Evidence for Large-Scale Structure at $z \approx 2.4$ From Lyman $\alpha$ Imaging

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ABSTRACT

The history of large-scale structure depends on cosmological parameters and on how merging unfolds among both galaxies and groups. There has been recent evidence for clustering among Lyman-α emitters, Lyman-break galaxies, and Lyman absorbers. We present deep wide-field medium-band imaging in redshifted Lyman α of fields surrounding regions selected to have HST detections of faint Lyman α emitters, over a range of surface densities, to characterize the larger-scale environment. The radio galaxy 53W002 was previously found using HST to be part of a rich grouping at $z = 2.39$, including $\approx 5$ spectroscopically confirmed, compact, lower-luminosity star-forming objects. Our new data show this to be part of a larger structure traced by bright active nuclei, all contained within a projected span of 6.8′ (3.2 Mpc). Of the 14 candidate emitters, six have been spectroscopically confirmed as active nuclei in the range $z = 2.390 \pm 0.008$. Various statistical tests give a significance of 95-99% for the reality of this structure on the sky. Our data thus strengthen the evidence for clustering at these redshifts.

The grouping around 53W002 is more extended than a relaxed King model, at the 90% confidence level. This may be evidence either for a configuration which has yet to decouple fully from the Hubble expansion, or for multiple subgroupings which will themselves at some point form a more compact, relaxed structure. The redshift range for measured members is comparable to the Hubble flow across the structure, which may imply that the structure is seen near turnaround and suggests that its mass cannot be derived from the velocity dispersion.

We surveyed two additional 14′ fields at $z = 2.4$, each centered on an HST WFPC2 field which has been searched for faint Lyman α emitters, as well as
three contiguous fields near 53W002 for objects at $z \sim 2.55$. Only a single emitter consistent with showing Lyman $\alpha$ at $z \approx 2.4$ appears in these fields, to a somewhat brighter flux limit, while a total of six candidate emitters appear in the three fields at $z \sim 2.6$. Comparison with the (deeper but narrower) WFPC2 surveys suggests that the surface-density contrast from field to field is larger for brighter objects. From this survey alone, groupings such as the 53W002 “cluster” must have an area covering fraction $< 0.04$ in this redshift range.

Three of the AGN in the structure at $z = 2.4$ show extended emission-line structure, with equivalent widths suggesting $in situ$ photoionization as far as 50 kpc from the nuclei. Such objects may populate deep surveys as diffuse Lyman $\alpha$ emission clouds when their cores are sufficiently obscured.
1. Introduction

As our ability to measure galaxy evolution has grown, so has the possibility of observing how galaxy clustering has evolved. On various linear scales, this is relevant to the merger rate of both galaxies (and perhaps their smaller progenitors) and groups, and to cosmological parameters. As reviewed recently by Cen (1998), the growth of representative cluster masses depends strongly on $\Omega_0$. This is due not to a direct relation between $\Omega_0$ and structure growth per se, but more to the fact that the calculations must be normalized to match the present-epoch mass spectrum, which introduces a coupling between the amplitude $\sigma_8$ of the power spectrum and $\Omega_0$ for viable models.

Several studies have indeed shown evidence for cluster-scale structures at redshifts $z > 2$. Our HST imaging (Pascarelle et al. 1996b, hereafter P96b; Pascarelle et al. 1998, hereafter P98), using a combination of broadband and medium-band filters to isolate Lyman $\alpha$ emission in the relevant redshift range, showed that the $z = 2.4$ radio galaxy 53W002 is part of a rich assemblage of Lyman $\alpha$ emitters. Most of these are compact (effective radius $r_e \approx 0.1$'' or 0.8 kpc), and are powered by star formation rather than by classical active nuclei. In P98, we showed that the surface density of such objects varies between different random lines of sight by approximately a factor of 4, with the 53W002 field being the richest we have observed thus far. A somewhat different grouping at similar redshift ($z = 2.38$) was identified by Francis et al. (1996, 1997), who found four Lyman $\alpha$ emitters very close to the redshifts of Lyman $\alpha$ absorbers seen against two background QSOs. These emitters are seen over a projected span of 0.63 Mpc, and are much redder than the objects found by P96b. In an analogous way, Malkan et al. (1995, 1996) used narrow-band near-infrared imagery to find three H$\alpha$-emitting objects at $z = 2.50$ in the foreground of the QSO SBS 0953+545 at $z = 2.58$, closely matching the redshifts of metal-line absorption systems seen in the QSO spectrum. Starting from a sample of Lyman-break galaxies, Steidel et
al. (1998, also Steidel 1999) have found a concentration of galaxies at \( z = 3.090 \pm 0.015 \) spanning about \( 4 \times 8 \) Mpc. And at even higher redshift, Hu & McMahon (1996) report spectroscopically-confirmed Lyman \( \alpha \) companions to the \( z = 4.55 \) QSO BR2237–0607.

These results show that it is now possible to trace developing clusters, and other large-scale structure, at high redshift. The new generation of wide-field imagers has enabled survey strategies that can tell how common, how extensive, and of what amplitude structures are in the galaxy distribution at various redshifts. As a first step in this direction, we present here a Lyman \( \alpha \) survey of large fields around the regions we have searched with \textit{HST}, to place the object counts from those fields in a larger context, and in particular to probe the spatial extent and bright end of the luminosity function of the cluster which includes 53W002.

In evaluating size and luminosity, we use \( H_0 = 80 \) km s\(^{-1}\) Mpc\(^{-1}\), \( q_0 = 1/2 \), which gives an angular scale of 128" per Mpc. Scaling for other values, linear sizes scale directly with \( H_0 \) and luminosities as \( H_0^2 \). For other values of \( q_0 \), as a shortcut, we note that linear sizes (luminosities) quoted here would be multiplied by 2.9 (8.2) for \( q_0 = 0.1 \) and by 0.49 (0.24) for \( q_0 = 1 \).

### 2. Observations

We observed several fields around the radio galaxy 53W002 at \( z = 2.39 \) (Windhorst et al. 1991), which had been shown from imaging in redshifted Lyman \( \alpha \) to be part of a structure containing additional AGN and star-forming galaxies (P96ab, P98). This field therefore offered a unique opportunity to probe a known structure at significant redshift. We observed two further WFPC2 fields using the same filter set, as part of a parallel survey for additional objects in the window around \( z = 2.4 \) (P98). For comparison, we
also observed a large region adjacent to the 53W002 area using a filter tuned for Lyman α emission at $z \sim 2.55$.

For the current wide-field extension of the HST medium-band survey, we used the PFCCD imager, with 2048² Tektronix CCD, for observing runs in the 1997 and 1998 summer seasons on the 4m Mayall telescope of Kitt Peak National Observatory. At the time, this system had significantly better throughput at 4100–4300 Å than the wider-field Mosaic system. Each exposure covered a region 14.3′ on a side with 0.420″ pixels. We isolated Lyman α in the redshift ranges $z = 2.32 – 2.45$ and $z = 2.49 – 2.61$ with intermediate-band filters, the first of which was intended as a clone of the WFPC2 F410M filter, manufactured by Custom Scientific, Inc., to the same specifications as the HST filter set. We refer to these as F413M and F433M to avoid confusion with the WFPC2 F410M filter; WFPC2 has no close counterpart to F433M. These filters have FWHM=150 Å and peak transmission at 4150 and 4330 Å respectively, as measured in a parallel beam; the peak transmission moves blueward by $\sim 12$ Å and the FWHM increases by about $\sim 19$ Å in the $f/2.7$ prime-focus beam of the Mayall telescope (Marcus 1998). In addition to the medium-band Lyman α filters, we also observed each field in $B$, for continuum magnitudes, and $V$ to account for color terms in the continuum subtraction (as in P96b). As it happened, we were able to observe three contiguous fields just to the northeast of 53W002 in F433M. No Lyman α emission candidates in the overlapping region were common to both filters, except for the brighter of the new QSOs discussed later, whose Lyman α emission is so strong that it was detected even in the extreme wings of the redder filter’s passband.

Total exposure times for each region and filter are listed in Table 1, with the area of full exposure extending 420″ in each coordinate from the listed position. Individual exposures were 30 minutes for the medium passbands, and 10-20 minutes in the broad bands, with dither motions of 20-30 arcseconds between successive exposures to suppress
residual flat-field and cosmetic effects in the stacked combination images. The various field pointings were sometimes shifted from an exact rectangular pattern to avoid stray light from bright stars within a region extending about 5′ outward from the CCD edge. The image stacks show image FWHM in the range 1.2–1.6″. The number of objects detected in each field depends on both seeing and total exposure times, and the number shown in Table 1 reflects detections in both $B$ and medium-band filters. The $B$ limiting magnitude is given for each field using a 3σ threshold.

The broadband data were converted to standard Johnson $BV$ magnitudes via secondary standard stars in M92, NGC 7006, and NGC 4147 (Christian et al. 1985, Odewahn et al. 1992). The photometric zero points were consistent to 0.02 magnitude or better from night to night. Both $B$ and $V$ magnitudes show color terms at the 0.03-magnitude level per unit change in $(B - V)$. A more important issue is that of the color correction in continuum subtraction, as outlined below.

The 1997 data suffered from an additive ghost image of the telescope pupil occupying much of the field, produced by internal reflections in the optical corrector. This ghost image was not present in the 1998 data, since the dewar had been offset from the optical axis to avoid the problem. As an additive artifact, the ghost image could be isolated by comparing medium- and broad-band sky flats, then removed by subtracting scaled versions to eliminate the ghosting in our stacked images as completely as possible. Many of the images suffered from spatially variable background structure in the “blank sky” regions due to scattered starlight from stars both within and outside the field of view, sometimes modulated by passing cirrus clouds, which we subtracted using a 101 $\times$ 101-pixel (42″) median filter, clipped around the brightest galaxies which would otherwise be partially subtracted. This allowed higher quality in the final average images, since pixels would not be artificially flagged for rejection because of a temporarily high background. This
leaves spurious residual dark halos around bright stars, but since these are additive, local background subtraction will still give accurate photometry quite close to such stars.

We identified emission- and absorption-line candidates starting with object lists and photometry generated using version 1.0a of SExtractor (Bertin & Arnouts 1996), using visual inspection to reject putative detections which were compromised by bright stars or artifacts near the edges of individual exposures comprising the stacked mosaics. The detection parameters were: object detection threshold $2.5\sigma$ above background over 5 contiguous pixels, and a deblending parameter 0.005 (which turned out to be essentially irrelevant at this level of crowding). Table 1 includes numbers of objects in each field appearing in the matched $B, V, m_{413}/m_{430}$ catalogs. Detections in all three bands were required to deal with color terms in the continuum-to-line comparison. The relative exposure depths suggest that we should not be missing comparable objects due to color effects (though the possibility of extreme colors, such as very red objects, still exists). This multiband matching requirement means that the listed detection totals do not simply reflect the relative exposure times. Coordinates were measured by fitting a celestial coordinate system to stars from the HST Guide-Star Catalog (GSC) on each frame; the formal accuracy is 0.25" rms, borne out by recovering positions of individual GSC stars.

The threshold for emission-line detection is not completely straightforward, since each object’s detectability depends both on the line flux and its equivalent width. Our primary criterion was for equivalent width incorporating individual error estimates, with a secondary list using formal significance of line emission as a basis for selection. Since the F413M medium-band filter sits on the blue edge of the $B$ passband, there is a color term accounting for the continuum slope between $B$ and 4130 Å (a similar but smaller term exists for the F433M filter). We follow W91 and P96B in using the traced filter properties to compute the locus of featureless power-law spectra (a reasonable approximation for galaxies in the
emitted ultraviolet) in the \((m_{413} - B) - (B - V)\) plane, as shown in Fig. 1 for the 53W002 field. This locus is well approximated by the line

\[(F413 - B) = 0.32(B - V) - 0.08,\]

which is a good fit to the observed distribution of “field” objects in our data (the numerical constants become 0.10 for the slope and 0.0 for the intercept in the case of the F433M filter). Our primary sample of emission-line candidates consists of objects which fall more than \(4\sigma\) below this relation where \(\sigma\) applies to the scatter of points on the emission side of the distribution’s ridge line (Fig. 1), which puts our threshold at 0.6 magnitude in F413M/F433M excess (observed equivalent width about 110 Å, corresponding to an emitted equivalent width 30-32 Å at \(z = 2.4 - 2.6\)). These candidates are listed in Tables 2 and 3 for the two filters, and enlargements of the intermediate-band and \(B\) images are shown in Figs. 2 and 3. Here, the tabulated \((m_{413} - B)\) and \((m_{430} - B)\) have been corrected for first-order color terms as described below; negative values indicate an excess in the narrower passband. The listed equivalent widths are in the observed frame; the emitted value will be smaller by \((1 + z) \approx 3.4 - 3.6\). The Lyman \(\alpha\) EW and flux for the three objects previously reported by P96b – their object numbers 18 and 19 plus 53W002 itself – are somewhat uncertain because each has a resolved Lyman \(\alpha\) emission region (see section 6 below), which produces somewhat different values depending on how the flux is extracted. There is evidence that object 19 is itself variable as well (P96a).

The reliability of this sample is supported by the fact that all the members observed spectroscopically (in the 53W002 field) are indeed active nuclei at \(z = 2.39\). To assess whether there is an additional population of detections with lower equivalent width but comparable statistical reliability, we also considered object selection by significance in the deep 53W002 F413M data, defined as

\[S = [(F413 - B) - 0.32(B - V) + 0.08]/\sigma\]
(where $\sigma$ here is the statistical error in the F413-B color) with the additional requirements of $B > 23.5$ and computed equivalent width $\geq 90$ Å to avoid spurious detections of bright objects where the formal errors are much smaller than the scatter introduced by spectral features in stars and lower-redshift galaxies. All of the detections in the primary list have significance $> 5\sigma$ by this criterion. Within the range of $B$ and $S$ that contains all the primary detections, the 53W002 field includes an additional five candidates, thus potentially augmenting the total number by about one third (which occur all over the field, unlike the clustered equivalent-width candidates). These are listed at the bottom of Table 2, but since this technique doesn’t generate any additional objects with line flux significantly above the threshold of the original list (even while relaxing the possible error bounds), we concentrate on the equivalent-width defined list. This list includes some objects with line fluxes as low as $3.7 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$, but a characteristic flux limit for approximate comparison with other results would be close to $5 \times 10^{-17}$ for the 53W002 field in the F410M filter. Corresponding values for the other fields are $1.4 \times 10^{-16}$ for HU Aqr and $1.0 \times 10^{-16}$ for NGC 6251 and the three fields observed with the F430M filter.

Contamination of the Lyman $\alpha$ sample by objects with [O II] $\lambda 3727$ emission at $z \simeq 0.11$ (F413M) or $z = 0.15$ (F433M) should not be important, for the following reasons. The Keck spectroscopy of several of our candidates, plus objects from the HST lists, by Armus et al. (1999), shows that all the emission-line objects either have multiple lines at $z \sim 2.4$ or a single line with equivalent width plus continuum shape inconsistent with [O II] as judged from nearby objects. Finally, these objects are all smaller than $1''$ in effective radius (that is, the blue continuum is either unresolved or almost so from the ground) and fainter than $B = 23$, which would translate simultaneously into linear extent of less than 4 kpc and absolute magnitude fainter than $M_B = -15$ for objects at redshift low enough to have [O II] emission in our passbands.
These data are not deep enough to recover the star-forming objects seen by Lyman $\alpha$ emission in the WFPC2 data of P96b and P98, even in the deepest Kitt Peak F413 exposure on the 53W002 field. The brightest such candidate in the HU Aqr WFPC2 field from P98 also falls slightly below our equivalent-width limit. These known $z = 2.4$ objects have emission-line intensities which would correspond to Kitt Peak detection levels typically $0.5\sigma$, which is confirmed by comparison of our ground-based detections. Therefore we are tracing structures using objects which are, as far as we can tell from the spectroscopically identified subset, fairly luminous active nuclei. For 53W002 and its two immediate neighbors, HST imagery shows these to be accompanied by dimmer star-forming objects. Whether these are smoothly distributed throughout the clumping or form smaller structures in the regions traced by AGN is an important question for further work.

The two strongest-emission new candidates in the 53W002 field, bright enough to appear on blink inspection of the data during the observing run, were observed spectroscopically using the Ritchey-Chretien spectrograph and T2KB CCD at the Mayall telescope a week after the 1997 imaging observations. Grating KPC-10A (316 lines/mm, first-order blaze at 4000 Å) gave 2.77 Å pixels with usable sensitivity over the 3700–8000 Å region, and resolution typically 2.1 pixels = 5.8 Å FWHM. Each object was acquired by offset from bright stars, as measured on the CCD frames. Mediocre seeing mandated a relatively wide 1.7” slit opening, and even so the seeing was variable enough that only single 60-minute exposures of high quality were obtained for each object. While conditions were not photometric, the data could be placed on a relative flux scale using observations of the hot standard star PG 1708+602 (and the objects’ broadband magnitudes are accurately known from the multiband imagery).

Both new candidates observed were found to be QSOs, as shown in Fig. 4. Redshifts were measured by taking centroids of the bright emission lines, by Gaussian fits to the
profile peaks, and by cross-correlation with the mean QSO spectrum assembled by Francis et al. (1991), adopting a mean of these redshift measures and using the differences as a measure of the error. Their spectroscopic properties are given in Table 4, with redshifts measured from Lyman $\alpha$ and C IV individually and from cross-correlation. Both have redshifts within $\Delta z = 0.005$ of the other objects in the 53W002 grouping (P96ab, Armus et al. 1999). We also include emitted-frame Lyman $\alpha$ widths, to make the point that these are fairly narrow-lined QSOs.

As this paper was in revision, we received word that Pascarelle, Yahil, & Puetter (1999) have confirmed candidate 6 from Table 2 with a redshift close to $z = 2.38$ based on Keck spectroscopy, giving a total of six confirmations of the imaging candidates.

3. Emission-Line Detections and Field-to-Field Variations

Our most striking result is seen from Tables 2 and 3, and Fig. 5, where we show the distribution of candidate Lyman $\alpha$ emitters in part of the 53W002 F413M field. There is an extensive grouping of emission-line candidates including 53W002 which has no counterpart in the other fields observed at either $z = 2.4$ or $z = 2.55$. Fourteen objects in the 53W002 field passed our equivalent-width criterion for line emission, while only one at the edge of the HU Aqr field did, and none in the NGC 6251 field. Among the F413M fields, with differing exposure times, the field-to-field ratios to a highest common limiting line flux would be 4:1:0 (the first value rising to 6 for the intermediate limit appropriate to the empty NGC 6251 field). There are 6 candidates in the $z = 2.55$ range sampled by the F433M filter, over almost three times the solid angle of the 53W002 field (and twelve times the solid angle encompassing the candidate emitters in that field). This shows that there are significant structures in place at $z = 2.4$, but not necessarily over a large fraction of the sky; a simple estimate based on these data alone is that such assemblages cover less than
0.04 of the sky in a redshift range $\Delta z = 0.15$, with the limit arising from the fact that the 53W002 field was observed precisely because we already knew that some additional objects were present. The amplitude we find from field to field is even greater than that found by P98 from fainter HST detections at the center of each of these fields, which might indicate that luminous AGN are more clumped than fainter objects. This could mean, for example, that the more massive objects (thus more likely to host AGN) start life more strongly biased toward initial mass peaks.

We can assess the statistical significance of the grouping around 53W002 in several ways. First, we address the reality of the clumping seen within the 53W002 field at $z = 2.4$. Most simply, the probability of $n$ objects falling within a single region covering a fraction $f$ of the solid angle surveyed will be $p = f^{(n-1)}$, where the location of the region is not otherwise specified. In this case, using the superscribed circle about the 14 candidates for the region size and the area of full exposure in the stacked F410M as the overall field surveyed, $f = 0.38$ and $p = 4 \times 10^{-6}$. A Monte Carlo simulation indicates a somewhat higher (though still small) probability of having 14 points drawn from a uniform random distribution fall within a circle of this size, $p = 0.0014$. Finally, we used the two-dimensional version of the Kolmogorov-Smirnov test as proposed by Peacock (1983) and examined in detail by Fasano & Francheschini (1987), employing the routines presented by Press et al. (1992). This test gives a significance level of 95% for the clustering within the 53W002 field. The critical values for the 2-dimensional test are slightly dependent on the distribution of sample points, but these points are not strongly correlated (Pearson $r = 0.40$) and the effect would only act at the $\pm 1\%$ level in this regime. This most conservative of the tests still shows the grouping with high significance.

To test the significance of variations in the number of objects from field to field, we use combinatorics to ask how likely it is that a uniform distribution sampled with our total
number of detections (to a common flux limit) would be so strongly weighted toward a specified field (since we already knew from previous data that there is an excess around 53W002). As noted above, to the highest of the three limiting fluxes, there are four objects in the 53W002 field, one in the HU Aqr field, and none in the NGC 6251 parallel field. Of the 207 ways to distribute 5 objects among three bins, 11 are at least this strongly weighted to the specified one, yielding a probability of $11/207 = 0.053$ of achieving this result by chance. Thus the significance of the higher number of objects in the 53W002 field is 95%, even without taking into account their concentration within the observed area in this field. We note that there is somewhat weaker evidence for clumping of the detections in the F430M filter ($z \sim 2.55$) in the 53W002 NE field; these objects all have derived line luminosities in the QSO range.

4. Lyman-\(\alpha\) absorption candidates

Many of the brightest Lyman-break galaxies observed by Steidel et al. (1996, 1998) show net absorption at Lyman \(\alpha\), indeed sometimes with no significant emission. One of the factors contributing to the strength or weakness of the emission may be metallicity, through the enhanced formation of grains which can absorb resonantly scattered Lyman \(\alpha\) photons (Bonilha et al. 1979), though observations of Lyman \(\alpha\) in starbursts of different metallicity show that there must be more to the story than this single parameter (Giavalisco et al. 1996, Lequeux et al. 1995, Thuan & Izotov 1997). Using imaging techniques, we are sensitive only to net emission, while some of the line emission may be cancelled by the line in absorption from stellar atmospheres and H I in the galaxy. Indeed, about 1/3 of the Lyman-break galaxies observed by Steidel et al. (1998) show net absorption at Lyman \(\alpha\). Therefore, we consider here the possibility of detecting objects with strong absorption at Lyman \(\alpha\).
As a guide to the strength of Lyman α absorption expected from star-forming galaxies, we use the HST GHRS spectrum of the bright knot in NGC 4214 obtained by Leitherer et al. (1996). After excising the narrow emission component, this spectrum shows an absorption line of equivalent width \( \approx 28 \, \text{Å} \), which would be an observed value of \( \text{EW}=95 \, \text{Å} \) at \( z = 2.4 \). This is just within our detection threshold for objects to \( B = 25 \) in the 53W002 field, so that we can extract absorption candidates in the same way as the emission candidates. Since even luminous star-forming galaxies are unlikely to exceed QSO luminosities, we restrict the selection to objects in the range \( 24 < B < 25 \), thereby avoiding much of the potential confusion from foreground stars and galaxies which have an absorption edge between the continuum and narrowband filters, and using the equivalent-width criterion to screen out stars with strong Hδ absorption. This is a particular issue for white dwarfs, which would also be distinguished by broadband colors much bluer than expected for any high-redshift galaxies. Accordingly, we restrict the candidate absorption objects to the range \( 0.15 < (B - V) < 1 \) and require significance of the absorption to exceed \( 4\sigma \). This color range is wider than we observe for the star-forming emitters in the WFPC2 data (P96b). These criteria leave 4 candidates in the 53W002 field (Table 5, Fig. 6). Three of these are in same spatial region as the emission candidates, but our ability to select these objects in a more precise way is limited by the fact that the scatter in the \((m_{413} - B), (B - V)\) diagram is asymmetric and larger to the absorption side, largely due to the natural signal-to-noise limitations at faint levels, so that there are many more interlopers at a given equivalent width for absorption than for emission.

5. The 53W002 “Cluster” at \( z = 2.39 \)

These results strengthen the evidence for some sort of clustering at early cosmic times. We consider here what kind of assemblage we see in the 53W002 field, and how it might
relate to the clustering we see today. This entails measures of its size, population, and dynamical state.

5.1. Cluster “Size” and Radial Distribution

The virial radius \( R_v = \frac{1}{n} \left[ \sum_{j<i} \left( \frac{1}{|r_i - r_j|} \right) \right]^{-1} \) of this assemblage of 14 objects is 157" or 1.2 Mpc in proper coordinates, which would correspond to 1.9 Mpc (a factor \( \pi/2 \) larger) in three dimensions for a typical projection geometry. The radial distribution is so extended that fewer than half the candidates (four) lie within this projected radius of the centroid.

For a distribution this sparsely sampled, whose centroid is not well determined by a strong central concentration, it may be more enlightening to consider the fraction of objects encompassed by circumscribed (projected) circles than by such a specific physical measure as the virial radius. All fourteen candidates are contained within a radius of 327", with 2/3 (10) contained within \( r=218" \) and half (seven) inside \( r=164" \).

To examine whether the distribution of these objects looks like contemporary relaxed systems, we consider how well a King-law profile with any core radius can be fitted to our observations. Because the center is ill-defined from such a sparse sample, we use as a statistic for comparison the cumulative number of objects within an encircled radius, whose center can drift to accommodate the maximum number within a given radius. From \( 10^4 \) Monte Carlo samples of 14 objects each drawn from a King profile (in number density), we generated the bounds containing various fractions of the trials and identify these with confidence intervals. Since the \( z = 2.4 \) structure is traced by active nuclei at \( B \leq 24.5 \) – which may occur in rather low-luminosity galaxies this close to the peak redshift for QSO number density – we use a model for number density rather than incorporating some level of mass segregation to represent the luminosity density in a typical rich cluster. The core
radius is also determined by fitting the radial scale of the distributions so that the true significance of each band may be slightly greater. The core radius was left as an adjustable parameter to be determined by the best fit to the observed cumulative distribution. This exercise should tell whether the observed two-dimensional distribution is likely to be drawn from one like the relaxed profiles of nearby (rich) clusters, and if so what its radial scale (the core radius for a King model) is. As shown in Fig. 7, the 53W002 association is less centrally condensed than a King model of any core radius. Specifically, if either the inner or outer four points in the number-radius relation are used to anchor the data to the Monte Carlo predictions, some points fall outside the 90% band (and if the inner points are fit, outside the 97% band). The difference is such that the inner points imply a core radius of 76" (0.6 Mpc), while the outer ones a core radius of 42" (0.3 Mpc). At this 90-97% confidence level, we can reject a relaxed King distribution for these objects.

If this grouping is not yet relaxed, we are left with an ambiguity in interpreting its linear scale – would it evolve more nearly in comoving or proper coordinates? If it has yet to turn around from the Hubble expansion, it will grow for some time in proper coordinates but shrink (slightly) in comoving ones until it turns around. On the other hand, it may have already turned around but not yet have virialized, in which case the proper-coordinate linear scale will remain nearly constant. Other reports of high-redshift structures have made differing assumptions on this matter – note that Steidel et al. (1998) quote a comoving extent for their structure at $z = 3.1$, while some other workers use proper length. For the 53W002 structure, some intermediate case would be most appropriate, still allowing a wide range of current length scales for comparison with the present epoch.

We can address the correlation function $w(\theta)$ as measured in the 53W002 field from these data. While it is clearly a high-amplitude structure, this measurement might furnish useful information on length scales as well as just how large an amplitude could be reached
by $z = 2.4$. Edge effects were assessed by Monte Carlo trials, employing the expression from Landy & Szalay (1993) as used by Neuschaefer & Windhorst (1995). At $\theta = 30''$ (200 kpc), $w(\theta) = 3.2$, and we see positive correlation out to a radius $r = 5.5'$ (2.4 Mpc) above a threshold value $w \sim 1$. Following the treatment by Neuschafer & Windhorst (1995), and using their sample to $g = 25$, thus result does indicate that the region around 53W002 (sliced in both angle and redshift) is more strongly clustered than the field by a factor $\sim 3$, since the “field” objects have an amplitude of only about 0.03 covering a redshift range roughly $z = 0.5 - 2$.

5.2. Galaxy and AGN Content

The objects from our emission candidate list which have been spectroscopically confirmed are all obvious AGN, with a mix of broad- and narrow-lined cases. This is not surprising given the flux constraints on spectroscopy with 4-m class telescopes, but it is already an unusual AGN population for a single group. Their absolute magnitudes are in the range associated with, for example, low-redshift PG quasars ($M_B = -21.4$ to $-22.4$ for our adopted cosmology, following Weedman 1986 in dealing with spectral slope). The brightest objects known from the WFPC2 field not to be such AGN have $M_B \sim -20.5$, so it remains unclear what the fainter KPNO detections at $B = 24 - 25$ represent. Certainly these would not be unusual luminosities for additional AGN, but this is a regime in which star-forming objects are not unreasonable either.

One hint might come from image structure. If AGN are weaker for the fainter objects, they might appear more clearly resolved since the core is less dominant. We compared image FWHM values (from the SExtractor tables and as computed by the IRAF imexamine task) for the emission candidates with those of bright, unsaturated stellar images nearby in the $B$ frame. Except for the extended structures around 53W002 and object 18, which
have substantial line-emission components, all the candidates are unresolved. This fits with the sizes of the objects in the WFPC2 field, whose typical half-light radii are $0.10''$, but doesn’t furnish any further constraints on whether these new objects are more likely to be AGN or bright star-forming systems.

Even for only passive evolution of the star-forming objects, it is significant that we see none brighter than $M_B = -21$, consistent with the $HST$ results but now covering a much larger region. A typical $L^*$ galaxy would have $M_B = -23$ at $z = 2.4$ unless either active evolution continued to substantially lower redshift, or merging of these small objects continued to form today’s luminous galaxies. More luminous galaxies could hide by lacking Lyman $\alpha$ emission, perhaps if they are more metal-rich and hence can suppress emission in this line, or if their star formation rate dropped quickly at early times. Near-IR line surveys could test the first possibility.

### 5.3. Velocity Dispersion

The five spectroscopically confirmed members of the 53W002 grouping have a velocity dispersion $\sigma_z = 0.0060$, translating into $\sigma_v = 532$ km s$^{-1}$ in the objects’ frame. Adding the two additional faint emitters from P98 drops this value to $467$ km s$^{-1}$. While one should respect the errors in estimating the velocity dispersion from such small samples, it does seem clear that we are not dealing with the dynamics of a rich virialized cluster with $\sigma_v = 1000$ km s$^{-1}$.

Since many of the previously reported $HST$ objects around 53W002 are apparently star-forming complexes, with very narrow Lyman $\alpha$, there is the possibility of introducing a systematic offset in comparison with redshift measurements of broad-lined AGN using the same line. This is less of an issue with the three narrow-lined (“type 2”) AGN previously
reported in this region (P96a,b). Comparison of the strong UV lines (Lyman \( \alpha \), C IV, C III]) with lower-ionization species or with narrow emitted-optical lines expected to arise far from the core (especially [O II] \( \lambda 3727 \)) have shown that substantial differences in central velocity can exist. The shifts can exceed 1000 km s\(^{-1}\) for radio-loud objects, but have a mean close to zero for radio-quiet QSOs (Espey et al. 1989, Marziani et al. 1996). In addition to being radio-quiet (Richards et al. 1999), the two new QSOs have rather narrow lines compared to many of the ones studied for velocity shifts (and compared to the Francis et al. 1991 composite), so the shifts may not be as large. In fact, their close match to the redshifts of other objects in the field would be a remarkable coincidence if systematic shifts of more than a few hundred km s\(^{-1}\) are present, but the possibility remains that the actual velocity range of these objects is larger than the value we measure from Lyman \( \alpha \) and C IV alone.

Furthermore, since the radial distribution suggests that the structure is not virialized and may still be coupled to the Hubble flow, we consider the limiting case in which the velocity range represents the Hubble flow across the depth of the structure rather than internal motions driven by gravity. For \( q_0 = 1/2 \) (or its \( \Omega + \Lambda \) counterpart), the Hubble parameter \( H \) would have been greater at \( z = 2.4 \) than today’s \( H_0 \) by a factor about 6 (scaling inversely with cosmic time for this cosmology), so that the relevant expansion rate would have been in the range 300–600 km s\(^{-1}\) Mpc\(^{-1}\) for \( H_0 = 50–100 \) km s\(^{-1}\) Mpc\(^{-1}\). For a characteristic line-of-sight depth of 1.5 Mpc, comparable to the observed transverse extent containing most of the members, this implies a “velocity dispersion” of 450-900 km s\(^{-1}\) even for a completely unbound assemblage. Since the positional data show clearly that the grouping has decoupled from the Hubble flow to the extent of showing a density contrast of at least a factor 4, we interpret this comparison as showing that this group is still turning around from the Hubble expansion, so that the velocity data do not necessarily allow us to measure its mass (or anything else about the detailed dynamics).
6. **Lyman α Haloes of Constituent AGN**

Three of the bright AGN in this field show extended Lyman α structures in WFPC2 data (P96b, P98). These are either linear or roughly biconical, fitting with a general paradigm of ionizing radiation directed mostly along the poles of some disklike structure. The KPNO data have better sensitivity to large regions of low surface brightness than does *HST*, and reveal new aspects of the extended line emission. For 53W002 and object 19 (in the P96b nomenclature), this is an extension of the Lyman α structure seen in WFPC2 images (Windhorst, Keel, & Pascarelle 1998), but for object 18, this resolved structure is not only much larger (extending more than 5″ from the core) than the ionization or scattering cone inferred from WFPC2 data, but it is most extended in a different direction. The inner parts of these structures are detected as well in Hα using IRTF narrowband imagery and in [O III] using NICMOS multiband and grism data (Keel et al. 1999).

We can examine the structure of the Lyman α images by comparing both the $B$ continuum and emission-line images of each candidate emitter to stellar profiles from the same region of each image. This gives some insurance against minor PSF changes across the field, and avoids problems due to somewhat different PSF widths between the $B$ and F413M images. We consider extended emission to be detected when there is some scaling between broad– and medium–band images for which the difference is flat across the core and shows flux more extensive than the PSF. Requiring a flat central profile is conservative, to minimize the possibility of false detections at the expense of underestimating the flux in the spatially extended component. Several of the brightest emission-line objects show Lyman α emission more extended than their continuum structures.

This analysis suggests that both scattering and local recombination play roles in these emission-line halos. The three objects with extended emission-line regions illustrate this:

Object 18 (P96b): The PSF subtraction shows that more than 75% of the Lyman α flux
from object 18 comes from outside the core, and recovers the gross features of the WFPC2 image. Similar results come from analysis of the $B$ image, while the relative count rates indicate that most of the $B$ light is in fact Lyman $\alpha$. Spectroscopy by Armus et al. (1999) shows that the extended cloud has almost no continuum component, consistent with these results. This accounts for the very blue color of the extended structure ($(B - V) = -0.4$), since there are no strong emission lines in the $V$ band.

53W002: For 53W002 and object 19, about half the line flux is spatially resolved, in accord with the HST PC data of Windhorst et al. (1998) and the ground-based Lyman $\alpha$ imaging from Windhorst et al. (1991). As noted earlier, the emission-line structure is approximately along the orientation of the $1''$ radio double source, but much larger.

Object 19 (P96b): As in 53W002, about half the line flux is resolved, in accord with the HST data as well. In this case, the extended emission is all in Lyman $\alpha$ to our detection threshold; less than 10% of the $B$-band flux comes from outside the core.

These extended structures are illustrated in Fig. 8, comparing the medium-band image, the PSF-subtracted version, and HST imagery of the brightest regions. The large-scale line emission is well aligned with the small-scale emission observed with $HST$, which is well shown in the color figure of Windhorst et al. (1998) including scattered continuum components. For object 18, the KPNO data reveal that the inner emission region is identical with the two major components seen with $HST$, but much more extensive and amorphous material appears at this deeper surface-brightness threshold.

For the two newly detected QSOs, any such resolved line-emitting region must have less than 10% of the total Lyman $\alpha$ flux (and as low as 5% for the brighter QSO 2). These values apply to structures that are extended on the scale resolved by the PFCCD images; as a guide, the image size in the final F413M stack has $1.2''$ FWHM.
Lyman $\alpha$ emission by itself is difficult to interpret, since we lack useful density indicators and its radiative transfer is sensitive to the velocity field and dust content. At a minimum, if mechanical energy input isn’t important in the extended nebulae, the number of Lyman $\alpha$ photons can give a lower limit to the number of ionizing photons reaching the gas, provided only that the situation is in a steady state. In turn, this can tell us whether the radiation field must be anisotropic to account for the structures we see - that is, whether we are correct in referring to some of these structures as ionization “cones”.

The continua on our line of sight are measured from about 1100-2000 Å in the emitted frame, so that we should be able to do a reasonable extrapolation to the Lyman limit and estimate the expected number of ionizing photons in the isotropic case. For the simple case of a photoionized cloud occupying solid angle $\Omega$ as seen from the central source, if we see the same ionizing continuum as the cloud does, the extrapolated continuum and observed Lyman $\alpha$ emission should satisfy

$$n_{LyC} \geq \frac{\Omega}{4\pi} \frac{n_{Ly\alpha}}{f_\alpha}$$

where $n_{LyC}$ is the number of Lyman continuum photons per second extrapolated from the observed continuum, $n_{Ly\alpha}$ is the observed number of Lyman $\alpha$ photons per second, and $f_\alpha$ is the fraction of recombinations whose cascade includes Lyman $\alpha$ (0.64 for case A, following the tabulations in Osterbrock 1989). The luminosity distance has cancelled on both sides, though we still need to make a plausible assumption about the clouds’ geometry to assign a subtended $\Omega$. The equality holds for an ionization-bounded nebula which is optically thin to all the Lyman lines, in the sense that violating these conditions increases the continuum/line ratio and therefore makes the observed continuum more sufficient to power the extended line region.

Applying this test to the three resolved Lyman $\alpha$ regions shows that at least object 18, with its very extensive line emission, has an ionization source that we don’t see. Extrapolating the observed continuum at its flat level in flux falls short of creating the
observed Lyman $\alpha$ emission by at least a factor 2, suggesting either a bump in the ionizing spectrum or anisotropic radiation. The $B - K$ continuum shape is not unusually red, in fact quite normal for narrow-line AGN and almost identical to the other two objects with extended line emission, so that anisotropic illumination makes sense if it is not caused by material that would redden the observed continuum. A similar issue appears for many type 2 Seyfert nuclei, with a Lyman-continuum deficit implied by the observed continuum and line intensities, and blue UV continuum slopes. This has been variously attributed to scattering or reflection of radiation from a small continuum region (as in Antonucci, Hurt, & Miller 1994), and surrounding star formation (Colina et al. 1997), with recent results suggesting that the nucleus itself may not be an important contributor to the UV flux in narrow-line objects. The geometry of the Lyman $\alpha$ cloud near object 18 offers little help; while the inner parts, as detected with $HST$ (P96a, Windhorst et al. 1998) resemble an ionization cone, the outer regions are extended at $90^\circ$ in projection to this axis. Of course, additional energy sources might be considered, such as the radio jet interactions proposed for powerful radio galaxies. However, of these three objects, only 53W002 itself has significant resolved radio emission; the other two are both substantially weaker and unresolved by the VLA at the 1" level (Richards et al. 1999). The flux data alone do not require anisotropic radiation for 53W002 and object 19, though the emission-line structure at least suggests an anisotropic gas distribution, and it is suspicious that the Lyman $\alpha$ structure in 53W002 aligns with the smaller double radio source (Windhorst, Keel, & Pascarelle 1998).

Independent of the ionization mechanism, such a rich collection of large clouds around the brightest illuminating sources raises the question of whether the extended gas belongs exclusively to the AGN hosts or exists more widely throughout this cluster, where we cannot observe it so easily. Detection of these structures in the continuum at a level above the weak free-free emission accompanying recombination would imply the presence of dust,
a tracer of the level of star formation early in the galaxies’ history. Furthermore, if the
nuclei are more often obscured early in cosmic time, we might expect to see “disembodied”
Lyman α clouds in upcoming deep surveys.

7. The Evolution of Structure: Forward to the Past

We have reported a Lyman α survey aimed at tracing structures in the range
$z = 2.3 - 2.6$, finding a clumping or clustering in one field, represented by 14 luminous
objects spanning about 3 Mpc. This adds to the existing evidence for structure in place, if
not necessarily well developed, at cosmologically early epochs.

What does the 53W002 structure turn into? Based on its extent as found here, we can
ask how many members might exist to the HST detection threshold. The existing WFPC2
data cover only a single 5.7-arcminute² area, while we find candidate members spread over
an area of about 93 arcminutes². If the WFPC2 field is representative, there would be 16
times as many faint star-forming members as we’ve detected to date. With 8 objects in the
HST field now spectroscopically confirmed as members (Armus et al. 1999), that means the
total membership would surpass 120 if we’re seeing a smooth distribution. Alternatively,
if the star-forming objects are in clumps traced by the AGN that we detect from KPNO,
there would still be $\sim 70$ in this structure. These numbers are lower estimates, since
objects undoubtedly occur below our detection thresholds. These two cases represent rather
different proposed histories for cluster and group formation – in one case, that clumps of
objects will merge into today’s galaxies, and in the other, that individual objects we see at
$z = 2.4$ will either passively evolve as they begin to exhaust their gas or continue to acquire
infalling material, with merging of initially separate galaxies a less important process.

Our velocity information is largely confined to the original WFPC2 field, with the
addition of the two newly-identified QSOs. Thus it is not very clear how the small velocity dispersion of these objects (of order 385 km s\(^{-1}\), including redshifts of members from Armus et al. 1999) should be interpreted for the whole structure. Furthermore, the extended spatial distribution suggests that the structure has not yet relaxed, and may not yet be fully decoupled from the Hubble flow. Recent simulations of galaxy formation from a clumpy medium by Haehnelt, Steinmetz, & Rauch (1998) indicate that line-of-sight velocity measurements not only have a factor 2 dispersion as seen from various directions, but underestimate the relaxed virial velocities by \(\sim 60\%\). These considerations all make a virial mass estimate very uncertain, and likely a lower limit. It may be more realistic to consider the velocity dispersion as applying to the megaparsec-scale clumping including 53W002 itself and the AGN in objects 18 and 19. The velocity range we see is comparable to the dispersion expected purely from the Hubble flow on an assemblage 3 Mpc deep at this epoch, so we may well be seeing the group near the time of turnaround from cosmological expansion, in which case the velocity dispersion tells very little about the internal dynamics.

These questions suggest several potentially fruitful lines for further work. Most notably, we need to know more about the content of this structure, especially for fainter objects both with and without strong Lyman \(\alpha\) emission. Multiband imagery sufficient to derive photometric redshifts and narrowband near-infrared measurements tailored to find emission from \([\text{O II}]\), \([\text{O III}]\), or \(\text{H}\alpha\) can help fill out our census of members. A more accurate accounting of how common such structures are in the early Universe will require wider-field multiband surveys, preferably with fine enough wavelength bands to both pick out line emitters and resolve multiple line-of-sight sheets or clusters. Eventually, dynamical studies should tell us how these early assemblages become the rich structural spectrum seen in today’s Universe.

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Figure Captions

Fig. 1.— Color-color selection of emission-line candidates from the 53W002 field, showing the color term in the locus of most objects in the two-color \((m_{413} - B), (B - V)\) plane. The dashed lines indicate the \(\pm 3\sigma\) bands for emission and absorption candidates for our equivalent-width selection. Emission candidates fall below the lower dashed line, with some rejected because of neighbor contamination or nearby cosmetic defects. Objects which we have spectroscopically confirmed are marked with triangles.

Fig. 2.— Montage of F413M and \(B\) subimages of the primary Lyman \(\alpha\) emission candidates, as listed in Table 2. Each section is 31 pixels = 13.0\('\) square, with north at the top, with the candidate centered. The intensity scaling for all images in each filter is the same, so that different objects may be directly compared. The relative scaling between F413M and \(B\) images has been set so that objects with no excess and neutral colors have approximately equal intensity in both. For compactness, each is labelled with the running number from Table 2. The black area adjacent to candidate 16 in the \(B\) image is a charge-transfer artifact from a bright star to the north. Candidates 1–6 have been spectroscopically confirmed at \(z = 2.39\). The final one, number 20, is in the HU Aqr parallel field.

Fig. 3.— Emission candidates at \(z \sim 2.55\) from the F433M filter. As in Fig. 2, the medium-band and \(B\) images of 13.0\('\) regions are shown centered on each candidate. The running numbers are as given in Table 3. The area just southwest of object 25 is affected by a stellar reflection in the medium-band interference filter.

Fig. 4.— Spectra of the newly identified QSOs. The data for the brighter object, candidate 2 = 171444.72+501744.9 from Table 2, have been shifted upward by \(5 \times 10^{-18}\) for clarity. Expected locations of the weaker Si IV+O IV] and C III[ features are marked for \(z = 2.393\).

Fig. 5.— A portion of the 53W002 field as seen in the F413M filter, with emission-line
candidates marked along with the region searched by P96 using a similar filter on HST with WFPC2. This region covers 0.45 by area of the entire field observed, and contains all the Lyman \( \alpha \) candidates. The two additional marked objects within the WFPC2 footprint are numbers 1 and 3 in our candidate list, and are spectroscopically confirmed as AGN as shown by P96. The two newly discovered QSOs are marked as such.

Fig. 6.— Absorption-line candidates at \( z \sim 2.4 \) from the F413M filter in the 53W002 the top. A pure continuum object of neutral color would have equal brightness in both frames; color terms will distort this slightly for some of the candidate absorbers.

Fig. 7.— Minimum encircling radii for various numbers of objects among the 53W002 candidates versus Monte Carlo predictions for a King model. The \( \pm 2, 3\sigma \) bands are actually the 90 and 95th percentile locations from the numerical trials. The data are plotted as normalized to core radii of 42 and 76 arcseconds, which fit the inner and outer portions, to illustrate that no single normalization fits without falling outside the 90\% bound somewhere.

Fig. 8.— Comparison of resolved structures in Lyman \( \alpha \), with the observed KPNO medium-band image on top, the PSF-subtracted version in the middle, and the \textit{HST} data from Windhorst, Pascarelle, & Keel (1998) in the bottom row. Each section is 10\'' square, with north at the top. The white triangular regions in two of the HST images shows where the “gutter” between the WF2 and WF3 chips falls. The WFPC2 data for objects 18 and 19 in the P96 nomenclature are interleaved images taken in a \( 2 \times 2 \) dither pattern on 0.05\'' centers, with that effective pixel size. For 53W002, the F410M image is from the PC (Windhorst et al. 1998) and has been smoothed with a Gaussian kernel of FWHM=0.23\'' to show the faint resolved emission at about PA=290\(^\circ\) from the nucleus. The PSF is almost perfectly circular, so that the elongation of 53W002 and object 19 at low levels in the KPNO data indicates resolved features.
Table 1
Summary of Fields Observed

| Field       | Filter | Center (2000) | Exposure (min) | Matched |
|-------------|--------|---------------|----------------|---------|
| 53W002      | 413M   | 17 14 10.3    | 480            | 3161    |
| HU Aqr par  | 413M   | 21 07 27.7    | 150            | 928     |
| NGC 6251 par| 413M   | 16 36 37.0    | 180            | 930     |
| 53W002 E    | 430M   | 17 15 22.4    | 240            | 1588    |
| 53W002 N    | 430M   | 17 14 01.6    | 240            | 2215    |
| 53W002 NE   | 430M   | 17 15 06.6    | 240            | 2167    |
Table 2
Candidate Lyman $\alpha$ emitters from F413M, $z \approx 2.4$

| No. | $\alpha$(2000) | $\delta$(2000) | $B$ (mag) | $(m_{4130} - B)$ (mag) | Obs. EW | F(Ly $\alpha$) (cgs) | Notes |
|-----|----------------|----------------|----------|------------------------|---------|----------------------|-------|
| 1   | 17:14:12.01    | +50:16:02.3    | 23.41    | $-1.29 \pm 0.04$       | 342     | 1.1(-15)             | P96b object 18 |
| 2   | 17:14:44.72    | +50:17:44.9    | 23.31    | $-1.24 \pm 0.03$       | 320     | 1.1(-15)             | New QSO |
| 3   | 17:14:11.30    | +50:16:09.4    | 23.91    | $-1.01 \pm 0.04$       | 230     | 4.5(-16)             | P96b object 19 |
| 4   | 17:14:12.39    | +50:18:18.0    | 24.37    | $-1.00 \pm 0.04$       | 226     | 2.9(-16)             | New QSO |
| 5   | 17:14:14.70    | +50:15:29.7    | 24.05    | $-0.80 \pm 0.05$       | 164     | 2.8(-16)             | 53W002 |
| 6   | 17:14:39.82    | +50:21:52.3    | 25.46    | $-0.85 \pm 0.09$       | 178     | 8.4(-17)             |       |
| 7   | 17:14:32.80    | +50:15:50.7    | 26.19    | $-0.78 \pm 0.15$       | 158     | 3.8(-17)             |       |
| 8   | 17:14:31.66    | +50:19:06.8    | 25.54    | $-0.66 \pm 0.11$       | 125     | 5.5(-17)             |       |
| 9   | 17:14:24.76    | +50:20:45.7    | 25.36    | $-0.62 \pm 0.09$       | 115     | 5.9(-17)             |       |
| 10  | 17:14:42.15    | +50:16:51.8    | 24.34    | $-0.73 \pm 0.08$       | 144     | 1.9(-16)             |       |
| 11  | 17:14:39.20    | +50:21:32.8    | 25.66    | $-0.83 \pm 0.13$       | 172     | 6.7(-17)             |       |
| 12  | 17:14:53.75    | +50:22:31.8    | 25.87    | $-0.62 \pm 0.15$       | 116     | 3.7(-17)             |       |
| 13  | 17:14:42.48    | +50:16:01.6    | 25.09    | $-0.67 \pm 0.09$       | 128     | 8.5(-17)             |       |
| 14  | 17:14:30.77    | +50:12:09.1    | 26.21    | $-0.82 \pm 0.16$       | 169     | 4.0(-17)             |       |

53W002 field: additional significance-selected candidates

| No. | $\alpha$(2000) | $\delta$(2000) | $B$ (mag) | $(m_{4130} - B)$ (mag) | Obs. EW | F(Ly $\alpha$) (cgs) |
|-----|----------------|----------------|----------|------------------------|---------|----------------------|
| 15  | 17:13:49.35    | +50:14:29.0    | 25.05    | $-0.52 \pm 0.07$       | 92      | 6.3(-17)             |
| 16  | 17:14:04.15    | +50:18:14.6    | 25.24    | $-0.53 \pm 0.09$       | 94      | 5.4(-17)             |
| 17  | 17:14:30.46    | +50:13:13.7    | 25.58    | $-0.58 \pm 0.10$       | 106     | 4.4(-17)             |
| 18  | 17:13:42.86    | +50:21:20.4    | 25.35    | $-0.57 \pm 0.11$       | 104     | 5.4(-17)             |
| 19  | 17:14:17.55    | +50:10:13.6    | 25.50    | $-0.55 \pm 0.12$       | 98      | 4.4(-17)             |

HU Aqr field

| No. | $\alpha$(2000) | $\delta$(2000) | $B$ (mag) | $(m_{4130} - B)$ (mag) | Obs. EW | F(Ly $\alpha$) (cgs) |
|-----|----------------|----------------|----------|------------------------|---------|----------------------|
| 20  | 21:07:57.26    | -05:25:41.1    | 22.25    | $-1.04 \pm 0.03$       | 241     | 2.2(-15)             |
Table 3
Candidate Lyman $\alpha$ emitters from F433M, $z \approx 2.6$

| No. | $\alpha$(2000) | $\delta$(2000) | $B$ | $(m_{4300} - B)$ | Obs. EW | F(Ly $\alpha$) | Notes |
|-----|----------------|----------------|-----|------------------|---------|----------------|-------|
|     | (mag)          | (mag)          |     | (mag)            |         | (cgs)          |       |
| 53W002 N field: |
| 21  | 17:13:17.36   | +50:27:12.8    | 24.55 | $-1.17 \pm 0.15$ | 291     | 3.2(-16)       |       |
| 53W002 E field: |
| 22  | 17:15:23.23   | +50:19:35.2    | 22.38 | $-1.17 \pm 0.05$ | 155     | 1.2(-15)       |       |
| 53W002 NE field: |
| 23  | 17:14:51.62   | +50:23:13.4    | 24.54 | $-0.87 \pm 0.16$ | 184     | 2.0(-16)       |       |
| 24  | 17:15:33.80   | +50:28:49.6    | 24.56 | $-0.99 \pm 0.15$ | 223     | 2.4(-16)       |       |
| 25  | 17:15:28.13   | +50:23:46.2    | 24.57 | $-1.02 \pm 0.16$ | 234     | 2.5(-16)       |       |
| 26  | 17:15:32.92   | +50:30:52.1    | 24.25 | $-1.06 \pm 0.11$ | 248     | 3.5(-16)       |       |
Table 4
Lyman $\alpha$ Absorption Candidates ($z \sim 2.4$) in the 53W002 Field

| No. | $\alpha_{2000}$   | $\delta_{2000}$   | $B$       | ($m_{413} - B$) | ($B - V$) |
|-----|------------------|------------------|-----------|----------------|-----------|
| 27  | 17:13:44.51      | +50:21:08.9      | 24.01 ± 0.04 | 1.94 ± 0.19    | 0.18 ± 0.10 |
| 28  | 17:14:05.79      | +50:19:17.8      | 24.81 ± 0.05 | 1.46 ± 0.18    | 0.24 ± 0.14 |
| 29  | 17:14:23.37      | +50:23:09.2      | 24.25 ± 0.04 | 1.56 ± 0.14    | 0.57 ± 0.07 |
| 30  | 17:14:20.42      | +50:10:51.2      | 24.29 ± 0.03 | 1.56 ± 0.14    | 0.86 ± 0.05 |
Table 5
New QSO redshift measurements

| Object         | Ly α FWHM (Å) | Ly α C IV | Cross-correlation | Mean        |
|----------------|---------------|-----------|-------------------|-------------|
| 2 (171444.72+501744.9) | 11            | 2.384     | 2.377             | 2.382 ± 0.002 |
| 4 (171412.39+501818.0) | 17            | 2.391     | 2.400             | 2.393 ± 0.006 |
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