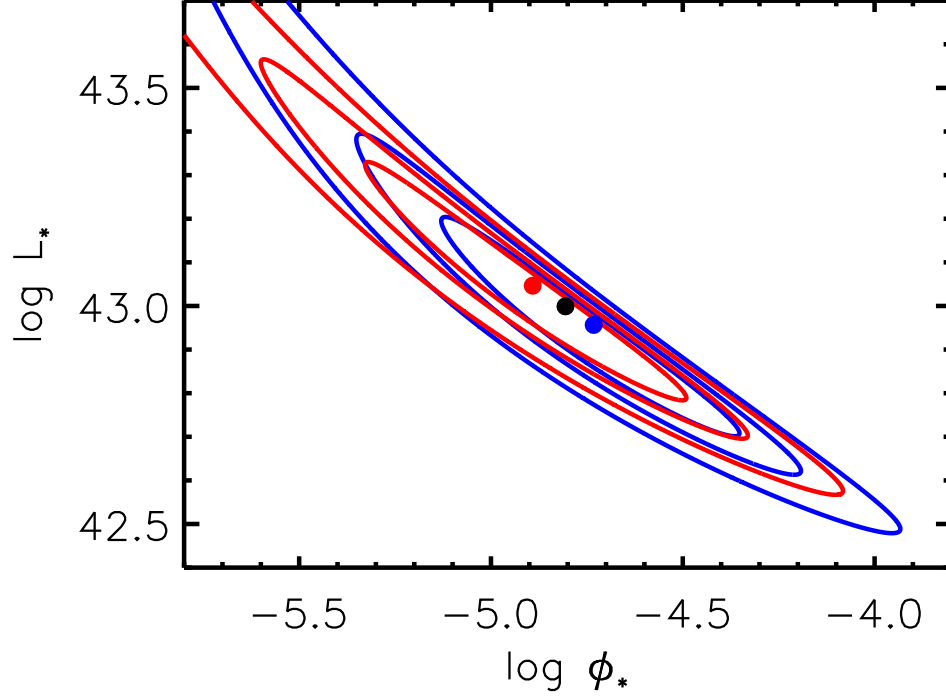


Fig. 4.11. — : 1σ , 2σ , and 3σ contours for the $z \sim 1$ luminosity function parameters L_* and ϕ_* assuming a faint end slope of $\alpha = -1.5$ (blue) and $\alpha = -1.7$ (red). The blue, black, and red circles show our best fit Schechter function results for the full LAE galaxy sample assuming $\alpha = -1.5$ (blue circle), $\alpha = -1.6$ (black circle), and $\alpha = -1.7$ (red circle). Regardless of the assumed faint end slope, $\log L_*\phi_* \sim 38.2$.

$z \sim 0.3$ ($\alpha = -1.6$, $\log L_* = 41.81 \pm 0.09$, $\log \phi_* = -3.77 \pm 0.08$; Cowie et al. 2010).

We obtain $\log L_* = 43.0 \pm 0.2$ and $\log \phi_* = -4.8 \pm 0.3$ (see Figure 4.5(a)). Limiting our sample to regions with deep X-ray data, we obtain $\log L_* = 42.8 \pm 0.2$ and $\log \phi_* = -4.5 \pm 0.3$ (see Figure 4.5(b)).

Both our $L_*(z \sim 1)$ values are roughly consistent with L_* values found for LAE galaxy LFs at $z \sim 3$ ($\log L_* = 42.7$, Gronwall et al. 2007; $\log L_* = 42.8$, Ouchi et al. 2008; $\log L_* = 42.8$, Ciardullo et al. 2012) and imply an L_* increase by a factor of ~ 15 from $z \sim 0.3$ to $z \sim 1$ (from $\log L_*(z \sim 0.3) = 41.81 \pm 0.09$ to $\log L_*(z \sim 1) = 43.0 \pm 0.2$). A large boost in L_* is in agreement with the evolution seen in other LFs tracing star-forming galaxies. Both H α and UV LFs are found to be

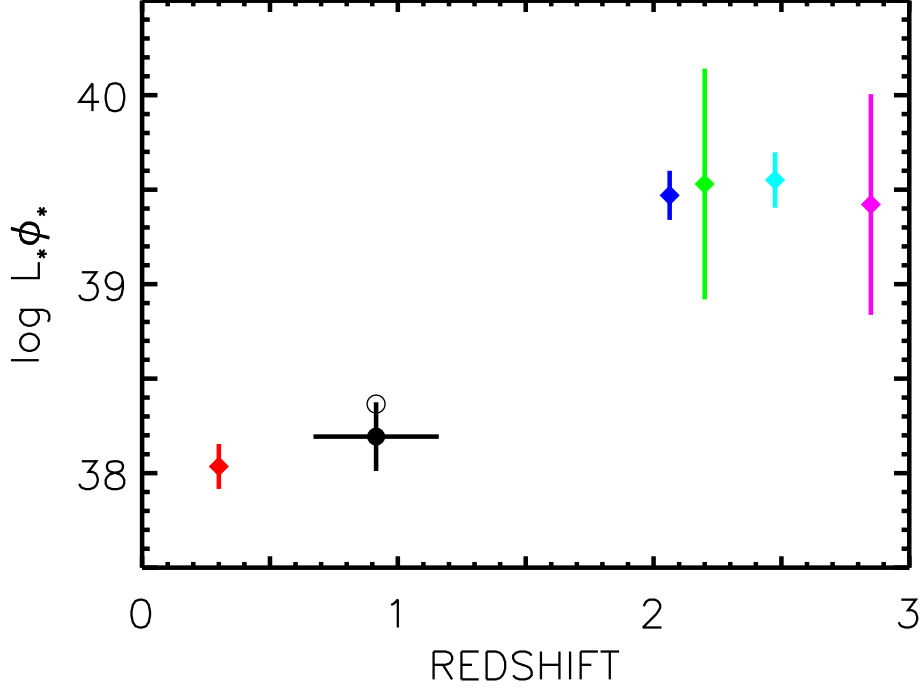


Fig. 4.12. — : The product $L_*\phi_*$ vs. redshift for the LAE galaxy LFs shown in Figure 4.5. The black solid circle shows the product $L_*\phi_* = 38.2 \pm 0.2$ from our best fit $z \sim 1$ LAE galaxy LF. The black open circle shows the product $L_*\phi_* = 38.4 \pm 0.2$ from our fit to the $z \sim 1$ LAE galaxy LF limited to regions with deep X-ray data. Both $z \sim 1$ fits assume a faint end slope $\alpha = -1.6$. Error bars are estimated from the published uncertainties in L_* and ϕ_* .

dominated by luminosity evolution over the redshift range $z \sim 0.3 - 2$. Sobral et al. (2013) investigated $H\alpha$ LFs and found that $L_*(H\alpha)$ increases by a factor of 10 from $z \sim 0$ to $z \sim 2$. Oesch et al. (2010) investigated UV LFs and found that $L_*(UV)$ increases by a factor of ~ 16 from $z \sim 0$ to $z \sim 3$.

However, our fitted Schechter parameters indicate a decrease in ϕ_* from $z \sim 0.3$ to $z \sim 1$ (from $\log \phi_*(z \sim 0.3) = -3.77 \pm 0.08$ to $\log \phi_*(z \sim 1) = -4.8 \pm 0.3$). It is only beyond $z \sim 1$ that there is a significant increase in ϕ_* . Referring again to other LFs tracing star-forming galaxies, we note that, unlike L_* , ϕ_* does not increase monotonically over the redshift range $z \sim 0.3 - 2$. Within the uncertainties of

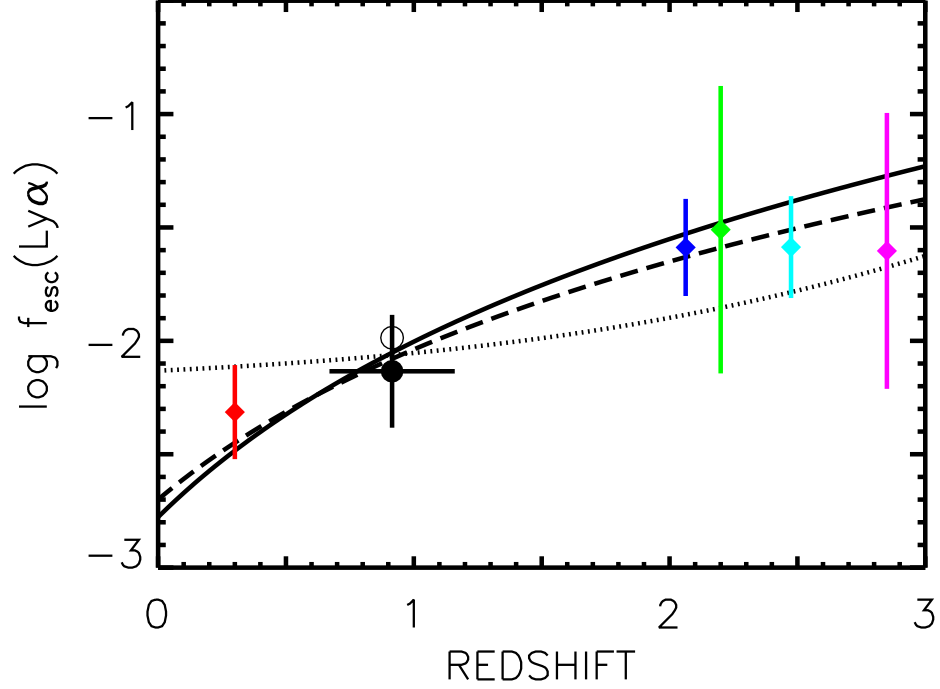


Fig. 4.13. — : Sample averaged Ly α escape fractions for all LFs presented in Figure 4.5. The black solid circle shows $f_{esc}(\text{Ly}\alpha) = 0.7\% \pm 0.4\%$ computed from our best fit $z \sim 1$ LF. The black open circle shows $f_{esc}(\text{Ly}\alpha) = 1.0\% \pm 0.6\%$ computed from our fitted LF limited to regions with deep X-ray data. Diamonds (from low redshift to high) indicate $f_{esc}(\text{Ly}\alpha)$ derived from Cowie et al. (2010), Ciardullo et al. (2012), Hayes et al. (2010), Cassata et al. (2011), and Blanc et al. (2011). Error bars are estimated from the published uncertainties in L_* and ϕ_* . The solid and dashed black curves are from Hayes et al. (2011) and Blanc et al. (2011), respectively, and show the best fit power law to $f_{esc}(\text{Ly}\alpha)$ data. The dotted black curve shows the best fit transition model from Blanc et al. (2011). The calculated points and the selected curves have not been corrected for IGM absorption, which should be negligible at $z \sim 1$ and within the 1σ uncertainties at $z < 3$.

their measurements, both Sobral et al. (2013, for $\phi_*(\text{H}\alpha)$) and Oesch et al. (2010, for $\phi_*(\text{UV})$) found very little evidence for ϕ_* evolution from $z \sim 0$ to $z \sim 2$. As discussed in more detail below, we find that our best fit Schechter functions with higher L_* values tend to have lower ϕ_* values. Given this issue and the poorly constrained faint end slope, a clearer picture of the evolution of individual Schechter function parameters awaits a $z \sim 1$ LAE survey probing lower Ly α luminosities. Such a

survey is not possible with currently available telescopes but would allow stronger constraints on the $L_*(z \sim 1)$ and $\phi_*(z \sim 1)$ values.

In Figure 4.10, we compare our $z \sim 1$ LF computed from the full LAE galaxy sample to other Ly α luminosity functions in close redshift proximity. We show the fitted Schechter functions as solid lines over the extent of their observed data points. For the $z \sim 2$ Schechter function parameters, the $\log L_*$ values range from 42.3 to 43.2, the $\log \phi_*$ values range from -3.7 to -2.9 , and the α values range from -1.7 to -1.5 (see the blue, green, cyan, and magenta lines in Figure 4.10). Due to the differing survey volumes and fitting assumptions, it is still possible that all $z \sim 2$ data are in overall agreement (Blanc et al. 2011; Ciardullo et al. 2012).

The Schechter function parameters ϕ_* and L_* are known to be strongly correlated, while assuming different values of α tends to leave the product $L_*\phi_*$ unchanged. We show this for our Schechter function fit in Figure 4.11. For these reasons, we consider the product $L_*\phi_*$ and the luminosity density, which is proportional to $L_*\phi_*$, to be more reliable than the values of individual Schechter parameters. In Figure 4.12, we show that a coherent picture emerges by comparing our results to the $L_*\phi_*$ values found in the literature. As noted by Blanc et al. (2011), there is a trend (in agreement with our uncertainty contours) for the $z \sim 2$ Schechter function fits with higher L_* values to have lower ϕ_* values. Thus, the $z \sim 2$ Schechter functions — which have L_* values that differ by about an order of magnitude — are found to have consistent $L_*\phi_*$ values. The product $L_*\phi_*$ increases by a factor of ~ 1.5 from $z \sim 0.3$ to $z \sim 1$ followed by an increase by a factor of ~ 20 from $z \sim 1$ to $z \sim 2$.

The observed Ly α luminosity density provides an estimate of the total amount

of Ly α light emitted by galaxies per unit volume:

$$\rho_{Ly\alpha}^{obs} = \int L\Phi(L)dL,$$

where $\Phi(L)$ is a Ly α Schechter function. Integrating this expression from 0 to $+\infty$ gives

$$\rho_{Ly\alpha}^{obs} = L_{\star}\phi_{\star}\Gamma(\alpha + 2),$$

where Γ is the Gamma function. The main source of uncertainty in this expression comes from the poorly constrained faint end slope α . Taking the extreme values for the $z \sim 2$ Schechter functions, $\alpha = -1.7$ and $\alpha = -1.5$, we find that Γ changes by a factor of 1.7. Modulo this factor, the evolution of the product $L_{\star}\phi_{\star}$ seen in Figure 4.12 from $z \sim 0.3$ to $z \sim 2$ results from the change in observed Ly α luminosity density.

To first order, the intrinsic production of Ly α photons in a galaxy is proportional to the SFR (Kennicutt 1998; Schaerer 2003). Thus, an overall increase in the Ly α luminosity density from $z \sim 0.3$ to $z \sim 2$ is expected due to the well established increase in the cosmic SFR density. However, observed Ly α luminosities will significantly deviate from intrinsic Ly α luminosities due to resonant scattering of Ly α photons by neutral hydrogen.

To quantify this, we calculate the $z \sim 1$ volumetric Ly α escape fraction, $f_{esc}(\text{Ly}\alpha)$, and compare its value to other measurements taken at nearby redshifts. The volumetric Ly α escape fraction measures the fraction of Ly α photons that escape from the survey volume. We emphasize that its value will be systematically lower than the Ly α escape fractions derived for individual LAEs. For example, Blanc

et al. (2011) find a $\sim 30\%$ median Ly α escape fraction for their $z = 1.9 - 3.8$ LAE sample but only a $\sim 3\%$ volumetric Ly α escape fraction.

The volumetric escape fraction is defined as the observed Ly α luminosity density divided by the intrinsic Ly α luminosity density,

$$f_{esc}(Ly\alpha) = \rho_{Ly\alpha}^{obs} / \rho_{Ly\alpha}^{int},$$

where the intrinsic Ly α luminosity density is found by taking a measure of the cosmic SFR density and then converting SFR to Ly α luminosity,

$$\rho_{Ly\alpha}^{int} = \rho_{SFR}(8.7)(1.26 \times 10^{41}).$$

The conversion factors come from the assumption of case B recombination (Brocklehurst 1971) and the SFR to H α Kennicutt (1998) relation. For consistency with Blanc et al. (2011), we integrate the Ly α LFs down to a $2.66 \times 10^{41} \text{ erg s}^{-1}$ limit and obtain cosmic SFR density measurements from Bouwens et al. (2010). Blanc et al. (2011) estimate that the choice of the luminosity integration limit may alter the computed luminosity density by at most 60% (for further discussion of this issue see Hayes et al. 2011). Bouwens et al. (2010) derive cosmic SFR densities from extinction corrected rest-frame UV LFs. We do not attempt to correct for IGM absorption, which should be negligible for our $z \sim 1$ sample.

Both Hayes et al. (2011) and Blanc et al. (2011) have compiled measurements from various Ly α LF studies spanning a redshift range of $z = 0.3 - 7.7$ to determine the evolution of $f_{esc}(Ly\alpha)$. Both groups fit power laws to these data and find evidence for a rapidly increasing $f_{esc}(Ly\alpha)$, which approaches 100% at high redshifts ($z \sim 9$).

We find a $z \sim 1$ $f_{esc}(Ly\alpha)$ of $0.7\% \pm 0.4\%$. In Figure 4.13, we show that the

$f_{esc}(\text{Ly}\alpha)$ computed from our best fit $z \sim 1$ Schechter function is consistent with the $f_{esc}(\text{Ly}\alpha)$ value of $\sim 0.9\%$ interpolated from the power law fits of Hayes et al. (2011) and Blanc et al. (2011). In Figure 4.13, we also show $f_{esc}(\text{Ly}\alpha) = 1.0\% \pm 0.6\%$ (open circle) computed from our fitted LF limited to regions with deep X-ray data. Hayes et al. (2011) argue that the rising trend in the volumetric $\text{Ly}\alpha$ escape fraction with increasing redshift is consistent with expectations due to the general decline of dust content in star-forming galaxies. We have now constrained the $f_{esc}(\text{Ly}\alpha)$ from $z \sim 0.3$ to $z \sim 2$ and find results consistent with this inferred trend.

4.7 Summary

We presented a catalog of 135 candidate $z \sim 1$ LAEs. We obtained optical spectral data for 90% of our sample. We found that only $\sim 13\%$ of our sample are either spurious, stars, or strong $\text{CIV}\lambda 1549$ emitters. Combining these optical data with the UV spectra and X-ray imaging data, we found that 49% of our $\text{Ly}\alpha$ emitters are AGNs. Eliminating AGNs and LAEs with $\text{EW}_r(\text{Ly}\alpha) < 20 \text{ \AA}$ gives a final sample of 60 star-forming LAEs, which we used to compute the $z \sim 1$ $\text{Ly}\alpha$ LF and the $z \sim 1$ $\text{Ly}\alpha$ volumetric escape fraction ($f_{esc}(\text{Ly}\alpha) = 0.7\% \pm 0.4\%$). We note that no improved $z \sim 1$ $\text{Ly}\alpha$ LFs are possible for the foreseeable future due to the lack of UV telescopes. Our best fit LF implies a significant increase in $L_\star$ between $z \sim 0.3$ and $z \sim 1$ without much change in the luminosity density. This requires a rapid increase in $\phi_\star$ between $z \sim 1$ and $z \sim 2$. It is clear that the intrinsic properties of the LAEs must be changing rapidly in the $z \sim 1 - 2$ interval, resulting in a rapid increase in the $\text{Ly}\alpha$ escape fraction. Our cataloged sources offer the best opportunity to study emitters with luminosities comparable to LAEs found in the early universe. With

the optical data in hand, Chapter 5 will compare our sample’s physical properties to a UV-selected control sample.

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Chapter 5

Future Research: What Makes a Ly α Galaxy a Ly α Galaxy?

5.1 Introduction

My thesis work has provided the first large sample of LAEs at $z \sim 1$. This sample fills in a previously unexplored redshift range and allows detailed study of luminous LAEs. This will be a key sample for connecting the low luminosity LAE sample at $z \sim 0.3$ to the higher luminosity LAE samples at $z \sim 2$.

A major accomplishment has been the successful optical spectroscopic followup of 98% of my LAE galaxy sample. This was used in Wold et al. (2014) to verify UV redshifts and to identify AGNs. My future work will further utilize these optical spectra to constrain the physical properties of $z \sim 1$ LAE galaxies. My strategy to accomplish this goal follows the blueprint used in the $z \sim 0.3$ LAE studies (Cowie et al. 2010, 2011). In these studies, properties such as metallicity and dust extinction were derived for a $z \sim 0.3$ LAE sample and for a $z \sim 0.3$ UV-continuum selected sample. This relative measurement removes potential sources of systematic error and helps to determine which properties are most important in determining whether a galaxy is a LAE.

Accordingly, rather than observing in single-object/long-slit mode, I used the multi-object spectroscopic (MOS) mode available on DEIMOS (observations described in Wold et al. 2014). I used the remaining space available in my MOS masks to observe a control sample, a UV-continuum selected sample without detected Ly α that has the same luminosities and lies in the same redshift interval as my primary LAE sample.

With these samples in hand, I now need to determine whether there are galaxy

properties that determine whether a LAE is produced in a UV-continuum selected galaxy. The $z \sim 0.3$ studies suggest that metallicity is a key diagnostic. However, for the majority of my sample deeper spectroscopic observations are needed to measure the [OIII] λ 4363 line flux. This auroral [OIII] line relative to the [OIII] λ 5007 line can be used to give a direct measure of metallicity (e.g., Izotov et al. 2006). I was awarded two additional nights on Keck DEIMOS to measure the metallicities of ~ 20 LAEs and ~ 60 UV-continuum selected sources. Unfortunately, the first Keck night had poor weather and no data were obtained. The second Keck night is scheduled for December 18, 2014. The following work demonstrates what can be accomplished with the spectra in hand. This will be expanded upon with additional data from upcoming observation runs.

5.2 Emission Line Measurement and Sample Selection

Out of the 59 LAE galaxies with optical data (excluding known AGNs), 45 have spectra that extend out to [OIII] λ 4959. This spectral range is needed to calculate direct metallicities (one of the main goals of this study). Out of the 1819 UV-continuum selected galaxies with optical redshifts, 595 have spectra that extend out to [OIII] λ 4959 and have redshifts greater than 0.67. My highest priority secondary targets were selected using the FUV, NUV, and U-band color cut described in Barger et al. (2008). Barger et al. showed that this is an efficient cut to identify $z > 0.6$ galaxies. I require my UV-continuum selected sample to have $z > 0.67$ to match the minimum redshift obtainable using my data cube LAE search method. Given the DEIMOS instrument setup used, I am studying LAE and UV-continuum selected galaxies at $0.67 < z < 1.12$.

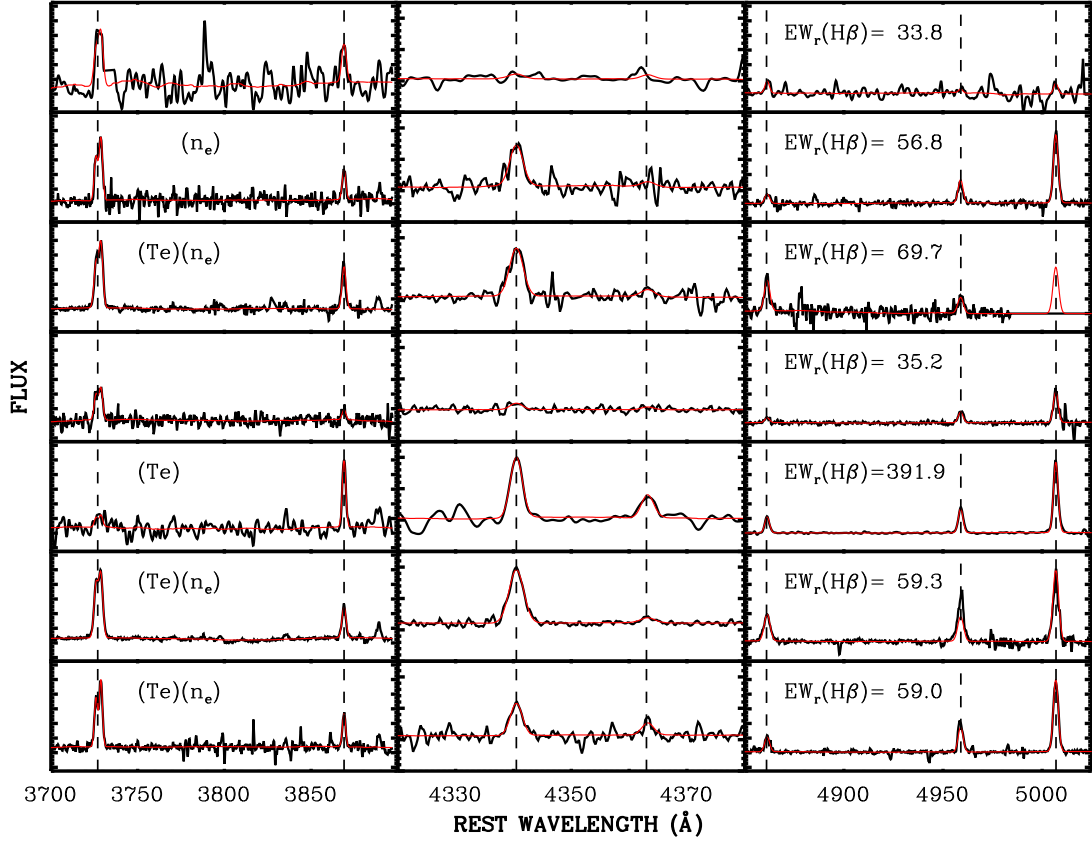


Fig. 5.1. — : 14 LAE spectra with $EW_r(H\beta) \geq 30 \text{ \AA}$ and $S/N(EW_r(H\beta)) \geq 3$. For each spectrum I show three spectral regions and my fitted $[OII]\lambda\lambda 3726, 3729$, $[NeIII]\lambda 3869$, $H\gamma$, $[OIII]\lambda 4363$, $H\beta$, and $[OIII]\lambda\lambda 4959, 5007$ emission lines (red). Spectra labeled with ‘(Te)’ have computed direct metallicities. Spectra labeled with ‘(n_e)’ have measured $[OII]\lambda 3726$ to $[OII]\lambda 3729$ ratios.

5.2.1 Emission Line Fits

For each spectrum (45 LAE and 595 UV-continuum selected spectra), I first removed any continuum flux with a sliding 200 pixel median. My final sample will only contain strong emission line objects, and I do not correct for stellar absorption which will generally only reach equivalent widths of $5 \text{ \AA}$ (Tremonti et al. 2004). I then select a $200 \text{ \AA}$ rest-frame region containing $[OII]\lambda\lambda 3726, 3729$ and $[NeIII]\lambda 3869$, an $80 \text{ \AA}$ rest-frame region containing $H\gamma$ and $[OIII]\lambda 4363$, and a $200 \text{ \AA}$ rest-frame region containing $H\beta$ and $[OIII]\lambda\lambda 4959, 5007$. In the blue spectral region, I fit 5 free pa-

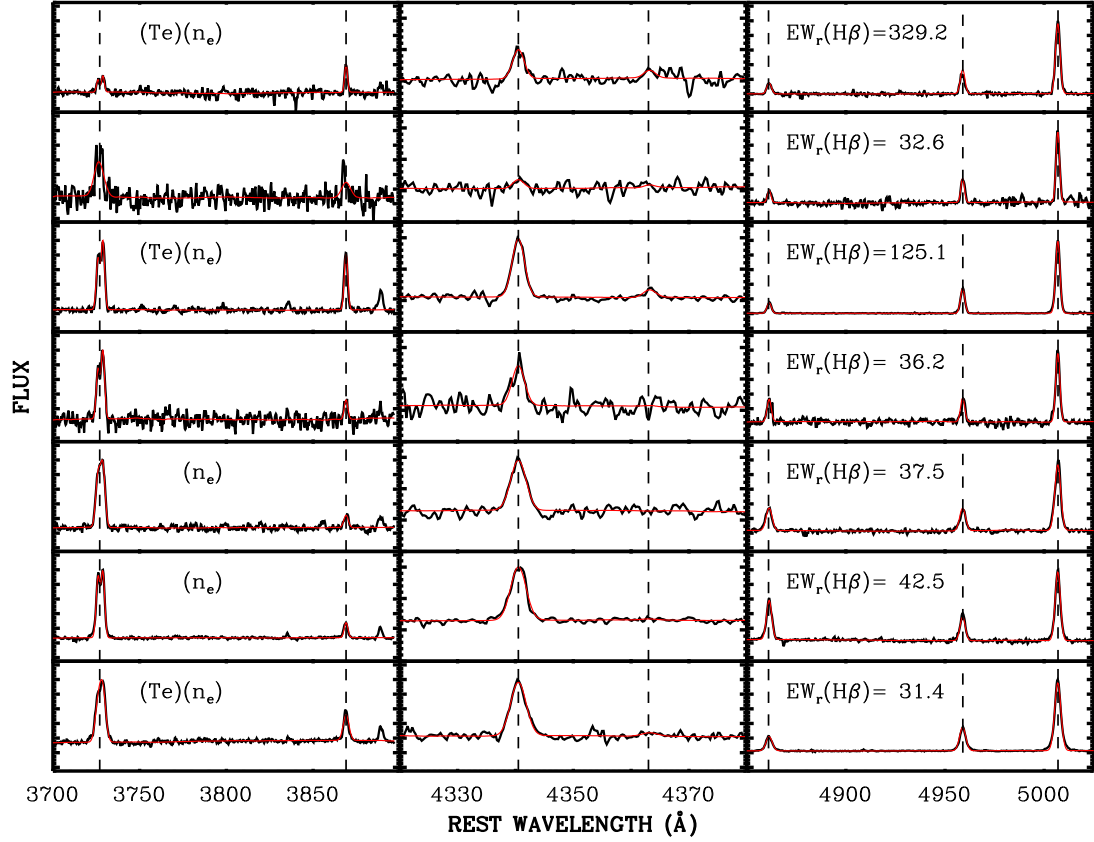


Fig. 5.1. — : (continued)

rameters (Gaussian central wavelength, FWHM, $[\text{OII}]\lambda\lambda 3726, 3729$ and $[\text{NeIII}]\lambda 3869$ line flux). The $[\text{OII}]\lambda 3736$ to $[\text{OII}]\lambda 3739$ ratio may vary from $2/3$ (low density limit) to $10/3$ (high density limit). In the middle spectral region, I fit 4 free parameters (Gaussian central wavelength, FWHM, $\text{H}\gamma$, and $[\text{OIII}]\lambda 4363$ line flux). In the red spectral region, I fit 4 free parameters (Gaussian central wavelength, FWHM, $\text{H}\beta$ and $[\text{OIII}]\lambda 4959$ line flux). I fix the $[\text{OIII}]\lambda 5007$ to $[\text{OIII}]\lambda 4959$ ratio at 2.9 (the ratio of their transition probabilities). The results of these fits applied to my final LAE and UV-continuum selected samples (all objects with $\text{EW}_r(\text{H}\beta) \geq 30 \text{ \AA}$ and $\text{S/N}(\text{EW}_r(\text{H}\beta)) \geq 3$) are shown in Figures 5.1 and 5.2.

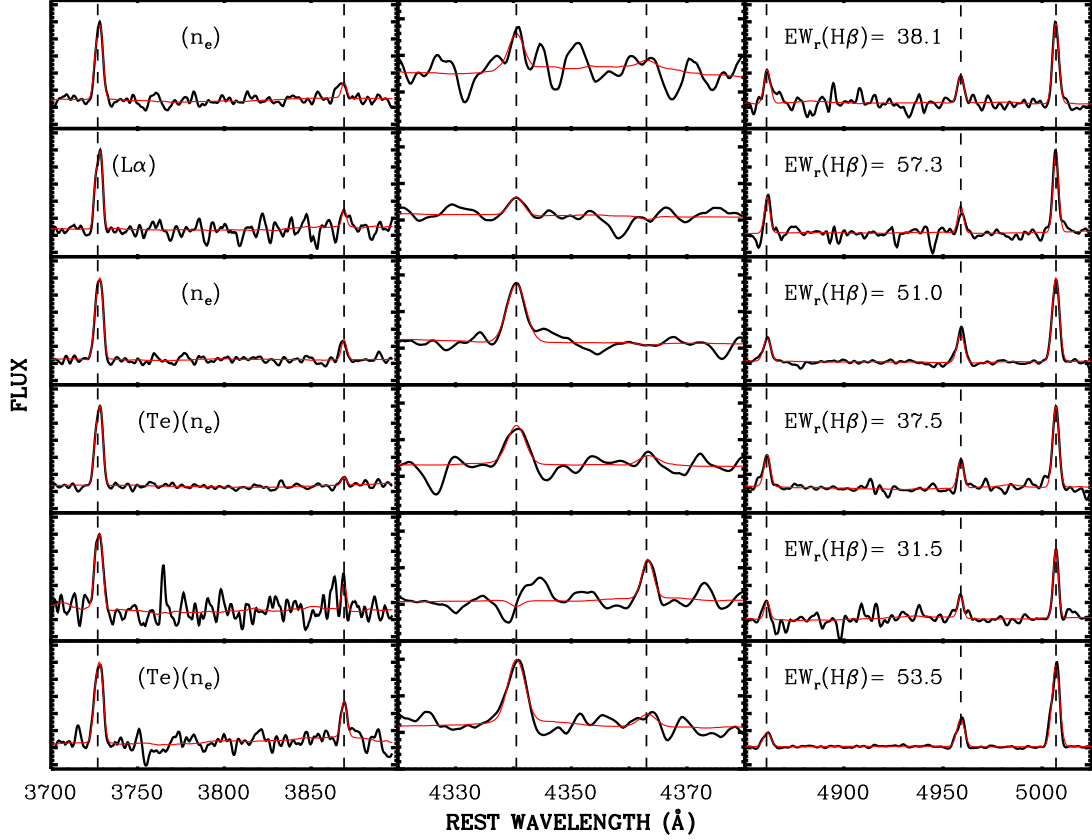


Fig. 5.2. — : 30 UV-continuum selected spectra with $EW_r(H\beta) \geq 30\text{\AA}$ and $S/N(EW_r(H\beta)) \geq 3$. Spectra labeled with ‘(L α)’ have $EW_r(Ly\alpha) \geq 20\text{\AA}$. Spectra labeled with ‘(Te)’ have computed direct metallicities. Spectra labeled with ‘(n_e)’ have measured [OII] λ 3726 to [OII] λ 3729 ratios.

5.2.2 Equivalent Width Sample Selection

High equivalent width Balmer line sources will contain the youngest, lowest metallicity galaxies in both the LAE and UV-continuum selected samples (e.g., Leitherer et al. 1999; Hu et al. 2009; Cowie et al. 2011). These low metallicity sources will have relatively strong [OIII] λ 4363 emission, which is the limiting factor for measuring “direct” metallicities. With deeper spectroscopic observations, I will be able to compute metallicities without an $EW(H\beta)$ selection, which is important for determining how the LAEs are drawn from the underlying population. However, with

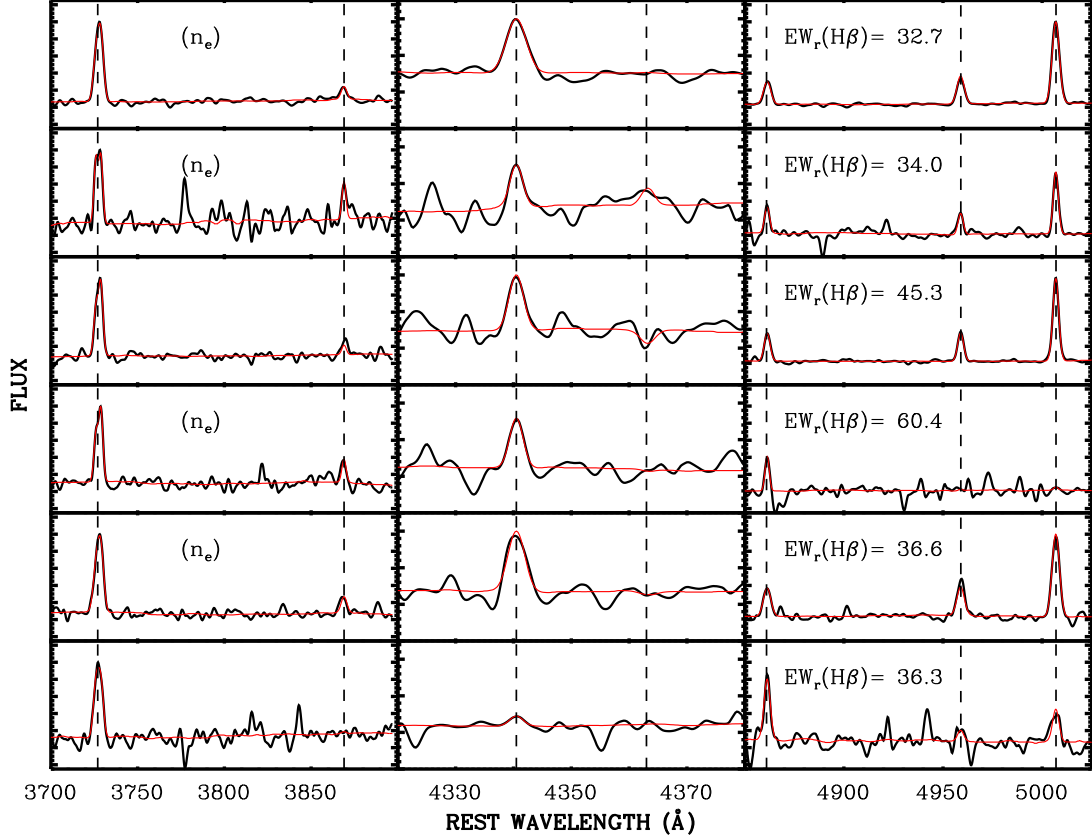


Fig. 5.2. — : (continued)

the currently available data, I am only able to analyze the higher $EW(H\beta)$ objects.

From my library of DEIMOS spectra, I select strong emission-line galaxies with rest-frame $EW(H\beta) > 30 \text{ \AA}$ and $S/N(EW(H\beta)) \geq 3$ from both the LAE and UV-continuum selected sample. The $EW(H\beta)$ was computed by dividing the $H\beta$ line flux by the spectral continuum flux density. The continuum flux density was computed by taking the median of the continuum within two $50 \text{ \AA}$ rest-frame regions that bracket the $H\beta$ line. These EWs are then divided by a factor of $(1+z)$ to obtain rest-frame values. In Figure 5.1, I show all spectra in my final LAE sample. In Figure 5.2, I show all spectra in my final UV-continuum selected sample. With deeper optical spectra that I will obtain in upcoming observing runs, I will investigate the feasibility

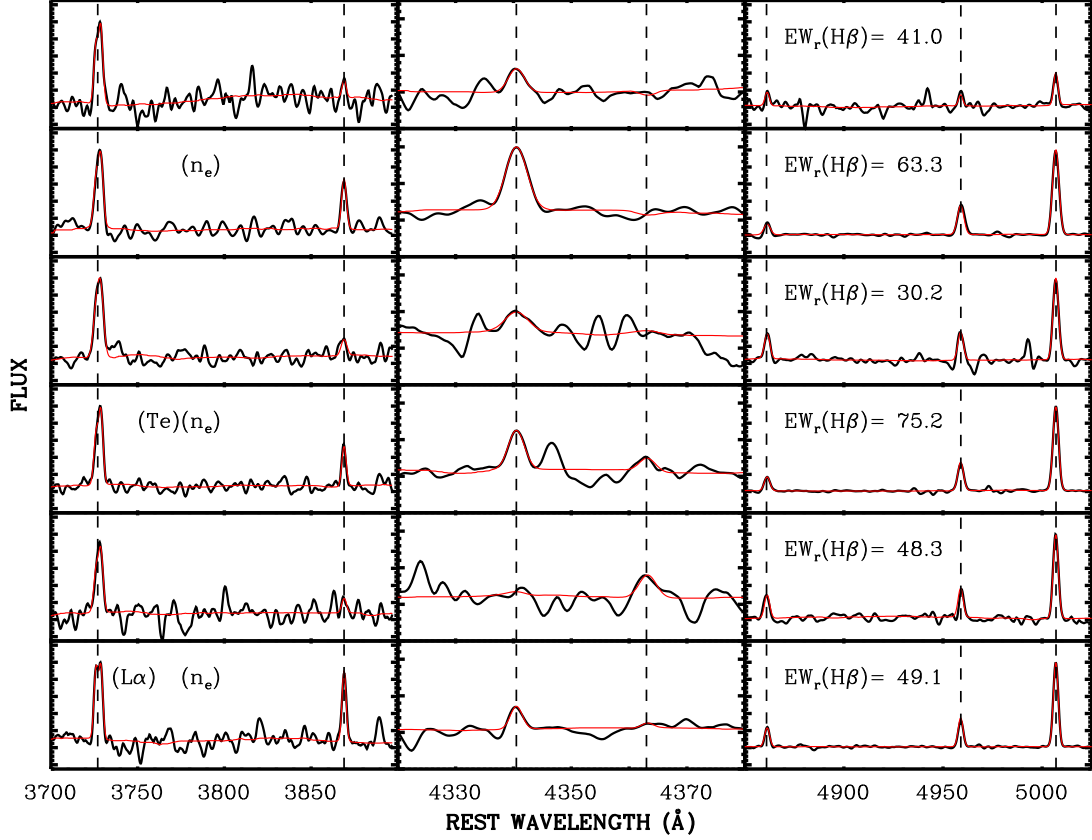


Fig. 5.2. — : (continued)

of relaxing this initial $EW(H\beta) > 30$ Å sample selection.

5.2.3 Sample Verification

Based on completeness simulations described in Wold et al. (2014), my *GALEX* NUV data cube search method should detect all LAEs above a Ly α line flux of $\sim 2 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$. I test this expectation by extracting NUV spectra for my UV-continuum selected sample and fitting Gaussians at the wavelength where Ly α would exist if present. The results of this exercise are shown in Figure 5.3. With the exception of one object, I find that my data cube search for LAEs has performed as expected. Furthermore, the highest Ly α flux UV-continuum selected object at

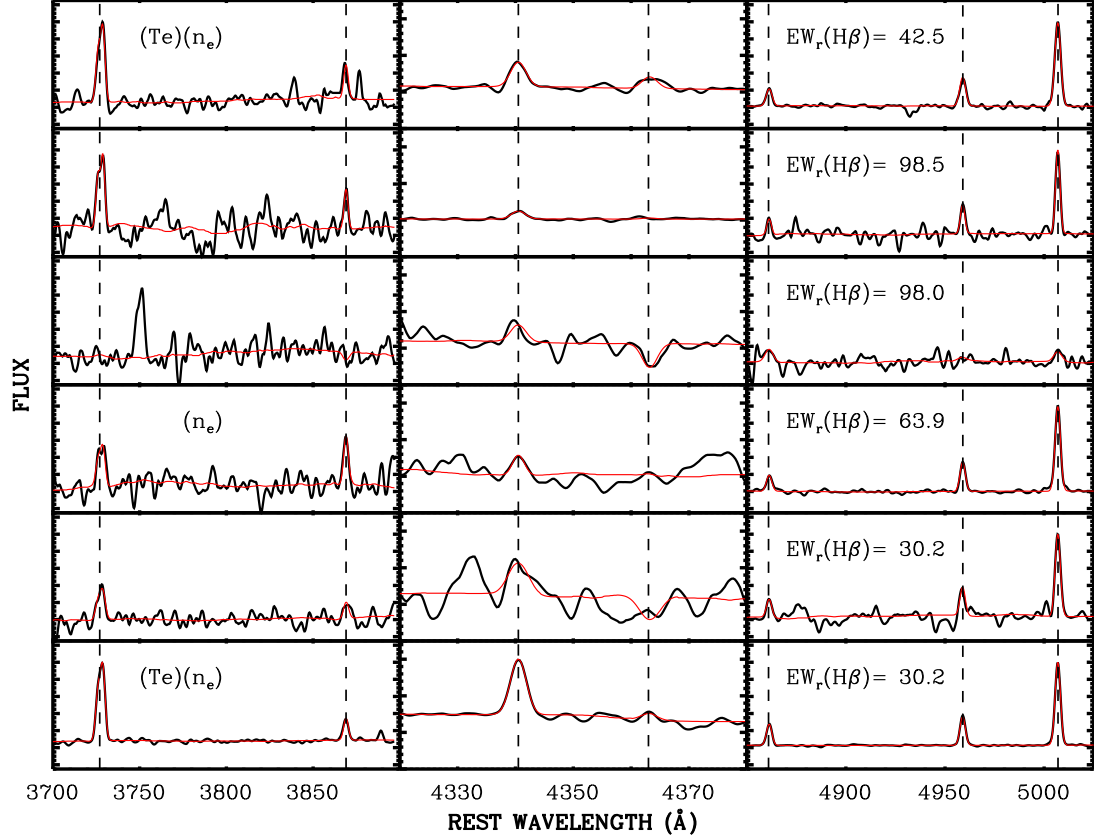


Fig. 5.2. — : (continued)

$\sim 5 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ is not real based on inspection of its 2-D *GALEX* spectrum. I inspected each object by hand and found only three UV-continuum selected objects with clear Ly α emission (all with measured Ly α fluxes of $\sim 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$).

Of these three UV-continuum selected objects with clear Ly α emission, two objects meet my definition of a LAE ($\text{EW}_r(\text{Ly}\alpha) \geq 20 \text{ \AA}$), and I remove these two objects from my final UV-continuum selected sample. This results in a final LAE sample size of 14 and a final UV-continuum selected sample size of 28.

In Figure 5.4, I compare the weighted average NUV spectrum of the LAE sample (red spectrum) with that of the UV-continuum selected sample (blue spectrum). I also show the weighted average NUV spectrum of the two LAEs found in the UV-

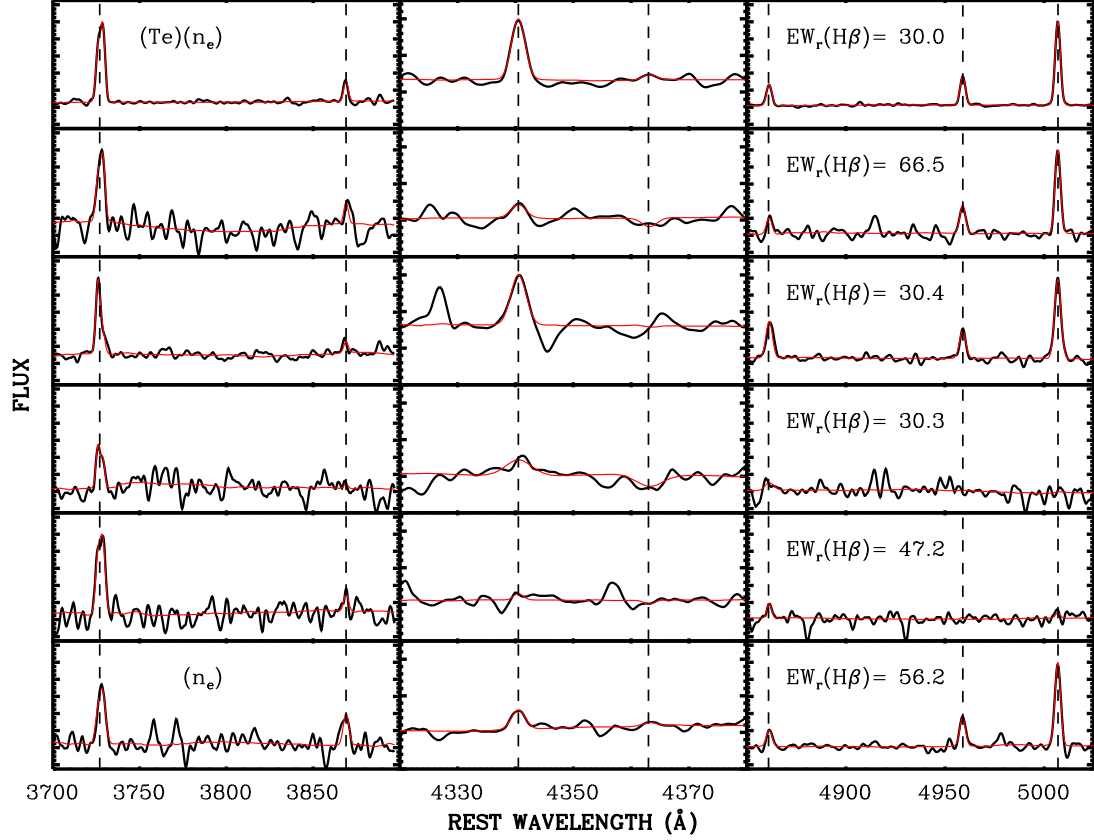


Fig. 5.2. — : (continued)

continuum selected sample (green spectrum). I find that my averaged UV-continuum selected spectrum has no clear Ly α emission. This spectrum could be representative of the UV-continuum selected objects, or this could be produced by a mixture of Ly α emission and absorption. I note that the continuum level for the averaged LAE spectrum is slightly higher than that of the UV-continuum selected spectrum, especially blueward of 1200 Å. This higher LAE continuum level in the rest-frame FUV is also noted for the $z \sim 0.3$ sample (see Figure 5, Cowie et al. 2011). Whether this is a selection effect or an intrinsic difference between LAEs and UV-continuum selected objects will be investigated in future work.

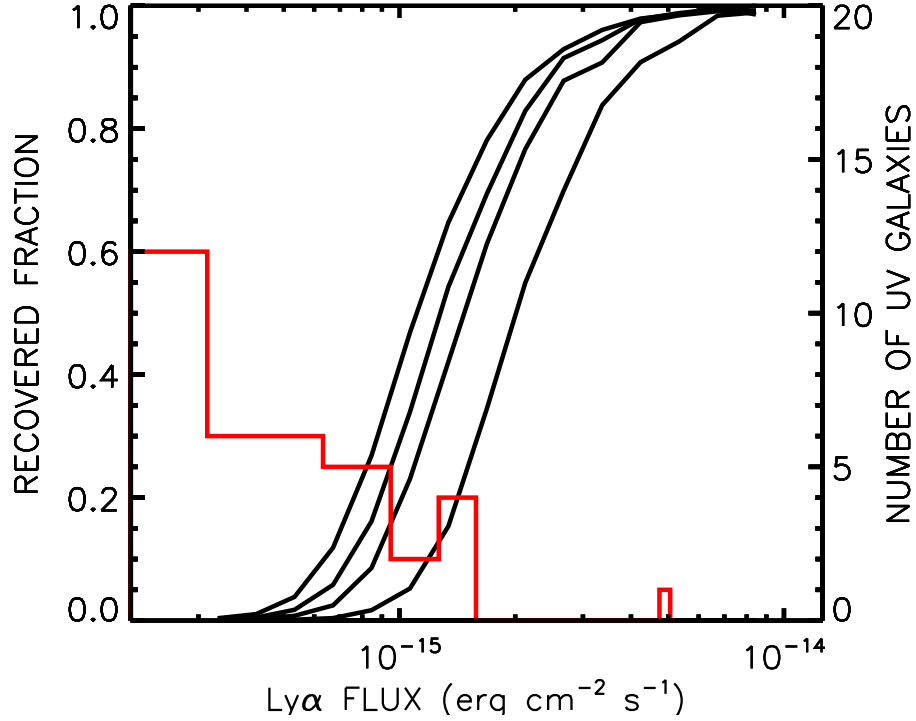


Fig. 5.3. — : Black curves show the fraction of simulated sources recovered as a function of the emission-line flux for each *GALEX* field. The red histogram shows the number of UV-continuum selected objects in my final sample as a function of $\text{Ly}\alpha$ flux.

5.3 $\text{H}\beta$ Equivalent Width Distribution

In Figure 5.5, I show the LAE and UV-continuum selected rest-frame $\text{EW}(\text{H}\beta)$ distribution. Fitting the rest-frame EW distributions with exponential functions, I find that the LAE distribution has a scale length of $66 \pm 30 \text{ \AA}$, while the UV-continuum selected distribution has a scale length of $18 \pm 4 \text{ \AA}$. I determined the scale length using the maximum likelihood method, and I computed the error using the parameterized bootstrap method. Given the large error in scale lengths, more data are needed to confidently state that the two EW distributions differ. This is reflected by the two-sided Kolmogorov-Smirnov statistic. A Kolmogorov-Smirnov test shows

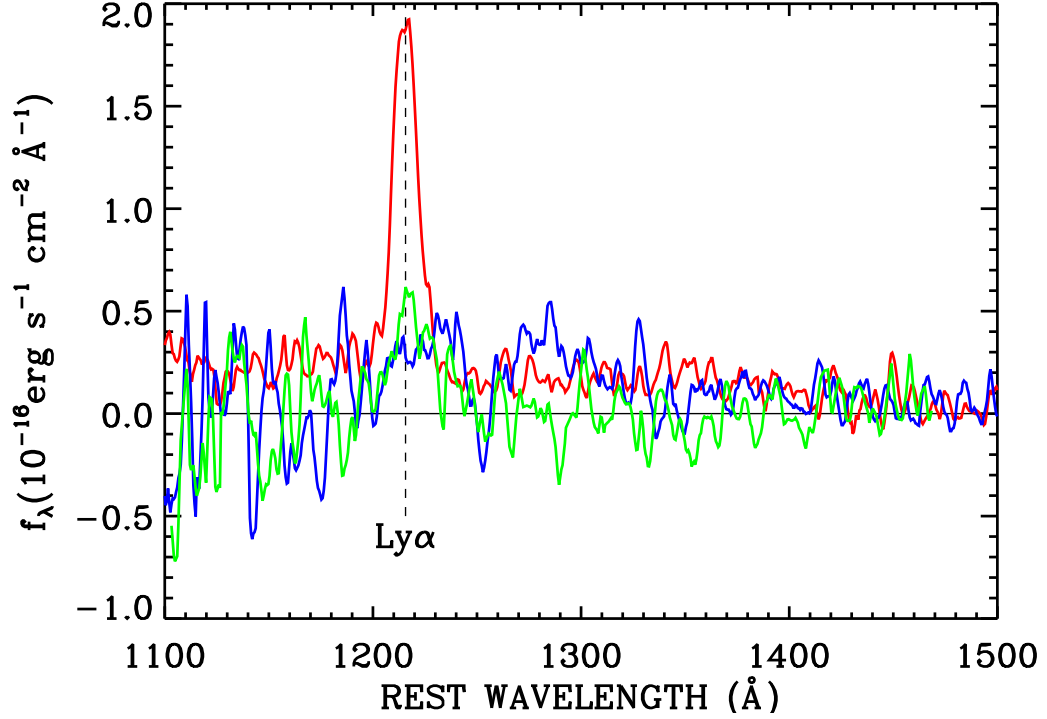


Fig. 5.4. — : Weighted average *GALEX* NUV spectra for my final LAE (red) and UV-continuum selected (blue) samples. Two UV-continuum selected galaxies with $\text{EW}_r(\text{Ly}\alpha) \geq 20\text{\AA}$ are excluded from the averaged spectrum. The weighted average spectrum from these two objects is shown in green.

that the two distributions do not differ at the 0.54 probability level.

5.4 NUV and Redshift Distribution

In Figure 5.6, I compare the LAE (red) and UV-continuum selected (blue) NUV distribution. For the LAE NUV measurements, I subtracted the $\text{Ly}\alpha$ flux from the cataloged NUV magnitudes. Thus, Figure 5.6 is comparing the continuum NUV magnitudes for both samples. Consistent with Figure 5.4, I find that the LAEs are on average slightly brighter than the UV-continuum selected sample. The mean LAE cataloged NUV magnitude is 22.8; while the mean LAE NUV magnitude with $\text{Ly}\alpha$ emission subtracted is 23.0. The mean UV-continuum selected NUV magnitude is

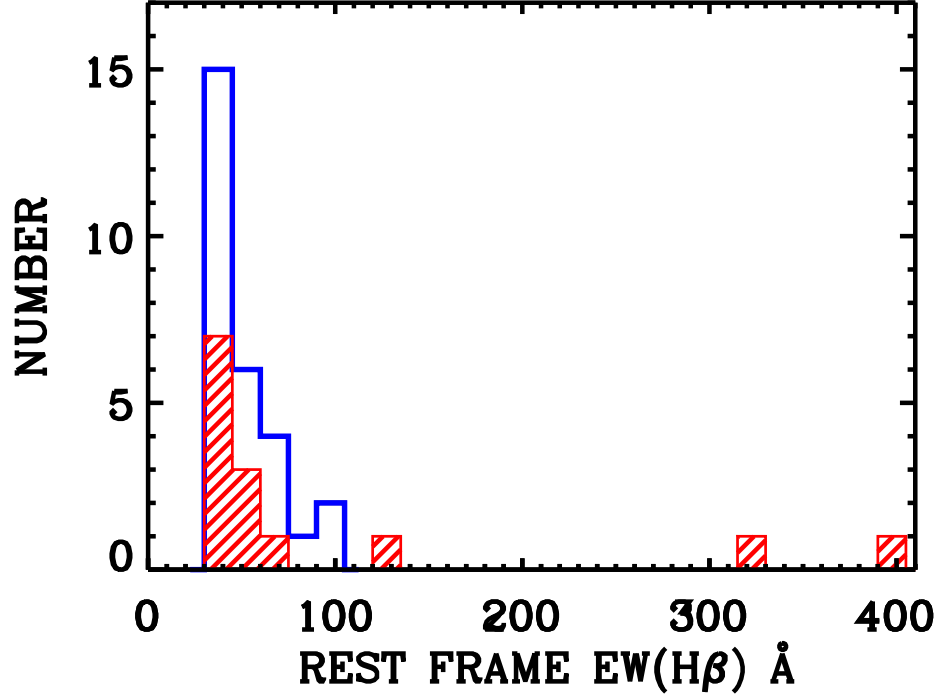


Fig. 5.5. — : LAE (red) and UV-continuum selected (blue) rest-frame $\text{EW}(\text{H}\beta)$ histograms.

23.9. Using the mean redshift for each sample, I computed the NUV magnitudes from the stacked spectra (Figure 5.4). These computed NUV magnitudes agree with the values listed above ± 0.1 magnitude.

In Figure 5.7, I compare the LAE (red) and UV-continuum selected (blue) redshift distributions. I note that the UV-continuum selected objects are on average at a lower redshift ($z_{\text{av}} = 0.80$ for the UV-continuum selected sample; $z_{\text{av}} = 0.86$ for the LAE sample).

In Figure 5.8, I show the absolute NUV magnitude distributions for both the LAE and UV-continuum selected samples. The absolute NUV magnitude distribution for the UV-continuum selected sample has been corrected for incompleteness and

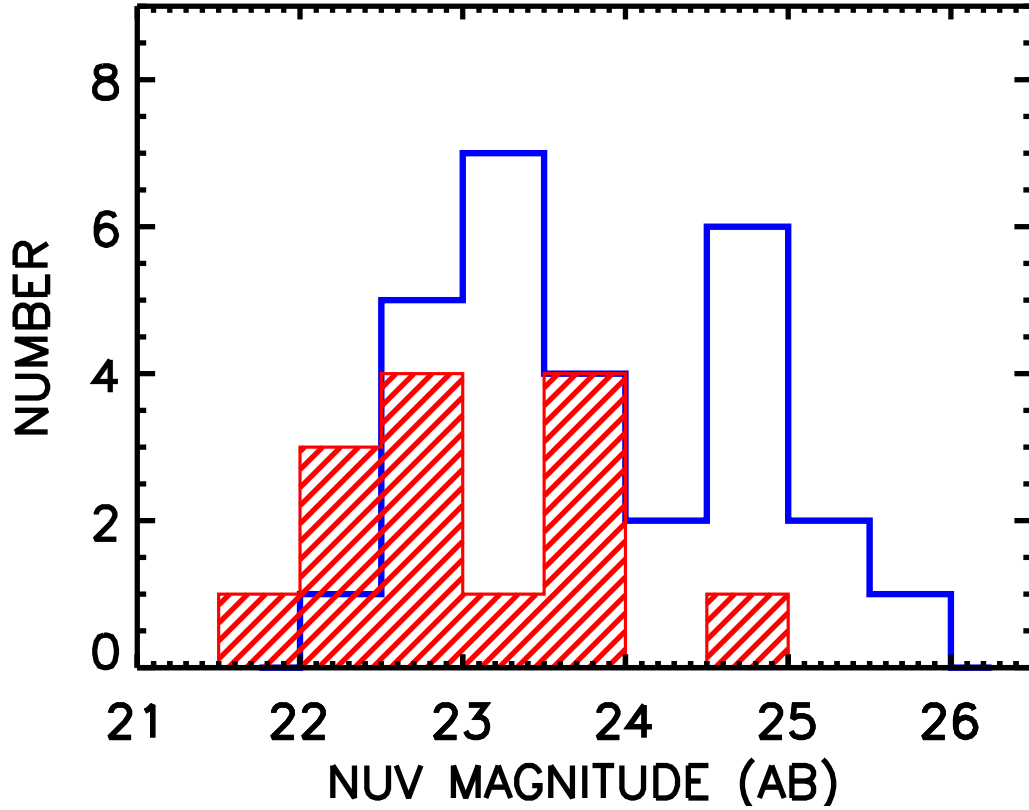


Fig. 5.6. — : LAE (red) and UV-continuum selected (blue) NUV histograms.

normalized to a sample size of 28 (the current UV-continuum selected sample size). To compute the corrected distribution, I calculate incompleteness factors (number of observed UV-continuum selected objects per number of total – both observed and not observed – UV-continuum selected objects) as a function of NUV magnitude. I then assign a weighting factor ($1/\text{incompleteness}$) to each $\text{EW}(\text{H}\beta) > 30 \text{ \AA}$ UV-continuum selected object based on its NUV magnitude bin. I calculate the absolute NUV magnitude for each $\text{EW}(\text{H}\beta) > 30 \text{ \AA}$ UV-continuum selected object. Finally, I form the corrected absolute NUV magnitude distribution by summing the weights for all UV-continuum selected objects falling within any given absolute NUV magnitude bin. I find that the average LAE is one magnitude brighter than the average

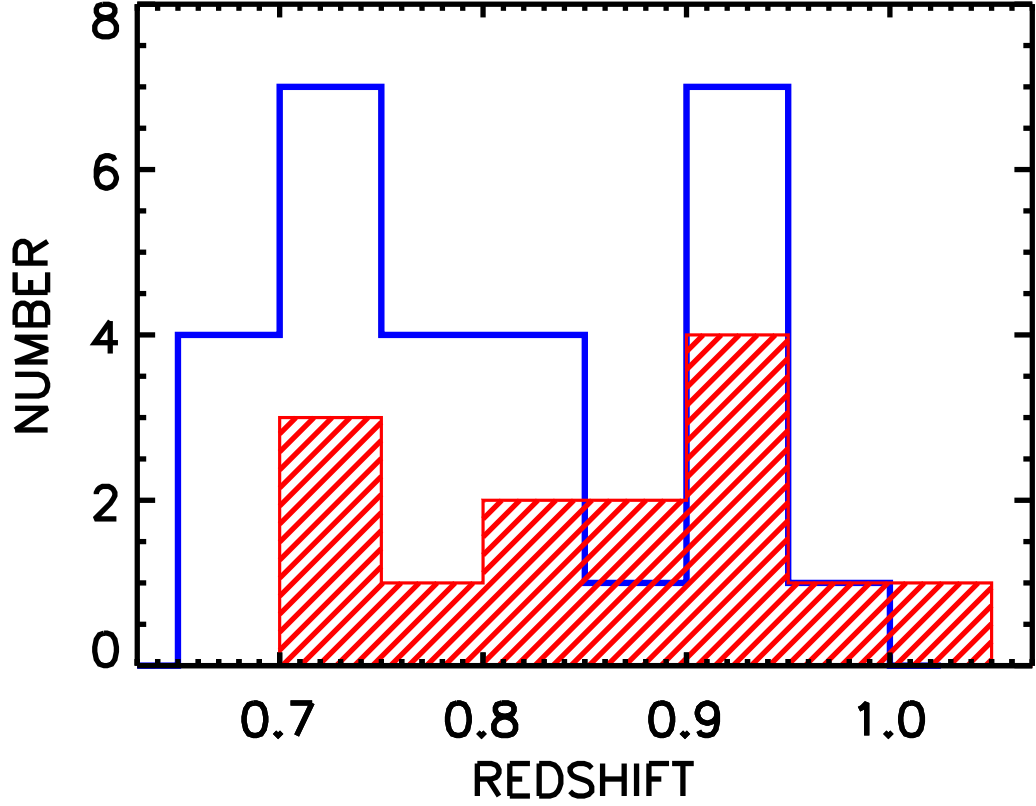


Fig. 5.7. — : LAE (red) and UV-continuum selected (blue) redshift histograms.

UV-continuum selected object.

5.5 Direct Metallicity and Ionization Parameter

From my LAE and UV-continuum selected samples, I have selected galaxies with $z = 0.67-1.12$, rest-frame $\text{EW}(\text{H}\beta) > 30 \text{ \AA}$ and $[\text{OIII}]\lambda 4363$ line flux with $\text{S/N} \geq 3$ to measure direct metallicities. The direct or T_e method (e.g., Izotov et al. 2006; Kakazu et al. 2007; Hu et al. 2009) derives the electron temperature from the ratio of the $[\text{OIII}]\lambda 4363$ line to $[\text{OIII}]\lambda 5007$, which can be used to obtain the O abundance. This is considered to be the most accurate method for determining O/H metallicity, with errors in relative T_e abundances likely to be $\ll 0.1$ dex. However, the uncertainty in absolute T_e abundances are still estimated to be ~ 0.1 dex (Kewley

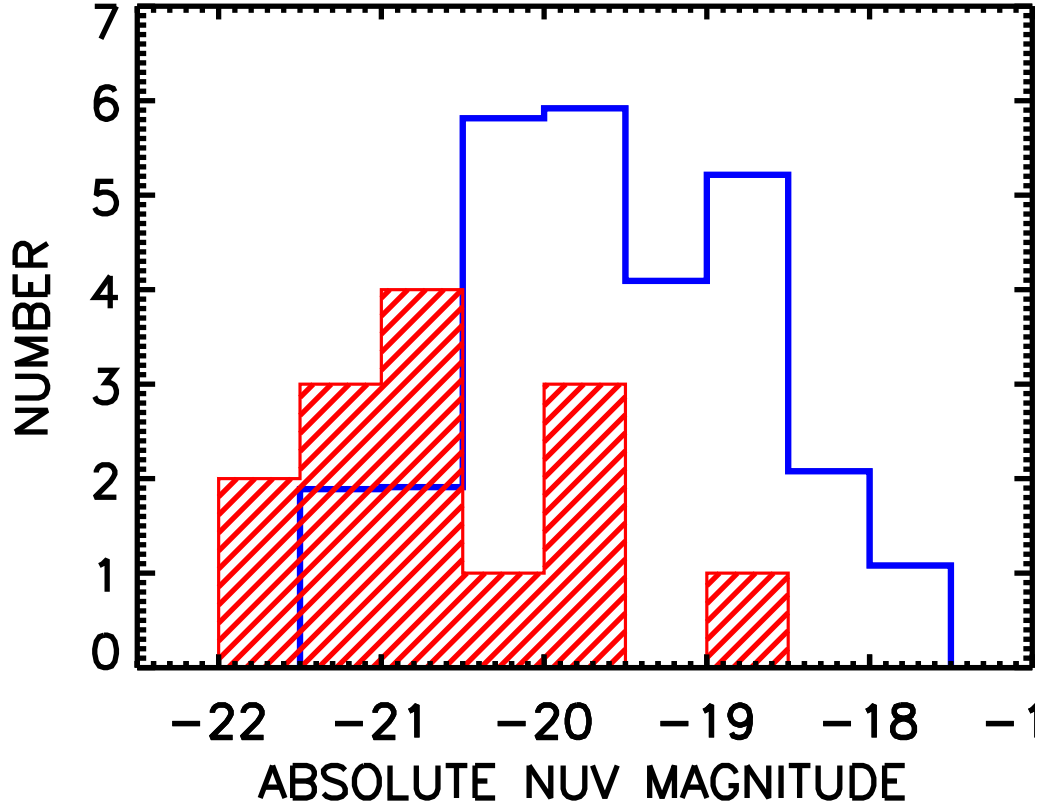


Fig. 5.8. — : LAE (red) and UV-continuum selected (blue) absolute NUV magnitude histograms corrected for incompleteness.

& Ellison 2008).

Over short wavelength ranges the DEIMOS response is essentially constant, allowing me to measure the relative line fluxes of neighboring lines. Given the proximity of $H\beta$ to $[\text{OIII}]\lambda\lambda 4959, 5007$ and the proximity of $H\gamma$ to $[\text{OIII}]\lambda 4363$, I determined extinction-corrected $[\text{OIII}]\lambda 4363$ fluxes by assuming case B recombination:

$$f([\text{OIII}]\lambda 4363) = 0.469 \left[\frac{f_{\text{OBS}}(H\beta)}{f_{\text{OBS}}(H\gamma)} \right] f_{\text{OBS}}([\text{OIII}]\lambda 4363).$$

I did not perform a Balmer line correction on the $[\text{OII}]\lambda 3727$ line because the higher order Balmer lines are too weak. Conservatively, I adopted a 50% error in the measurement of the $[\text{OII}]\lambda 3727$ line flux.

Using these line fluxes, I computed the direct abundances using the Izotov et al. (2006) formulae, which were developed with the latest atomic data and photoionization models, and I assumed an electron number density of 100 cm^{-3} . The choice of electron density has little effect on the metallicity calculation, as electron temperature is insensitive to the electron density.

In Figure 5.9, I show direct $12+\log(\text{O}/\text{H})$ versus rest-frame $\text{EW}(\text{H}\beta)$ for both LAE (red) and UV-continuum selected (blue) samples. In this figure I also display a histogram showing the number of rest-frame $\text{EW}(\text{H}\beta) > 30 \text{ \AA}$ objects without a $\text{S/N} \geq 3$ in $[\text{OIII}]\lambda 4363$ line flux. For this preliminary sample, I note no strong anti-correlation of $12+\log(\text{O}/\text{H})$ and rest-frame $\text{EW}(\text{H}\beta)$. Further data are needed to investigate whether the tight anti-correlation seen in the $z \sim 0.3$ sample (see Cowie et al. 2011, Figure 9f) is no longer present in my $z \sim 1$ sample. I note that my $z \sim 1$ sample is probing metallicities about 0.5 dex lower than the $z \sim 0.3$ sample.

I computed the ionization parameters (q) for this sample using the parameterized forms of the dependence of $[\text{OII}]\lambda 3727/[\text{OIII}]\lambda 5007$ on q and $12+\log(\text{O}/\text{H})$ from Kobulnicky & Kewley (2004). The ionization parameter is defined as the ratio of the mean ionizing photon flux to the mean hydrogen atom density. It provides a rough estimate of the age of the galaxy since short-lived massive stars are the dominant source of ionizing flux. I find $\log(q)$ values ranging from 7.2 to 8.9 with an increasing trend with $\text{EW}(\text{H}\beta)$. This is not surprising given the correlation between Balmer line equivalent widths and galaxy age (e.g., Leitherer et al. 1999). These observed values are similar to the high ionization parameters reported for two LAEs at $z = 2.2$ ($\log(q) = 7.9$ and $= 8.4$; Nakajima et al. 2013).

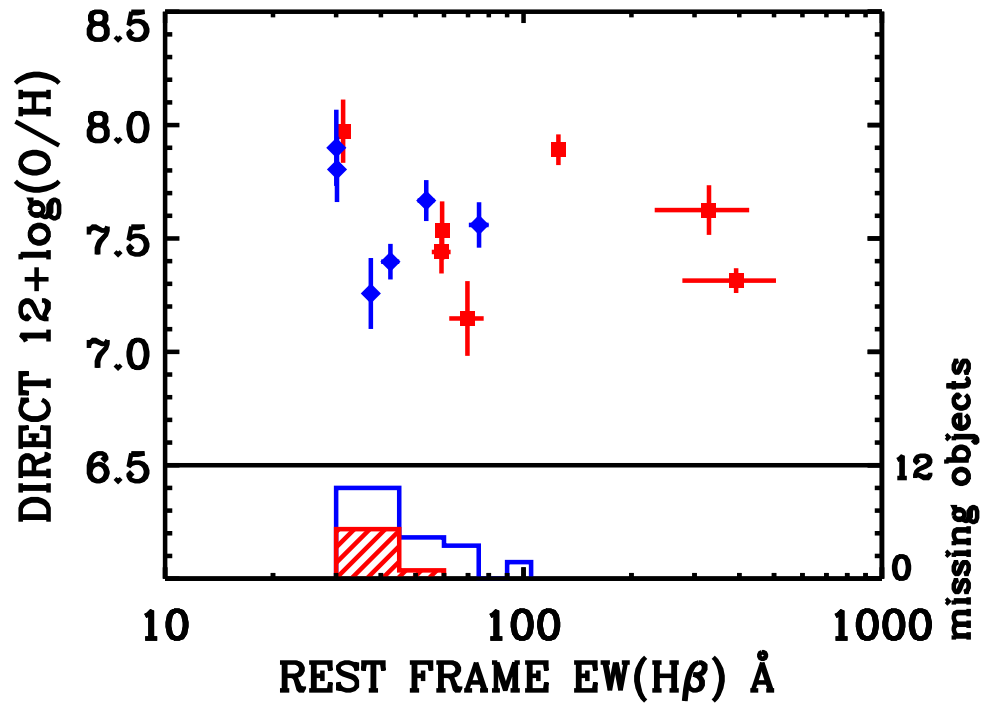


Fig. 5.9. — : Direct $12+\log(\text{O}/\text{H})$ vs. rest-frame $\text{EW}(\text{H}\beta)$ for galaxies with rest-frame $\text{EW}(\text{H}\beta) > 30 \text{ \AA}$, $[\text{OIII}]\lambda 4363$ line flux with $\text{S/N} \geq 3$, and redshifts within the $z = 0.67\text{--}1.12$ interval. These include the optically confirmed $\text{Ly}\alpha$ emitters (red squares) and the optically confirmed UV-continuum selected galaxies (blue diamonds).

5.6 Density

The combined effect of supernovae and stellar winds in starburst galaxies are thought to be able to generate an over-pressurized, high-central-density bubble of hot gas which may drive a galaxy-wide superwind. For example, the local starburst galaxy M82 is found to have central densities on the order of 10^3 cm^{-3} (Westmoquette et al. 2009), while the Milky Way has densities roughly four orders of magnitude lower. Many studies have suggested that LAEs are starbursting galaxies with outflows. Here, I investigate if there is an observable difference between the electron densities observed in my LAE and UV-continuum selected sample.

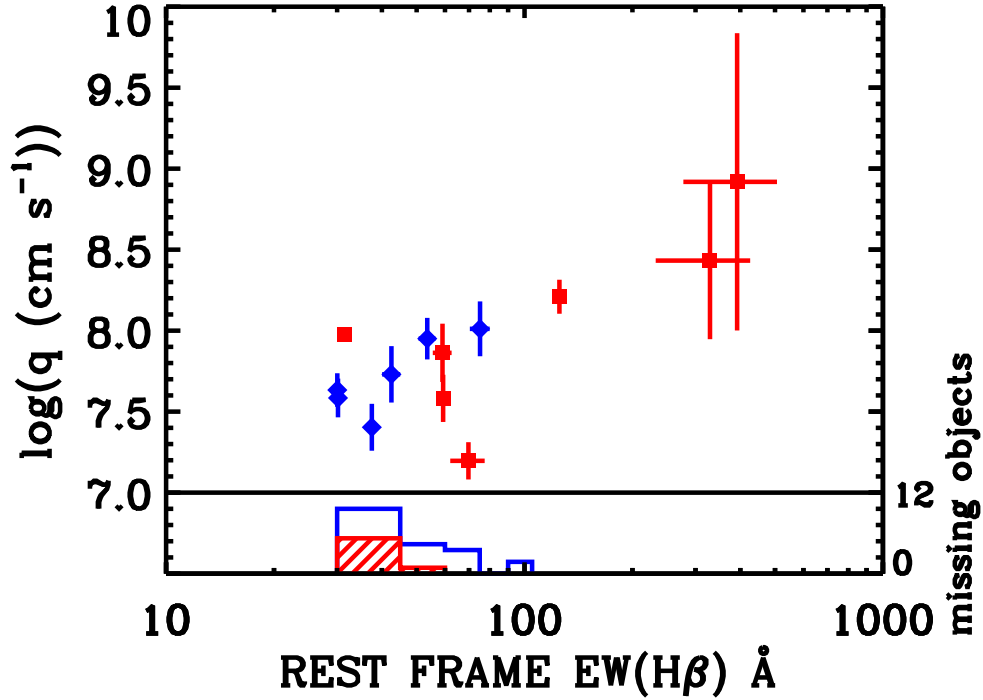


Fig. 5.10. — : LAE (red) and UV-continuum selected (blue) ionization parameters vs. rest-frame $\text{EW}(\text{H}\beta)$ for objects with direct metallicity measurements.

In Figure 5.11, I show the $[\text{OII}]\lambda 3726/[\text{OII}]\lambda 3729$ (a sensitive density diagnostic) distribution for my LAE and UV-continuum selected sample with $[\text{OII}]\lambda 3726$ and $[\text{NeIII}]\lambda 3869$ $\text{S/N} \geq 10$. I simultaneously fit the $[\text{OII}]$ and $[\text{NeIII}]$ lines. Having a $[\text{NeIII}]$ line with $\text{S/N} \geq 10$ helps to clearly define the Gaussian central wavelength and the Gaussian FWHM free parameters. I find that LAEs have on average a much higher density ($\text{mean}(n_e) \sim 250 \text{ cm}^{-3}$) than found in my UV-continuum selected sample ($\text{mean}(n_e) \sim 70 \text{ cm}^{-3}$). I note that my observed $[\text{OII}]$ doublets are blended (see Figure 5.1 and 5.2) and that most of the UV-continuum selected objects are pegged to the lowest $[\text{OII}]\lambda 3726/[\text{OII}]\lambda 3729$ value allowed by my fitting routine. However, I emphasize that the same fitting routine was performed on both the LAE

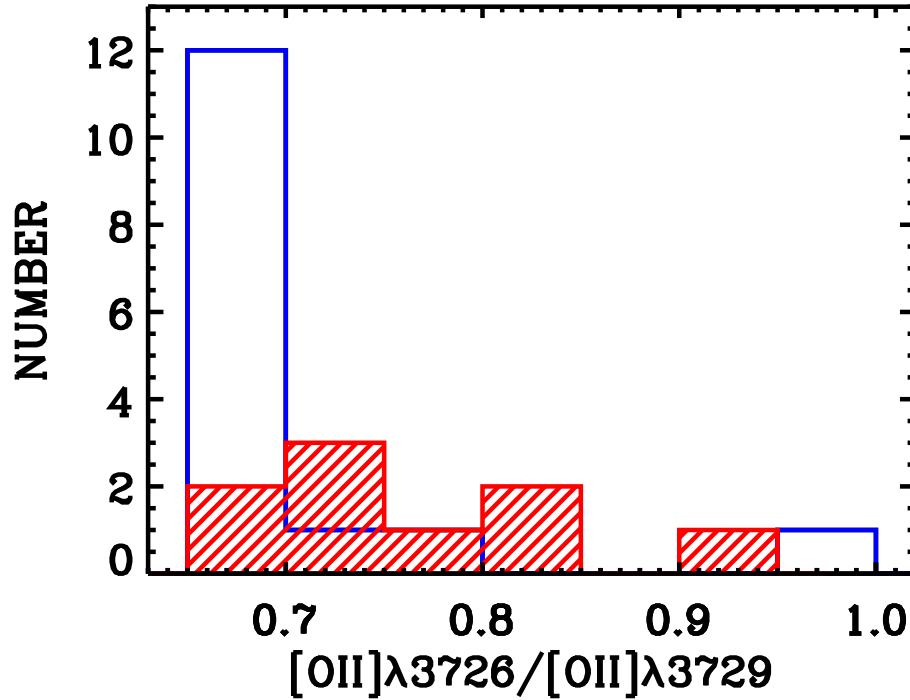


Fig. 5.11. — : LAE (red) and UV-continuum selected (blue) $[\text{OII}]\lambda 3726/[\text{OII}]\lambda 3729$ histograms for objects with $[\text{OII}]\lambda 3726$ and $[\text{NeIII}]\lambda 3869$ line fluxes with $S/N \geq 10$.

and UV-continuum samples. Additional sample size and a subset of observations with higher spectral resolution would put this tentative result on firmer ground.

5.7 Summary

At high redshifts ($z \gtrsim 5-6$), nearly 100% of star-forming galaxies are thought to be LAEs; however, their properties are extremely hard to constrain. At $z \sim 1$, the intrinsic galaxy structure can be separated from the effects of the intergalactic medium. This is also the first redshift where LAEs comparable in luminosity to the high-redshift LAEs are seen. My thesis provides the first large sample of $z \sim 1$ LAEs. I have shown that it is possible to construct a LAE and UV-continuum selected sample from which various physical properties can be investigated. With

deeper data obtained from my upcoming observing runs, I will use the techniques outlined here to investigate the emission-line properties of $z \sim 1$ LAEs. This study will serve as an important reference point for studies of high-redshift LAEs.

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