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A ~10 Mpc VOID IN THE Lyα FOREST AT $z = 3.17$[1]

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ABSTRACT

The spectrum of the $z = 3.285$ quasar, Q0302−003, shows a large (~10 Mpc) void in the Lyα forest at $z \approx 3.17$. By simulating the absorption spectrum of the quasar with a range of Lyα forest cloud parameters, we find that the probability of such a void occurring by chance is $\sim 2 \times 10^{-4}$. Since the void is near (although not centered on) the redshift of a bright foreground quasar, we discuss the possibility that the void results from ionization of the clouds by the EUV radiation of this QSO.

Subject headings: cosmology — galaxies: intergalactic medium — quasars

1. INTRODUCTION

The narrow Lyα absorption lines seen in the spectra of high-redshift quasars are generally believed to originate in primordial chemical composition clouds distributed in intergalactic space. Various models for these clouds have been proposed, which include clouds in pressure equilibrium with the hot intergalactic medium (Ikeuchi & Ostriker 1986), clouds confined gravitationally by minihalos of cold dark matter (Rees 1986), winds from dwarf galaxies (Fransson & Epstein 1982), and many others.

Comparison of the large-scale distribution of the Lyα forest clouds with the predicted distribution of various astronomical objects can elucidate the origin of the clouds. The distribution of clouds at $z = 2$–3 exhibits very little, if any, clustering (Sargent et al. 1980; Bechtold 1987; Webb 1987; Ostriker, Bajtlik, & Duncan 1988; Webb & Barcons 1991), while if the clouds were protogalaxies, we would expect them to show structures similar to those shown by present-day galaxies (Salmon & Hogan 1986). Several authors have searched for megaparsec-sized voids in the Lyα forest, but only one has been reported so far, and its statistical significance has been questioned (Carswell & Rees 1987; Crotts 1987, 1989; Ostriker et al. 1988; Duncan, Ostriker, & Bajtlik 1989; Bi, Bonner, & Chu 1989; see Bechtold 1990 for review). By contrast, large (with sizes of the order of tens of megaparsecs) voids are known in the distribution of galaxies, with a volume filling factor of the order of 90% (de Lapparent, Geller, & Huchra 1986; Kirshner et al. 1987).

Voids in the Lyα forest can serve as a test for various theoretical models for large-scale structure. However, lack of Lyα forest absorption lines may not necessarily mean that a particular volume of space contains no hydrogen. We observe the clouds only through Lyα absorption, i.e., the presence of H I. If the clouds in one area were for any reason more ionized than average, more of the hydrogen would be H II, and we could observe a void there. Recently, several groups (Bajtlik, Duncan, & Ostriker 1988; Kovner & Rees 1989; Lu, Wolfe, & Turnshek 1991) have discussed the so-called proximity effect—enhanced ionization of Lyα clouds in the vicinity of quasars—which may induce voids in the distribution of the clouds.

In this *Letter* we present a void in the Lyα forest in the spectrum of the $z_{\rm em} = 3.285$, $m(1450\ \text{Å}) = 17.79$ quasar, Q0302−003 (Barbieri & Cristiani 1986; hereafter we will refer to this quasar as Q1), which we believe is statistically significant. The difficulty in establishing a void's significance originates primarily from the uncertainties in the cloud number density and its evolution. The probability that a given void is significant depends exponentially on the line density (Ostriker et al. 1988); therefore, small uncertainties in line statistics result in large uncertainties in void statistics. We avoid these uncertainties by simulating the absorption spectrum of the considered quasar with a variety of input parameters and then use an automated line-searching procedure for both the simulated spectra and the original spectrum. We compare the distribution of the line separations in the simulations with the observed distribution and thus estimate the statistical significance of the void.

The void lies at a redshift close to the redshift of a nearby bright foreground quasar, Q0301−005 ($z_{\rm em} = 3.223$, hereafter Q2), and therefore is an attractive candidate for being produced by the proximity effect. We discuss this possibility and use it to estimate the UV background at the redshift of the void.

2. ANALYSIS

2.1. *Observations*

Spectra were obtained in 1989 September, November, and December at the MMT, with the Red Channel spectrograph (Schmidt, Weymann, & Foltz 1989), TI CCD, and "high-resolution echellette" grating, and with the Blue Spectrograph, Reticon photon counter, and 832 lines mm^{-1} grating in second order (Latham 1982). The Red Channel spectra were flattened and extracted using IRAF routines in the usual way, calibrated with exposures of a He-Ne-Ar lamp and further reduced with the use of software developed by us (see Bechtold & Shectman 1989). The Reticon data were reduced in the standard way with the Ohio State IRS software. The combined spectrum has a resolution of ~120 km s^{-1} (FWHM) and approximately uniform signal-to-noise ratio of the order of 14 per resolution element in the Lyα forest region of the spectrum (Fig. 1). The Blue Spectrograph spectrum had slightly better resolution and was rebinned before combining with the other spectra. The raw counts of the spectra (sky + object) were preserved and used to determine the variance. The dotted line on Figure 1 shows the 1 σ noise.

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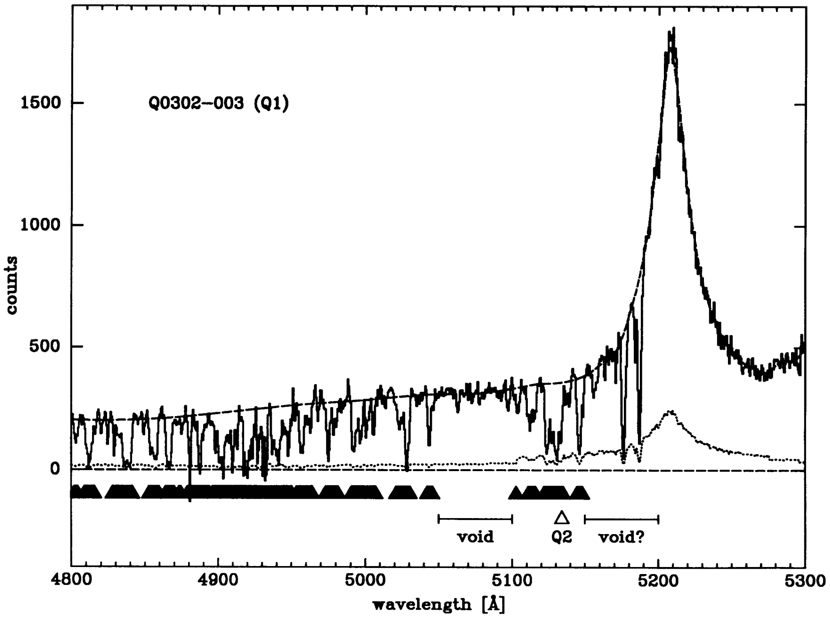

FIG. 1.—The spectrum of Q0302−003 (Q1). The dotted line shows the 1 σ noise; the dashed line shows the continuum fit. Black triangles mark the positions of the absorption lines detected with the use of our automated procedure. Two lines not marked, at 5177 and 5187 Å, are most probably Mg II lines from the absorber at $z_{abs} = 0.85$. The positions of two void candidates are marked. The open triangle marks the redshift of a bright foreground quasar, Q0301−005 (Q2), separated from the line of sight to Q1 by 17′.

The continuum was fitted to the spectrum with a cubic spline, as described by Bechtold & Shectman (1989). We then used an automated procedure to find the significant lines in the spectrum (after Young et al. 1979). This routine marked the resolution elements for which the absorption equivalent width was greater than 5 times the equivalent width uncertainty. The contiguous resolution elements flagged were then combined and counted as one line. The " line list " constructed in this way was used in the further analysis. We emphasize that such a list is different from usual line lists as it contains many blended but clearly distinct lines, which we treat as if they were single. However, using this method, we do not lose any information about the voids.

2.2. *The Void at $z \approx 3.17$*

There is an apparent lack of absorption lines in the spectrum of Q1 between $\lambda \approx 5050$ Å and $\lambda \approx 5100$ Å (redshift of ~3.15 and ~3.20, respectively). This corresponds to the proper size of the void of $6h_{75}^{-1}$ Mpc for $q_0 = 0.5$, or $15h_{75}^{-1}$ Mpc for $q_0 = 0.1$ ($h_{75} = H_0/75$ km s^{-1} Mpc^{-1}). The 5 σ rest equivalent width threshold for the Lyα lines at the position of the void for our spectrum is equal to 0.15 Å, which means that inside the void there is no cloud with neutral hydrogen column density greater than 3×10^{13} cm^{-2}.

There is also a second possible void in this spectrum, between $\lambda \approx 5150$ Å and $\lambda \approx 5200$ Å, as the two lines at 5177 and 5187 Å are most probably Mg II absorption lines ($\lambda\lambda$2796, 2804) at $z_{abs} = 0.85$; in other data (not shown) we have also identified two Fe II lines ($\lambda\lambda$2587, 2600) belonging to this absorption system. In our analysis, however, we will concentrate on the first, much more obvious void candidate and return to the second one later.

In order to estimate the significance of the void, we have developed a numerical Monte Carlo code which generates artificial QSO absorption spectra. The simulated spectra had the same spectral resolution, signal-to-noise ratio, and sampling as the spectrum shown in Figure 1 and were analyzed in the same way. Our aim in running the simulations was to reproduce the observed scaled line separation and then estimate the probability of seeing a gap as large as the gap between 5050 and 5100 Å by chance. Detailed description of the code and of the analysis process is presented elsewhere (Dobrzycki & Bechtold 1991).

Because the line density changes with redshift, we scale each line separation by the local line density, as in Ostriker et al. (1988). Namely, we consider x, the ratio of the line separation in redshift, Δz, to the local average line separation, $\langle \Delta z \rangle$:

$$x = \frac{\Delta z}{\langle \Delta z \rangle}, \tag{1}$$

where

$$\langle \Delta z \rangle \equiv [A^*(1+z)^\gamma]^{-1}, \tag{2}$$

which comes from the usual way of parameterizing the line number density evolution, $dN/dz = A^*(1+z)^\gamma$.

In order to reproduce the observed distribution of gaps, we simulated the spectrum of Q1 varying both the input total number of lines and γ. Then we compared the simulated distribution with the distribution in the spectrum of Q1 (including the candidate void) in order to derive A^* and γ. We stress (and indicate with the index $*$) that A^* is different here from what we would have if we were using a line list. We found that our results did not depend strongly on the value of γ used, for γ ranging from -1 to 5. This is not surprising, since in the case of our single spectrum the redshift range covered is relatively short and the value of the number density evolution index is therefore not strongly constrained.

We show the cumulative distributions of the scaled line separations for our best fit on Figure 2; the Kolmogorov-Smirnov probability that these two distributions agree is 0.95. In this best-fit case, the scaled size of the void is 10.1, i.e., this void is more than 10 times larger than the local average separation between lines or line blends. We emphasize that the scaled

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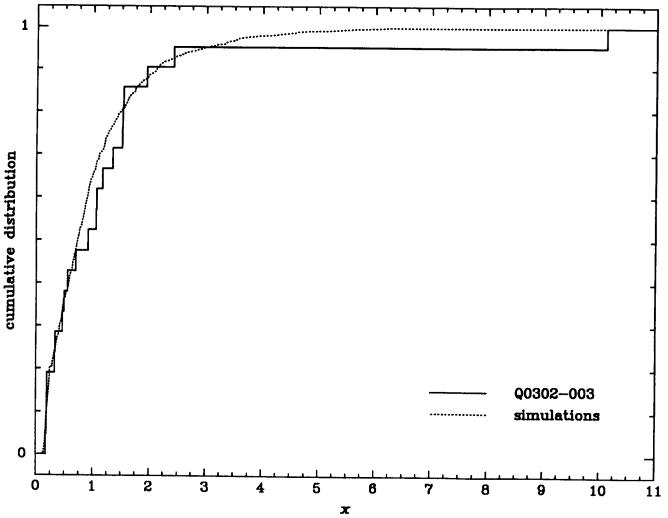

FIG. 2.—Cumulative distributions of the scaled void sizes, x, as defined in equation (1), in the simulations (*dotted line*) and in the observed spectrum (*solid line*).

size of the void would be much larger if we were using the normal line list, since our A^* is smaller than the usually derived A.

With A^* and γ from the best fit, we simulated the spectrum of Q1 over 50,000 times. A void as large as or larger than the candidate void occurred in only 11 of the simulated spectra. Thus, given the observed distribution of gaps in Q1, the probability of finding a gap that large or larger by chance is estimated to be $P_> = (2.2 \pm 0.7) \times 10^{-4}$.

One might argue that we should take into account the distribution of lines in other QSOs that have been observed previously. Clearly, if we were to observe a very large number of QSOs with randomly distributed absorption lines, the probability of observing any particular gap by chance approaches one. However, it should also be noted that in our case the void's scaled size has been derived from the distribution *fitted* to the distribution observed in Q1 (including the void), while the general distribution is most likely not the same. If the void is real, we expect that as more line intervals are considered, the distribution will be skewed toward small separations and our void will be farther out on the tail.

In order to estimate how sensitive our result is to uncertainties in our fit to the distribution of observed gaps, we estimated $P_>$ for a distribution that was 1 σ away from the distribution observed in Q1, in the sense of lower line density. In this case the scaled size of the void is 8.1, giving the upper limit for $P_>$ equal to $(2.5 \pm 0.6) \times 10^{-3}$.

2.3. *Implications for Background EUV Flux and Quasar Structure*

In Figure 1, the open triangle under the spectrum marks the redshift of a bright foreground quasar, Q0301−005 [Q2; m(1450 Å) = 18.16, $z_{\rm em} = 3.223$], separated from the line of sight to Q1 by 17′ (5–8h_{75}^{-1} Mpc). The center of the void is displaced by $\Delta z \approx 0.05$ blueward from Q2. The distance between the center of the void and Q2 is 7–17h_{75}^{-1} Mpc, depending on the cosmological model.

Barbieri & Cristiani (1986) list two more quasar candidates in the vicinity of Q1. However, 0302−0016 is a star (Corbally 1991), and 0301−0029 is much fainter ($V \sim 19.0$) and farther away (20′) from Q1 than Q2. Apart from these two and Q2, there are no other quasars or quasar candidates in the 30′ circle around Q1 brighter than ~20 mag.

Because of the presence of Q2 it is possible that the void is produced by the proximity effect. If this is the case, then we would like to use the observed spectrophotometry of Q2 to estimate the ambient background UV flux at the Lyman limit, by requiring that at the position of the void the ionizing flux from Q2 dominates over the background flux. Also, we would like to place a lower limit on the lifetime of Q2 by requiring that the quasar has been shining long enough for its ionizing front to reach the void.

However, since the void is displaced from Q2, it is clear that the simplest such picture is not appropriate. There are several possible effects which could produce a displaced proximity effect void. First, Q2 may not be radiating isotropically but may be obscured at right angles to the line of sight (Sanders et al. 1989; Antonucci & Miller 1985). Second, Q2 may have "turned on" on a time scale close to the light travel time to the void. In this case, we still see the lines at its redshift because the information on their increased ionization has been so far unable to reach Earth because of the longer light path (Felten 1991). Moreover, in relating the observed spectrophotometry of Q2 to the background UV radiation field, one assumes that the QSO has not varied significantly on time scales shorter than the quasar-void light travel time (in this case ~30 million yr) or the cloud recombination time scale (about 10,000 yr, Bajtlik et al. 1988). Note that Crotts (1989) also found evidence for either anisotropic emission or at least ~Myr QSO lifetimes in his analysis of the proximity effect in quasar spectra near the redshift of close quasars.

If Q2 is not an isotropic source, a schematic picture of both quasars is shown in Figure 3. The possible existence of a void in the spectrum of Q1 at higher redshift than Q2 seems to support this explanation, giving a nice picture of the beamed radiation from the quasar in two opposite directions. Assuming that Q2 is an axisymmetric source and that the wide lines in the spectrum of Q1 lie outside the radiation cones we can estimate the beaming angle (θ on Fig. 3). We find $\theta \approx 140°$, which is in good agreement with what is expected from the

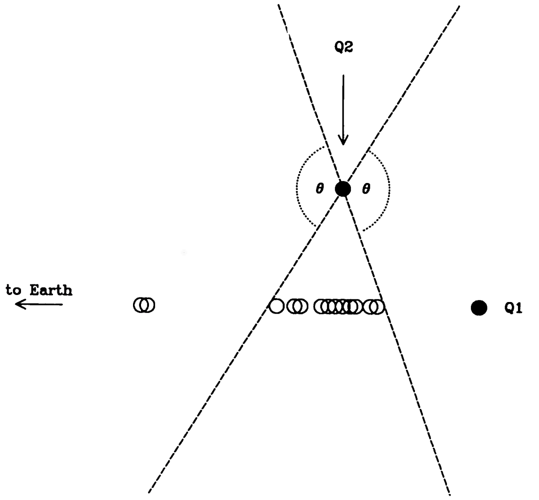

FIG. 3.—Schematic picture of the vicinity of Q0302−003 (Q1) and Q0301−005 (Q2), drawn to scale for $q_0 = 0.5$. Open circles mark the positions of the significant lines in the spectrum of Q1. We show the limits of the hypothetical radiation cones of Q2; the beaming angle θ is found to be approximately 140°.

accretion disk quasar model (Sanders et al. 1989). However, one has to remember that in the case of the higher redshift void, one cannot neglect the proximity effect from Q1 itself as its origin.

If we make the simplest assumption, that the energy emitted in the direction of the void is equal to the energy emitted toward Earth, then we can derive the ionizing flux at the Lyman limit from Q2 in the position of the void from available spectrophotometry. We have

$$\log F_\nu = \begin{cases} -21.0\,, & q_0 = 0.1 \\ -20.7\,, & q_0 = 0.5 \end{cases} \qquad (3)$$

in ergs $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{Hz}^{-1}$ (independent of Hubble's constant). We obtained these values by extrapolating the apparent magnitude at $\lambda_{\mathrm{rest}} = 1450$ Å to the Lyman limit with the power law, $f_\nu \propto \nu^{-\alpha}$. Both α and m(1450 Å) were taken from Sargent, Steidel, & Boksenberg (1989). We then derived the quasar luminosity at 912 Å and the flux from the quasar at the position of the void. Thus, we have

$$\log J_\nu < \log\left(\frac{F_\nu}{4\pi}\right) \approx \begin{cases} -22.0\,, & q_0 = 0.1 \\ -21.8\,, & q_0 = 0.5 \end{cases} \qquad (4)$$

in units of ergs $\mathrm{s}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{Hz}^{-1}\,\mathrm{sr}^{-1}$ for the upper limit for the UV background flux at the Lyman limit. We estimate the uncertainty in the value of $\log J_\nu$ to be 0.5, originating from uncertainties in the spectrophotometry and extrapolation to the Lyman limit.

This estimate of J_ν is one order of magnitude smaller than the value of $J_\nu = 10^{-21\pm0.5}$ ergs $\mathrm{s}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{Hz}^{-1}\,\mathrm{sr}^{-1}$ (Bajtlik et al. 1988; Lu et al. 1991), obtained from the statistical studies of the proximity effect. This disagreement can be accounted for in various ways. First, the quasar may radiate more energy in the direction of the void. A second possibility is that the discrepancy may be produced by quasar variability on time scales short compared to the larger of the quasar-void light travel time and the clouds's recombination time scale. Thus, in order to ionize the clouds to the necessary level in the epoch of observation, Q2 would have to be one order of magnitude brighter ~30 million yr ago.

We emphasize that the void significance we quoted in the previous section is a conservative value: it shows the probability of that large a void happening by chance in a random distribution of the Lyα clouds. We do not consider the probability of finding a void near the a priori known redshift of a foreground quasar.

3. CONCLUSIONS

1. We have shown that at $z \approx 3.17$ there exist a large (~10 Mpc) void in the Lyα forest in the spectrum of the $z = 3.285$ quasar, Q0302−003 (Q1). By simulating absorption-line spectra with a range of Lyα forest cloud parameters, we argue that the probability of seeing such a void by chance is $\sim 2 \times 10^{-4}$.

2. The void is placed near the redshift of a foreground quasar, Q0301−005 (Q2). There may be another void in the spectrum of Q1, also near Q2. From the assumption that the void is due to the proximity effect, we derived the background UV flux at $z \approx 3.2$ to be $J_\nu \approx 10^{-22}$ ergs $\mathrm{s}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{Hz}^{-1}\,\mathrm{sr}^{-1}$, which is smaller than the canonical value of $J_\nu \approx 10^{-21}$. The possible explanations of this discrepancy are (1) that the ionizing radiation from Q2 is highly anisotropic, and/or (2) that the quasar has decreased in brightness by a factor of 10 in the time scale of 3×10^7 yr, and/or (3) that the ambient background ionizing flux is really smaller than the often quoted value of $\log J_\nu \approx -21$.

3. If the void is due to the proximity effect, then the lifetime of Q2 has to be at least 3×10^7 yr. If the apparent displacement of the void with respect to the foreground quasar were caused by the light travel time effects, then this would be close to the actual lifetime of Q2.

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