The Astrophysical Journal, 560:L5–L8, 2001 October 10

ON THE THRESHOLD OF THE REIONIZATION EPOCH[1]

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Received 2001 July 26; accepted 2001 August 30; published 2001 September 13

ABSTRACT

Discovery of the cosmic reionization epoch would represent a significant milestone in cosmology. We present Keck spectroscopy of the quasar SDSS 1044−0125, at $z = 5.73$. The spectrum shows a dramatic increase in the optical depth at observed wavelengths $\lambda \gtrsim 7550$ Å, corresponding to $z_{\rm abs} \gtrsim 5.2$. Only a few small, narrow transmission regions are present in the spectrum beyond that point and out to the redshifts where the quasar signal begins. We interpret this result as a signature of the trailing edge of the cosmic reionization epoch, which we estimate to occur around $\langle z \rangle \sim 6$ (as indeed confirmed by subsequent observations by Becker et al.) and extending down to $z \sim 5.2$. This behavior is expected in the modern theoretical models of the reionization era, which predict a patchy and gradual onset of reionization. The remaining transmission windows we see may correspond to the individual reionization bubbles (Strömgren spheres) embedded in a still largely neutral intergalactic medium, intersected by the line of sight to the quasar. Future spectroscopic observations of quasars at comparable or larger redshifts will provide a more detailed insight into the structure and extent of the reionization era.

Subject headings: cosmology: observations — galaxies: formation — quasars: individual (SDSS 1044−0125)

1. INTRODUCTION

There has been a great progress over the past several years in our understanding of galaxy evolution and formation. Samples of normal galaxies are now studied out to $z \sim 4.5$ (Steidel et al. 1999), and several galaxies are now known at $z > 5$ (see Stern & Spinrad 1999 for a review and references). Quasars at $z > 5$ (Stern et al. 2000; Zheng et al. 2000; Fan et al. 2000 and references therein) also represent a valuable probe of both galaxy and structure formation and the intervening primordial intergalactic medium (IGM).

The observational frontier is now shifting to the formation of the first objects, protogalaxies and primordial active galactic nuclei (AGNs), which is generally expected to occur some time in the redshift interval $z \sim 6$–15 or so. As the first sources of UV radiation turn on, they reionize the universe, ending the "dark ages," which start at the recombination epoch ($z \sim 1100$). In this "cosmic renaissance" (effectively, the start of the galaxy formation epoch), the universe undergoes a phase transition from being neutral to being mostly ionized.

Detection of the reionization epoch would thus be a major cosmological milestone. The standard observational test is the prediction of an extended, optically thick absorption due to neutral hydrogen at $\lambda_{\rm rest} < 1216$ Å (Gunn & Peterson 1965). A limit to this effect at $z \approx 5$ was published by Songaila et al. (1999). To date, only a gradual thickening of the absorption due to the Lyα forest was seen.

In this Letter, we present evidence that suggests we are already probing the trailing end of the reionization era, at $z \sim 5.5 \pm 0.3$ or so. The evidence is based on the high signal-to-noise ratio (S/N), Keck spectroscopy of the quasar SDSS 1044−0125 discovered by Fan et al. 2000. Subsequent recent observations of quasars at $z \gtrsim 6$ by Becker et al. 2001 provide additional evidence that the reionization era indeed occurs around $z \sim 6$. Taken together, the available data support a picture of an extended and patchy reionization era, ending at $z \sim 5$–6.

2. OBSERVATIONS AND DATA REDUCTIONS

Our low-resolution spectra were obtained on the W. M. Keck Observatory 10 m telescope (Keck I) on UT 2000 December 30, using the Low-Resolution Imaging Spectrometer (LRIS; Oke et al. 1995). The observations were obtained with the 400 line mm^{-1} grating ($\lambda_{\rm blaze} = 8500$ Å) through 1$''$.2 slitlets, with two different slit masks, with a mean dispersion of ≈1.86 Å pixel^{-1}, and a GG495 long-pass order-sorting filter. The first set, totalling 2400 s of integration, was at a slit position angle (P.A.) $= 249^\circ.6$, covering the quasar spectrum ~6240 Å–1 μm, and a mean air mass ≈1.08. The second, with 3600 s of integration, was at P.A. $= 137^\circ$ (very close to parallactic angle at the time), covering ~7300 Å–1 μm, and a mean air mass ≈1.13. The differential slit losses are estimated to be negligible for our purpose. Individual integrations were dithered along the slit. Data were reduced in IRAF, using standard slit spectroscopy procedures. Ne + Ar arc lamp spectra obtained through the masks were used for wavelength calibrations, and the wavelength zero points were adjusted using telluric emission lines. The night was photometric, but unfortunately no flux standards were observed with these slit mask + grating combinations, and we used an average of archival response curves for this grating obtained earlier. Our spectroscopic magnitudes are in an excellent agreement with the CCD photometry presented by Fan et al. (2000).

The combined LRIS spectrum is shown in Figure 1. It shows a dramatic drop due to the Lyα absorption at $\lambda_{\rm obs} \lesssim 8100$ Å and a second discontinuity at $\lambda_{\rm obs} \lesssim 6900$ Å due to the Lyβ forest (this may be the strongest detection of the Lyβ drop observed to date). In order to estimate the possible continuum level in the absorbed region, we use three power laws, $f_\nu \sim \nu^\alpha$, with $\alpha = [0, \ -0.5, \ -1]$, which span a plausible range for quasars. They have been normalized to $f_\nu = 72\ \mu$Jy at 9000 Å and are shown as dashed lines in Figure 1.

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[1] Based on the observations obtained at the W. M. Keck Observatory, which is operated by the California Association for Research in Astronomy, a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration.

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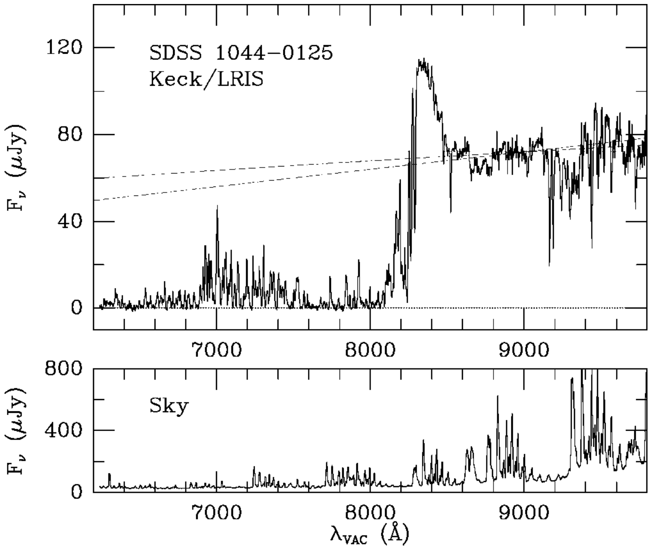

FIG. 1.—Spectrum of SDSS 1044−0125 obtained with LRIS (*top*) and the corresponding night sky (*bottom*). The three dashed lines represent a plausible range of the unabsorbed quasar power-law continua.

Our high-resolution spectra were obtained on the W. M. Keck Observatory 10 m telescope (Keck II) on UT 2000 April 28, UT 2001 January 1 and 2, and UT 2001 March 24, using the Echelle Spectrograph and Imager (ESI; Sheinis et al. 2000). We used the echelle mode, which contains 10 orders, with a complete optical wavelength coverage, from ∼3900 to ∼10900 Å. The instrument has a spectral resolution of 11.4 km s^{-1} $pixel^{-1}$ and a mean dispersion in the wavelength region of interest here of ≈0.154 Å $pixel^{-1}$. A total of 11 exposures of 1800 s each were obtained, some in slightly nonphotometric conditions. Data were reduced using standard procedures. We used the program MAKEE (written by T. Barlow) to reduce the spectra. Individual exposures from each night were combined prior to spectrum extraction using a rejection algorithm to remove cosmic rays. Spectra were then optimally extracted. Exposures of bright stars were used to provide the spectrum traces (necessary due to a heavy absorption present in the quasar spectrum). Dispersion solutions were found from exposures of arc lamps, spectra were corrected to the Heliocentric system, and the wavelengths were transformed to vacuum values. The spectra for each night were flux-calibrated using a single response curve measured during one of the nights and averaged using the exposure time weighting.

Since the flux zero points for the ESI data are uncertain, we convolved both ESI and LRIS spectra with Gaussians with $\sigma = 20$ Å, thus bringing them to effectively the same, very low resolution. From the ratio of these spectra, we determined the flux correction factor and applied it to the ESI data.

The final ESI spectrum is shown in Figure 2. The absence of flux (save for a few remaining narrow gaps in absorption) in the wavelength interval ∼7550–8100 Å, between the patch of the Lyα forest in the wavelength range ∼6900–7550 Å and the quasar signal at greater than 8100 Å, is quite striking. (The Mg II doublet at $\lambda \approx 9180$ Å was noted by Fan et al. 2000; using a weighted average of several lines, we measure the absorber redshift to be $z = 2.27865$.)

The sharp Lyβ drop at $\lambda \approx 6910$ Å allows us to estimate a better redshift for the quasar: $z = 5.73 \pm 0.01$. This is less than 5.80, originally estimated by Fan et al. 2000, for the following reason. The object was found to be a broad absorption line (BAL) quasar by Maiolino et al. (2001). We believe that its Lyα line is nearly completely absorbed and that Fan et al. (2000) mistakenly interpreted the red half of the [N V] λ1240 line as Lyα. This unfortunately precludes the study of the red wing of the Lyα absorption, which may contain useful information about the structure of the reionization front (Madau & Rees 2000; Loeb & Barkana 2001; Barkana & Loeb 2001). Our redshift is supported by the possible Lyγ line and a drop near $\lambda \approx 6540$ Å and a Lyman limit (clearly seen in the two-dimensional spectra images) at $\lambda \approx 6135$ Å. The effects of the

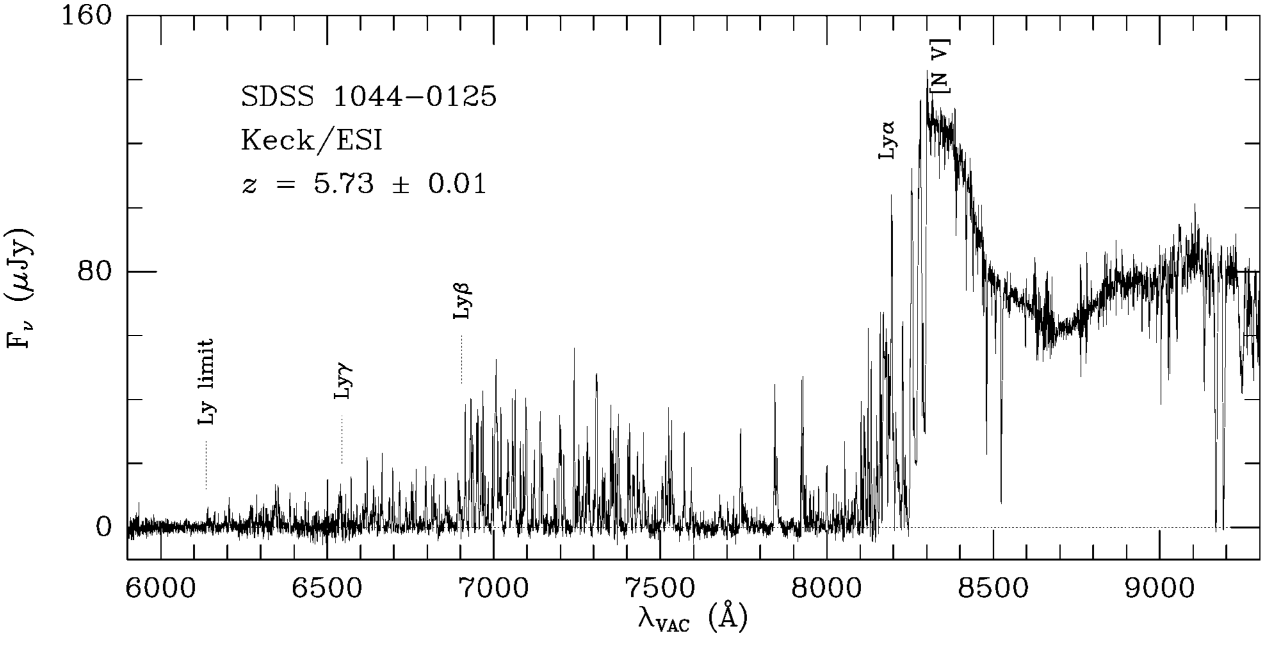

FIG. 2.—Spectrum of SDSS 1044−0125 obtained with ESI. Lyman series breaks corresponding to redshift $z = 5.73$ are indicated. In this redshift interpretation, most of the quasar's Lyα line is absorbed. The dramatic change in the density of the Lyα forest at $\lambda \gtrsim 7550$ Å, and probably the corresponding Lyβ absorption at $\lambda \lesssim 6900$ Å, are suggestive of the onset of the reionization era at $z > 5.2$.

blue BAL wing of [N v] and Lyα may extend as far as $\lambda \sim$ 7900–8000 Å, but this is not critical for our discussion below.

3. DISCUSSION AND CONCLUSIONS

There has been much recent progress in theoretical understanding and modeling of the reionization era (excellent reviews include, e.g., Madau 2000, Loeb & Barkana 2001, Barkana & Loeb 2001, Shapiro 2001, etc.). A good understanding of the structure and extent of the reionization is important by itself, as it reflects the earliest phases of structure formation, and also for the modeling of cosmic microwave background radiation foregrounds at high angular frequencies.

A simple picture of a clean-cut Gunn-Peterson trough now appears unlikely. The key issue is the clumpiness of the IGM and the gradual development and clumpy distribution of the first ionizing sources, either protogalaxies or early AGNs (see, e.g., Miralda-Escudé, Haehnelt, & Rees 2000). The reionization is expected to occur gradually as the UV emissivity increases (see, e.g., McDonald & Miralda-Escudé 2001) and ionization overcomes the recombination rate, with the lowest density regions becoming fully reionized first. This is also suggested by modern numerical simulations (e.g., Gnedin 2000, Ciardi et al. 2000, Umemura, Nakamoto, & Susa 2001, etc.) that predict an extended period of reionization, ranging from $z \sim 15$ to $z \sim 5$ or so.

As we approach the reionization era from the lower redshifts, the Lyα forest thickens, with an occasional transmission gap due to the intersection of ionized bubbles along the line of sight; eventually a complete Gunn-Peterson trough is reached. In other words, the inherent nonuniformity of galaxy and structure formation is reflected in the structure of the IGM phase transition corresponding to the reionization. Further complications arise from the proximity effect due to the source used to probe the IGM, i.e., a luminous quasar, and the nature, luminosity, and duration of other sources near the line of sight.

This general picture is illustrated well in Figure 20 of Loeb & Barkana (2001; which is the same as Fig. 40 of Barkana & Loeb 2001 or Fig. 6 of Loeb 1999). The qualitative correspondence with the observed spectrum of SDSS 1044−0125 (Fig. 2) is striking. The dramatic increase in the opacity of the Lyα forest at $\lambda \gtrsim 7550$ Å, i.e., $z \gtrsim 5.2$, is exactly what is expected in the approach to (or the tail end of) the reionization era. This is further illustrated in Figure 3, which shows a dramatic thickening of the Lyα forest absorption at these redshifts. A slightly different interpretation is that we are seeing a somewhat later evolutionary stage of the reionization process, i.e., remaining islands of (mostly) neutral gas embedded in a growing sea of ionized hydrogen.

The strong observed Lyβ break may also be due in part to the patches of diffuse absorption we see so clearly in Lyα. The overall appearance of the spectrum is suggestive of some of the models by Haiman & Loeb (1999), for the reionization redshift (in their terminology) a few percent lower than the source redshift.

The dark portions of our spectrum at $z \sim 5.2$–5.6 have the flux consistent with zero, to within the photon noise. The lower limit to the optical depth (rms, per pixel) is $\tau \gtrsim 4$; if we average the flux over the dark portions of the spectrum, this limit is considerably higher, $\tau \gtrsim 6$ or 7, depending on the redshift window used. Even if we assume a very conservative systematic sky subtraction error of ~1% of the continuum, the implied optical depth limit would be $\tau \gtrsim 4.6$. The extrapolation of the empirical scaling laws found by Press, Rybicki, & Schneider (1993) and Kim, Cristiani, & D'Odorico (2001) to these redshifts suggests $\tau \sim 2$. This again indicates that we are seeing more absorption than would be expected from a simple extrapolation of the Lyα forest.

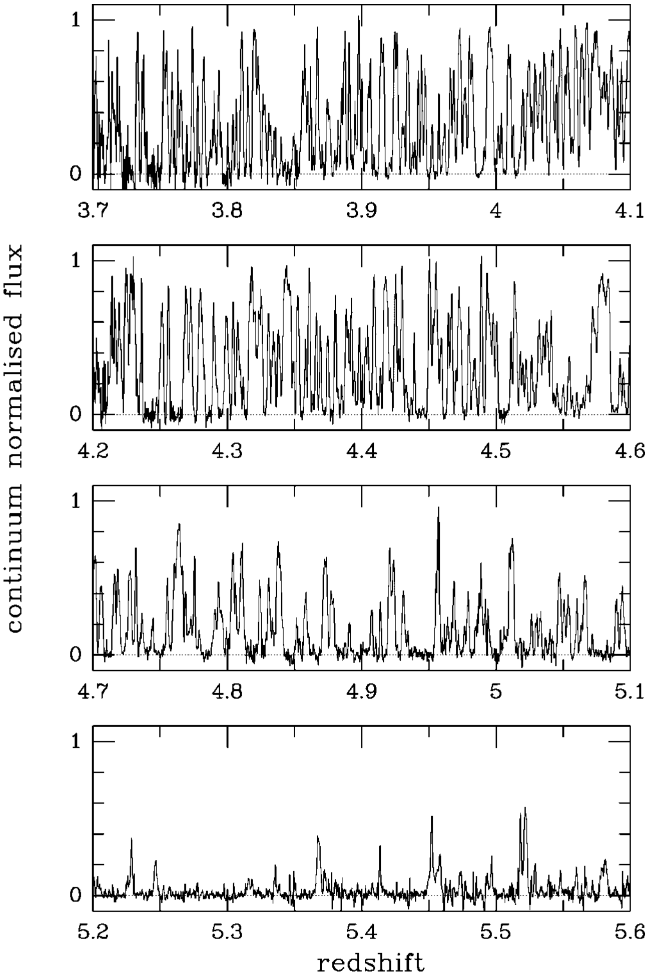

FIG. 3.—Schematic illustration of the evolution of the Lyα forest, in four redshift intervals. The top two panels are from an ESI spectrum of SDSS 1737+5828 at $z = 4.94$; the bottom two are from the spectrum of SDSS 1044−0125, presented here. The spectra have been renormalized by the best estimate of the continuum (for the bottom two panels, we used the middle power law shown in Fig. 1). Almost all narrow spikes in the bottom panel are due to imperfect night-sky emission-line subtraction.

The few remaining transmission spikes are naturally interpreted as being due to the as yet unpercolated reionization bubbles along the line of sight. An issue arises of whether the damping wings of the remaining neutral hydrogen clouds would suppress such transmission spikes (see, e.g., Miralda-Escudé 1998). However, as shown by Madau & Rees (2000) and Cen & Haiman (2000), this depends strongly on the extent of the Strömgren spheres produced by the ionized sources, i.e., their luminosities and lifetimes, akin to the usual quasar proximity effect. Indeed, one expects some clustering of the first luminous sources, which are expected to form at the highest peaks of the density field, due to biasing (see, e.g., Djorgovski 1999 and references therein). The probably massive host of SDSS 1044−0125 is likely to have some luminous neighbors.

We also checked whether any of the dark regions we see at $z \sim 5.2$–5.6 may be damped Lyα systems with associated metallic lines, mainly the C IV doublet. None were found, as is expected from as yet unenriched gas.

In their discovery paper, Fan et al. (2000) addressed the issue of reionization and concluded that it is not detected in their data, on the basis of the few remaining transmission spikes. Their heavily binned spectrum seems roughly comparable to our LRIS data shown in Figure 1, from which we cannot conclude much; a higher resolution spectrum, such as our spectrum shown in Figure 2, is necessary. Furthermore, in their original redshift interpretation (which was due to the then unknown BAL nature of the object), Fan et al. (2000) may have mistaken the leftover quasar flux around the Lyα as being a part of the Lyα forest.

After this Letter was submitted, Becker et al. (2001) presented spectroscopy of this and three additional quasars at $z \sim 5.82$–6.28, discovered by Fan et al. (2001). They present compelling evidence for a Gunn-Peterson trough in the spectrum of the most distant quasar, suggesting the reionization epoch at $z \sim 6$, as anticipated here. This is a crucial result.

However, the discussion of the remaining spectra by Becker et al. (2001) was limited by the available data, with relatively short exposure times. In order to increase the apparent S/N, they binned the spectra by a factor of ∼25 in wavelength, from ∼0.154 to 4 Å pixel^{-1}. The resulting loss of resolution makes it hard to detect dark windows similar to those seen in our ESI spectrum, especially given the differences in the S/N. They further evaluated the mean optical depth in very wide bins, with $\Delta z = 0.2$, which clearly precludes the detection of any dark windows with a smaller extent in redshift. Given these differences in the data and the analysis, we see no inconsistencies with our results.

Taken together, the data so far suggest an extended and patchy end to the reionization era, as expected from modern models of structure formation and of the reionization itself. Probing along more lines of sight with high-S/N, high-resolution spectroscopy is necessary in order to place more quantitative observational constraints. Further insights will be obtained from direct detections of luminous sources responsible for the reionization at these and higher redshifts, their luminosity function, and clustering properties.

We thank the staff of the W. M. Keck Observatory for their expert assistance. The LRIS data were obtained in the course of a collaborative project with F. Harrison and P. Mao. We thank numerous colleagues whose constructive comments helped us improve the discussion presented in this Letter. S. G. D. acknowledges partial funding from the Bressler Foundation. The work of D. S. was carried out at the Jet Propulsion Laboratory, Caltech, under a contract with NASA.

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