The Astrophysical Journal, 621:89–94, 2005 March 1
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IMPLICATIONS OF THE Lyα EMISSION LINE FROM A CANDIDATE $z = 10$ GALAXY

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Received 2004 March 30; accepted 2004 August 6

ABSTRACT

The $z = 10$ galaxy recently discovered by Pello and coworkers has a strong Lyα emission line that does not appear to have the expected asymmetry with more transmission on the red side. The blue wing of a Lyα line originating at high redshift should be strongly suppressed by resonant hydrogen absorption along the line of sight, an expectation borne out by the observed asymmetric shapes of the existing sample of Lyα-emitting sources at lower redshifts ($3 < z < 6.7$). The observed line is inconsistent with the galaxy being embedded in a fully neutral intergalactic medium (IGM) and having no receding peculiar velocity relative to the surrounding absorbing gas at the 95.0%–98.8% confidence level. Absorption on the blue side of the line of the Pello et al. source could be reduced if the IGM in the vicinity of the galaxy is highly ionized, but we show that this requires an unrealistically high ionizing emissivity. We suggest instead that the Lyα-emitting gas is receding relative to the surrounding gas with a velocity of $\gtrsim$35 km s^{-1}, which reduces the inconsistency confidence level to less than 76.0%–94.5%. We find that with this velocity shift, the observed strength and shape of the line is more consistent with the galaxy being surrounded by its own Strömgren sphere embedded in a fully neutral IGM. More generally, we predict that at any given redshift, the bright Lyα emitters with broader lines would exhibit stronger asymmetry than fainter ones. Bright galaxies with symmetric Lyα lines may be signposts for groups and clusters of galaxies, within which they can acquire random velocities comparable to or larger than their line widths.

Subject heading: galaxies: high-redshift

Online material: color figures

1. INTRODUCTION

Three independent observations combine to paint a complex picture of the cosmological reionization process. First, the recent quasar absorption spectrum observations by the Sloan Digital Sky Survey show strong evidence that the reionization process completes at $z \sim 6$ (Becker et al. 2001; Fan et al. 2002; Cen & McDonald 2002). Second, the latest *Wilkinson Microwave Anisotropy Probe* (*WMAP*) observations detect a high Thomson scattering optical depth, suggesting that the intergalactic medium (IGM) experienced a significantly ionized state at high redshift somewhere between $z = 15$ and 25 (Kogut et al. 2003) for (at least) a significant redshift interval. This is somewhat contradicted by the third observational line of evidence of the IGM having a relatively high temperature at $z \sim 3$–4, which requires a reionization epoch no earlier than redshift $z = 9$–10 (Hui & Haiman 2003; Theuns et al. 2002). While the overall picture is consistent with a pre-*WMAP*, physically motivated double reionization model (Cen 2003; Wyithe & Loeb 2003), a detailed probe of the ionization state of the IGM at high redshift is sorely wanted.

Lyα emission lines from high-redshift sources can serve as probes of the ionization state of the IGM. The damping wing of the Gunn-Peterson (GP) absorption from the IGM can cause a characteristic absorption feature (Miralda-Escudé 1998). For a Lyα-emitting galaxy embedded in a partly neutral IGM, the absorption produces conspicuous effects, i.e., attenuating the emission line, making it asymmetric, and shifting its apparent peak to longer wavelengths (Haiman 2002; Santos 2004). In practice, the expectation is that strong conclusions cannot be drawn from a single galaxy. For example, the relatively strong Lyα line of the $z = 6.6$ galaxy discovered by Hu et al. (2002) is still consistent with being embedded in a neutral IGM but surrounded by its own ionized Strömgren sphere (Haiman 2002; Santos 2004).

The recent claim of the detection of a Lyα-emitting galaxy at $z = 10$ (Pello et al. 2004; hereafter P04) provides a new opportunity to study the IGM at $z = 10$. This source is especially interesting, since at its high inferred redshift, absorption by the IGM should increase significantly. In this paper, we examine both the observed shape and overall attenuation of the detected Lyα line, in models where the line is processed through the IGM. We find that in order to achieve the observed symmetry of the Lyα line profile, the emitting gas in the galaxy may be receding faster than the surrounding gas by at least 35 km s^{-1}. Given this required recessional velocity, we find that the P04 source is marginally consistent with being embedded in a fully neutral IGM at $z = 10$, with the line suffering an attenuation by a factor of 30.

Throughout this paper, we assume the background cosmology to be flat ΛCDM with $(\Omega_\Lambda, \Omega_m, \Omega_b, h) = (0.7, 0.3, 0.04, 0.7)$.

2. THE OBSERVED Lyα EMISSION LINE

We first consider a characterization of the symmetry of the observed Lyα emission line. The general expectation, based on simple models of absorption, is that the blue side of the line should be strongly suppressed relative to the red side (Haiman 2002; Santos 2004); this expectation is borne out by Lyα-emitting sources detected at lower redshifts, nearly all of which show such asymmetry when observed at high enough spectral

S/N (Rhoads et al. 2003; Shapley et al. 2003; Trager et al. 1997; but see Taniguchi et al. 2003 for a narrow-line emitter that does not clearly show a large asymmetry). All Lyα emitters at $z \sim 6.5$ display asymmetric profiles (Hu et al. 2002; Kodaira et al. 2003; Rhoads et al. 2004; Kurk et al. 2004; Stern et al. 2004; Taniguchi et al. 2004). In contract, Figure 5*b* of P04 reveals that the line is asymmetric in the opposite sense, with apparently more flux on its *blue* side. Our goal here is to quantify the significance of the apparent lack of the expected asymmetry. We define a flux ratio, $R \equiv L_b/L_r$, as a measure of the line symmetry, where L_b and L_r are the total flux in the Lyα line blueward and redward of its *apparent* peak wavelength, respectively.

In general, consider the spectrum of an emission line with significant flux detected in $N = N_b + N_r$ pixels (N_b and N_r being the number of pixels on the blue/red side of the line, respectively). The signal (flux) in each pixel is given by $b_1,\ b_2,\ \ldots,\ b_{N_b}$ and $r_1,\ r_2,\ \ldots,\ r_{N_r}$, with associated noise $\sigma(b_1)$, $\sigma(b_2)$, . . . , and $\sigma(r_1)$, $\sigma(r_2)$, . . . In this case, we can obtain the mean value and the uncertainty of the line asymmetry parameter R by usual error propagation as

$$\langle R \rangle = \frac{b_1 + b_2 + \ldots + b_{N_b}}{r_1 + r_2 + \ldots + r_{N_r}} \tag{1}$$

and

$$\sigma(R)^2 = \frac{\sigma(b_1)^2 + \sigma(b_2)^2 + \ldots + \sigma(b_{N_b})^2}{(r_1 + r_2 + \ldots + r_{N_r})^2} \tag{2}$$

$$+ \left[\sigma(r_1)^2 + \sigma(r_2)^2 + \ldots + \sigma(r_{N_r})\right]^2 \times \frac{(b_1 + b_2 + \ldots + b_{N_b})^2}{(r_1 + r_2 + \ldots + r_{N_r})^4}. \tag{3}$$

In the emission-line spectrum displayed in Figure 5*b* of P04, there are five pixels with $S/N > 1$ with fluxes of 0.77, 1.47, 1.50, 1.81, and 0.88 in order of increasing wavelength in units of 10^{-18} ergs s^{-1} cm^{-2} Å^{-1}, with the apparent line center at the fourth pixel. We take the noise to be a constant 0.2 in each full pixel. We choose to use the raw data (Fig. 5*b*) instead of the smoothed line profile (Fig. 5*a*) because the former allows us to more easily make a direct statistical comparison between models and observations, avoiding having to deal with the apparently doubly smoothed data. Assuming the line center at the middle of the fourth pixel, we find

$$R = 2.59 \pm 0.36. \tag{4}$$

Thus, the line appears to have an asymmetry with more flux on the *blue* side of the line, which is the opposite of the expectations.

A significant uncertainty here is the identification of the apparent center of the line. Given the rather noisy spectrum, the computed value of R could substantially vary depending on the choice of the apparent line center. We do a simple Monte Carlo analysis to derive the distribution of the R-values, under the assumption that each of the 5 pixels is a Gaussian distributed random variable, with the quoted mean and a noise of 0.2 in each pixel. For each ''realization'' of the array of 5 values, we first find where the apparent peak is, rather than assuming that it is the fourth pixel, before we compute the value of R. The probability distribution of R-values changes from a single Gaussian of width 0.36 to a three-peaked function, corresponding to whether the peak happens to lie at the second, third, or fourth pixel, as shown in Figure 1. Both probability distributions, as obtained from 100,000 Monte Carlo trials, are displayed in Figure 1 (the dashed curve correspond to the fixed peak, and the solid curve to the correctly identified peaks). We find that this increases the overall probability of $R < 0.9$ from a near-negligible $\sim 5\ \sigma$ event to about 14%.

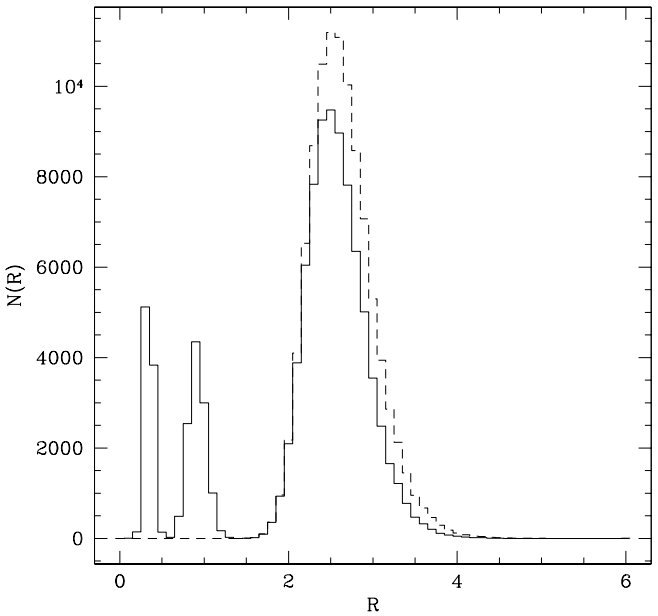


FIG. 1.—Probability distribution of R in 100,000 Monte Carlo trials, with the peak fixed at the 4th pixel (*red dashed curve*), and with the correct identification of the peak pixel (*blue solid curve*). The probability that the peak moves by 1 or 2 pixels to the blue is 11% and 9%, respectively, and we find that there is a 10% likelihood for $R < 0.9$.

Clearly, inferences about the apparent (a)symmetry of the emission line are greatly hampered by low spectral S/N and spectral resolution. Nevertheless, as we see below, the current data can already rule out specific predicted profiles that have small R values. It would be highly desirable to repeat this type of analysis with a higher quality spectrum, when available, possibly with the *James Webb Space Telescope* (*JWST*), although improvements should be possible with deep Keck/VLT spectra.

3. TRANSMISSION OF THE Lyα EMISSION LINE

An ionizing source embedded in the high-redshift IGM will maintain an ionized region around it (Strömgren sphere). We solve the equation of motion for the ionization front exactly (Shapiro & Giroux 1987; Cen & Haiman 2000; Haiman 2002) in an evolving density field, taking into account recombinations. The optical depth between the source and the observer at $z = 0$, at the observed wavelength $\lambda_{\rm obs} = \lambda_s(1 + z_s)$, is given by $\tau(\lambda_{\rm obs},\ z_s) = \int_{z_r}^{z_s} dz\, c(dt/dz) n_{\rm H}(z) \sigma_\alpha [\lambda_{\rm obs}/(1+z)]$, where z_s is the source redshift, $c\,dt/dz$ is the line element in the assumed ΛCDM cosmology, $n_{\rm H}$ is the neutral hydrogen density, σ_α is the Lyα absorption cross section at $\lambda_{\rm obs}/(1+z)$, and z_r is the reionization redshift. There are two separate contributions to the optical depth from within ($z_i < z < z_s$) and outside ($z_r < z < z_i$) the Strömgren sphere, where z_i is the redshift somewhat below z_s, corresponding to the boundary of the Strömgren sphere [$z_i \approx z_s - R_s/R_h(z_s)$, where $R_h(z_s)$ is the size of the cosmological horizon at z_s]. A numerically computed Voigt profile (see eq. [6] of Press & Rybicki 1993) is used for σ_α. Outside the Strömgren sphere the IGM is assumed to have a neutral fraction $x_{\rm H\,I}$ with mean density.

Inside the H II region, the neutral hydrogen density is calculated assuming photoionization equilibrium, with a gas temperature of $T = 10^4$ K. We assume a lognormal distribution for the gas density and compute the effective opacity $\tau_{\rm eff} = -\ln\langle\exp(-\tau_{\rm H\,I})\rangle$, where the brackets denote averaging over the probability distribution of $\tau_{\rm H\,I}$. We also adopt an ionizing emissivity of the source as described in the next section. We find that our results are insensitive to the choice of clumping (defined as $C \equiv \langle n_{\rm H}^2\rangle/\langle n_{\rm H}\rangle^2$) in the range $1 < C < 1000$ as a result of two competing factors. On one hand, a larger C gives a larger fraction of low optical depth regions for the assumed density distribution. On the other hand, a larger C results in a larger overall neutral fraction in ionization equilibrium. Therefore, the adoption of the lognormal form for the density distribution is not critical for our results. Nevertheless, to explicitly check the validity of the assumption of a lognormal density probability distribution function (pdf), we derive the pdf directly from a hydrodynamic simulation (see Cen et al. 2004 for details). We find that the adopted lognormal distribution is significantly broader than the simulated results (with the effective gas clumping factor closer to 2.7 at $z = 10$ in the simulation). Thus, our calculation here is conservative, in the sense that it underestimates true residual absorption hence asymmetry. In the subsequent calculations we use a lognormal density pdf with a chosen clumping factor $C = 10$.

4. RESULTS

We use a fiducial model to find the attenuation of the Lyα line as a function of wavelength. Our model starts with a Gaussian emission line at z_s, and assumes that the source is surrounded by a spherical Strömgren sphere that propagated into the IGM with a uniform neutral fraction $x_{\rm H\,I}$. If the Lyα line escaping host galaxy were already intrinsically asymmetric (with more flux on the red side) as a result of internal radiative transfer effects, our subsequent analysis would be somewhat too conservative. The fiducial model we adopt has the following parameters: $z_s = 10.00175$ (source redshift); SFR $= 3\ M_\odot\ {\rm yr}^{-1}$ (or $\dot{N}_\gamma = 1.1 \times 10^{53}$ ionizing photons per second, corresponding to a usual Salpeter IMF); $\Delta v_i = 70\ {\rm km\ s}^{-1}$ (intrinsic line width, equivalent to FWHM = 4.4 Å); $f_{\rm esc} = 0.50$ (escape fraction of ionizing radiation); $t_s = 10^8$ yr (age of the source); $\Delta v = 0\ {\rm km\ s}^{-1}$ (velocity offset of line relative to its surrounding absorbing gas); $x_{\rm H\,I} = 1$ (neutral fraction in IGM outside H II region); and a lognormal density pdf with the chosen clumping factor $C = 10$.

Our results for the resulting effective optical depth and transmitted line profile in the fiducial model are shown in Figure 2. The key output parameters can be summarized as follows: $R_s = 0.28$ Mpc physical (3.1 Mpc comoving), $F/F_0 = 0.02$ [attenuation of total line flux, not including the factor of $(1 - f_{\rm esc})$ discussed below], FWHM = 2.3 Å of the transmitted line, and $R = 0.56$.

The attenuation of the line is large, but within the extreme of the limits quoted by P04 (SFR = 0.8 from line, SFR = 75 from UV, implying a factor of 94 attenuation overall). Note that when comparing our results to the ratio of the star formation rate (SFR) inferred from the line and the continuum, the line attenuation has to be multiplied by the fraction $(1 - f_{\rm esc})$ of the ionizing photons that do not escape from the galaxy and hence contribute to powering the Lyα line (on the other hand, a small $f_{\rm esc}$ will result in a small Strömgren sphere and large attenuation; see Haiman 2002 for further discussion). We find that the product of the attenuation times $(1 - f_{\rm esc})$ is maximized for $f_{\rm esc} \sim 0.5$. Overall, in the model shown in Figure 2, the SFR as estimated from the line strength would be a factor of $0.5 \times 0.02 = 0.01$ of the true value. The line width is reduced by $\sim$50% to 2.3 Å, but is consistent with the observed width. However, *the asymmetry is significant*: $R = 0.56$, in apparent conflict with the observed value of R. We perform a Monte Carlo simulation to quantify the probability, with which our fiducial model can be rejected, as follows.

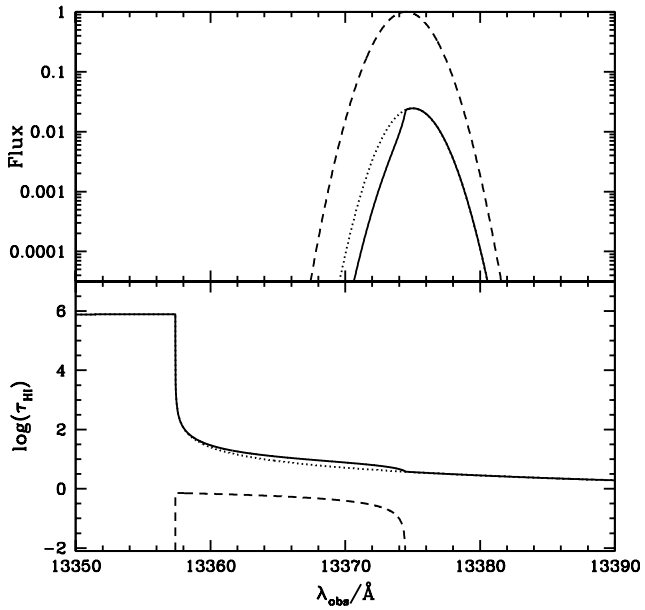


FIG. 2.—Effects of absorption by the ambient IGM on the emitted Lyα line. The bottom panel shows the Lyα line opacity from the damping wing of the GP trough of the IGM (Miralda-Escudé 1998) (*dotted curve*), and from the neutral H I within the Strömgren sphere (*dashed curve*). Note that for the latter, we compute the effective opacity $\tau_{\rm eff} = -\ln\langle\exp(-\tau_{\rm H\,I})\rangle$, where the brackets denote averaging over the probability distribution of $\tau_{\rm H\,I}$. We assume a lognormal density distribution, with its only free parameter, C, set to 10; and ionization equilibrium within the H II region, implying $\tau_{\rm H\,I} \propto \rho^2$. The solid curve shows the total opacity (sum of GP damping wing and resonant absorption). The top panel shows the intrinsic line emitted by the galaxy, assumed to be a thermally broadened Gaussian with a width of 70 km s^{-1} (the normalization is arbitrary, shown by the dashed curve). The dotted curve shows the transmitted profile in the presence of the GP damping wing, but ignoring absorption from within the H II region. Note that the line would be symmetric. The solid curve shows the transmitted profile including both the GP damping wing and the resonant absorption within the H II region. The line is asymmetric with $R = 0.56$. [*See the electronic edition of the Journal for a color version of this figure.*]

We start with the fiducial spectrum shown in our Figure 2 (*top panel, solid curve*) having $R = 0.56$, which is then convolved with the instrumental point-spread function (PSF) (as kindly provided in an electronic data file by D. Schaerer). This symmetrizes the line to have $R = 0.82$. We then sample it at the observed pixel scale of 0.62 Å, center a middle pixel at the wavelength of the apparent peak, and place 4 pixels on either side of it, for a total of 9 pixels surrounding the apparent peak after the convolution. Subsequently, we rescale the fluxes so that the peak flux equals the apparent peak flux in Figure 5*b* of P04 (the value is 1.81), add Gaussian noise (with rms = 0.2) to each of the 9 pixels independently. Finally, we measure R in the resulting 9 pixel spectrum and compare it with that measured directly from the raw data (above). Using 100,000 trials, we find that the probability of exceeding $R = 2.59$ in our fiducial model is 1.2%. It is therefore justified to conclude that the fiducial model is in significant conflict with the observed data.

The central point is that while most of the overall line attenuation is due to the damping wing (Fig. 2, *dotted curve*),

the asymmetry is caused by the resonant H I in the H II region (Fig. 2, *dashed curve*), because the former runs much more smoothly across the central region of the Lyα line than the latter, in this case with $\Delta v = 0$.

There are several ways, in principle, to make the transmitted Lyα line profile symmetric, to be in accord with the observed one. (1) The IGM is highly ionized by a strong background flux that reduces the neutral fraction, even near the galaxy. We find that a neutral fraction of $x_{\rm H\,I} \lesssim 1.3 \times 10^{-7}$ would be required to produce a line with a symmetry parameter of $R > 0.9$. This would require an unrealistically large ionizing background of $\Gamma_{12} \sim 1000$ s^{-1}. (2) The intrinsic width of the Lyα emission line is large. We find that the width would have to exceed $\sim$1000 km s^{-1}. This is in clear conflict with the observed line width of less than 200 km s^{-1}. (3) The SFR of the galaxy is high, reducing the neutral fraction inside the H II region. We find that an SFR of at least a factor of 300 higher than we used in the fiducial model would be required, which is unrealistically high compared to the values inferred by P04. (4) The emitting galaxy happens to sit inside a large H II region produced by other sources, which are not detected. None of these options appears to be physically plausible, except method (4), which may require a more detailed discussion. For method (4) a quasar seems unlikely, because it would be easily detectable even without gravitational lensing magnification. However, a group of strongly clustered small galaxies around this emitting galaxy that collectively amount to a luminosity that is more than 300 times the assumed luminosity of the detected galaxy could restore the symmetry of the Lyα emission line. This would require packing all of these galaxies into a region of comoving size of $\leq$150 kpc. While not impossible, this seems unlikely, because these putative galaxies would be nearly touching one another, and also because more than one of these galaxies would be expected to lie close enough to the lensing caustic to be detectable.

We here suggest an alternative, physically compelling possibility: that is, that either the emitting galaxy or the emitting gas in the galaxy is receding with a velocity relative to the surrounding absorbing gas in the H II region. Figure 3 shows the flux ratio and attenuation as a function of the assumed recessional velocity. We see that both the observed line profile and line attenuation can be made to match the observation, if the recessional velocity is at least 35 km s^{-1}. Physically, the Lyα-emitting gas needs to recede with a velocity that is comparable to the half-width of the Lyα emission line in order to escape from the residual absorption inside the Strömgren sphere for the blue branch. We find that the raw asymmetry with this velocity changes from 0.56 to 0.9 (before smoothing), or from 0.82 to 0.95 (after smoothing). The likelihood that this 35 km s^{-1} model is correct is 4.4% (to be compared with 1.2% for the fiducial model), which is a significant improvement over the fiducial model. Models with still larger recessional velocities would be still somewhat more acceptable.

We note that, in order to perform the above likelihood analysis, we had to make a few somewhat ad hoc choices:

The location of the central pixel used to sample the theoretical profile.—We allow this location to vary by $\pm$ half a pixel and find that this has little effect on the resulting likelihood (still 1.2% for the fiducial model).

The number of pixels used to sample the line.—If we use the middle 5 pixels, instead of 9 pixels, the probability increases by a factor of $\sim$2.

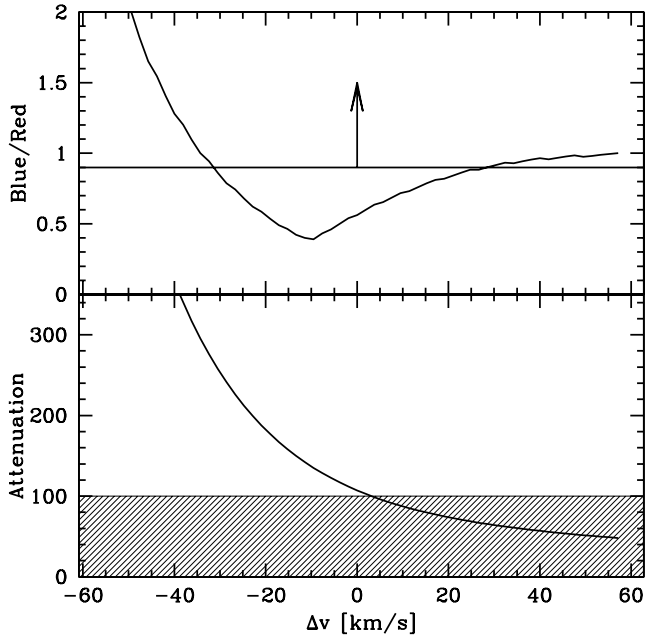


FIG. 3.—Apparent line asymmetry (defined as the ratio of fluxes on the blue and red side of the apparent line) and the total line attenuation (defined as the ratio of the total transmitted flux and the emitted flux) as a function of the assumed velocity offset of the Lyα-emitting gas relative to the Hubble flow. The cross-shaded regions in the bottom panel and the region containing the vertical arrow in the top panel indicate permitted regions, given the observed line profile (*top*) and the observed Lyα flux to continuum flux ratio (*bottom*). Note that the line can be symmetrized by either a negative or positive velocity. For positive velocities (representing extra redshift), the shift needed is approximately half of the apparent line width to move the line out of the resonant absorption. Negative velocities with a similar magnitude also symmetrize the line. This is because the line is more heavily absorbed, and the apparent peak then corresponds to a wavelength on the red wing of the intrinsic line, with the peak of the intrinsic line yielding a substantial blue wing for the transmitted line. However, the overall attenuation of the line in this case is too large for the parameters of the Pello et al. (2004) source.

The peak flux value.—If we allow 1.6 instead of 1.8, this makes the noise relatively more significant and easier to produced high R values; the probability is boosted by a factor of $\sim$2.

The statistic we use.—We could have decided to allocate the flux in the entire peak pixel to the red side (rather than splitting equally between red and blue), both in the data and in the prediction. The data would then have $R = 1.39$ (not 2.59), and it would be about twice as easy to fit it (likelihoods increase by a factor of 2).

When all four effects are included, the overall likelihood is 5.0% for the fiducial model, while the likelihood for the 35 km s^{-1} model increases to a much more acceptable 26%. Hence, the 35 km s^{-1} model fares a factor of 4–5 better than the fiducial model, clearly making the model statistically much more likely. However, a more discriminatory analysis would only be possible when better observations become available.

Let us now examine the possibility of having a recessional velocity of 35 km s^{-1}. One option is that the Lyα-emitting gas within the galaxy has a recessional velocity of 35 km s^{-1} relative to the surrounding gas. Such a velocity may be produced by outflowing gas powered by supernovae, which is ubiquitously seen at lower redshift (Shapley et al. 2003). It would be natural to suppose that such a high-redshift galaxy is also capable of blowing winds at $\geq$35 km s^{-1}. However, this solution is probably not viable, because outflowing gas is expected to

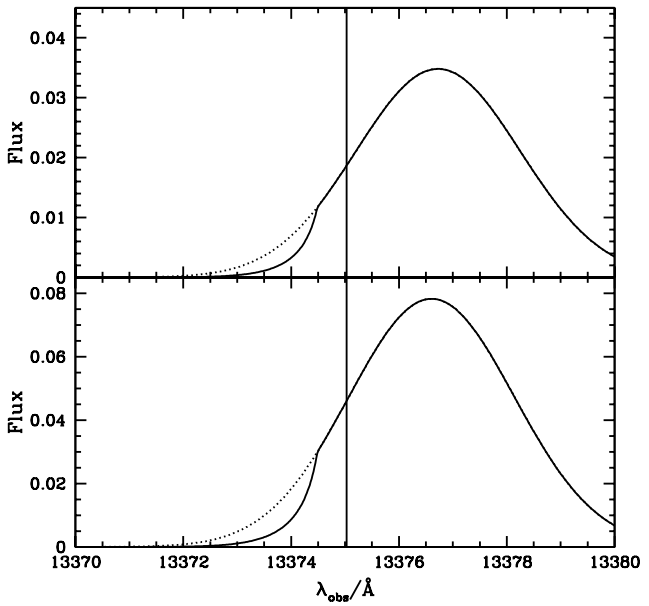


FIG. 4.—*Top*: $x_{\rm H\,I} = 1$ and $\Delta v = 35$ km s^{-1}; *bottom*: $x_{\rm H\,I} = 0.8$ and $\Delta v = 35$ km s^{-1}. In each panel the dotted curve shows the Lyα emission line with only the damping wing due to the IGM, whereas the solid curve includes absorption by both damping wing and residual neutral hydrogen inside the Strömgren sphere. The total transmission is now reduced by a factor of 60 (*top*) and 30 (*bottom*), as opposed to 100 in the $\Delta v = 0$ model (Figs. 2 and 3). We further note that for $x_{\rm H\,I} = (0.6,\ 0.17)$ the attenuation becomes (13, 3) (not shown in the figure). [*See the electronic edition of the Journal for a color version of this figure*.]

always result in asymmetric intrinsic Lyα lines with more flux on the red side prior to additional scattering by IGM, as confirmed by Lyman break galaxies (Shapley et al. 2003) at $z = 3$–4, which are known to launch winds at speeds comparable to, or exceeding the line widths. Higher redshift Lyα emitters at $z = 5$–6 all seem to show asymmetric Lyα line profiles (Rhoads et al. 2003), where some preliminary evidence for winds has been reported (Ajiki et al. 2002; Frye et al. 2002).

Second, we consider the possibility that the galaxy itself has a recessional velocity greater than 35 km s^{-1} relative to the ambient IGM. Using linear theory, we find that the rms bulk velocity of a sphere of radius of 0.5 Mpc is 65 km s^{-1} at $z = 10$ in the standard ΛCDM model (Spergel et al. 2003), whereas the velocity dispersion inside such a sphere is only 6.6 km s^{-1}, which is much smaller than the required 35 km s^{-1} relative velocity between the galaxy and the surrounding gas. Note that most of the absorbing gas causing the asymmetry arises inside such a sphere (which is about a quarter of the Strömgren sphere). Therefore, while the galaxy and its surrounding gas may be moving together at a significant peculiar velocity, a recessional velocity of 35 km s^{-1} of the galaxy relative to its surrounding absorbing gas is unlikely. However, another possibility is that the detected galaxy is a member of a larger, group of galaxies, which have formed a nonlinear system, with a velocity dispersion of $\geq$35 km s^{-1}. In that case, the galaxy can be moving at $\geq$35 km s^{-1} relative to the surrounding gas. In addition, the presence of other, undetected galaxies would somewhat further help create a larger H II region and hence reduce the asymmetry. This, in fact, seems to us a compelling solution, in that it could also explain why the lower redshift galaxies do *not* have symmetric lines (they are not part of large enough virialized systems relative to the line width).

The suggestion for the need of this recessional velocity from the line symmetry alone raises the question: Can we place interesting constraints on the ionization state of the IGM? Figure 4 shows the emission-line profile for two cases with different neutral fractions for the IGM. While the adopted $f_{\rm esc} = 0.5$ is close to maximizing the transmitted line flux, we note that the Lyα line may have suffered additional obscuration by, for example, dust in the emitting galaxy. The combined uncertainty in $f_{\rm esc}$ and intrinsic absorption weakens the constraint on $x_{\rm H\,I}$. With $x_{\rm H\,I} = 1$ we find that the overall attenuation due to combined IGM and residual Lyα scattering is $\leq$70 (for $\Delta v \geq 35$ km s^{-1}), which is consistent the upper limit of 100 of P04. An 80% neutral IGM produces a total attenuation (including the factor of $1 - f_{\rm esc} = 0.5$) of $\leq$30, reasonably close to the midrange of 40 quoted by P04. However, if the intrinsic absorption including dust were 80%, and if the Lyα line to continuum ratio is at the low end of range (0.05) quoted by P04, then $x_{\rm H\,I} \leq 0.2$ would be preferred.

In conclusion, we find that if one allows a total attenuation of 60, then no strong constraint can be placed on $x_{\rm H\,I}$. Tighter constraints can only be made possible with (1) more accurate calibrations of SFRs using Lyα emission and UV continuum, and/or (2) a greatly improved knowledge of the intrinsic absorption of Lyα emission and UV continuum, although these improvements may not be possible in the near term.

5. DISCUSSION

Following the announcement of the $z = 10$ candidate galaxy, several recent works (Loeb et al. 2004; Ricotti et al. 2004; Gnedin & Prada 2004) have considered constraints on the neutral fraction of the IGM. In particular, allowing for a maximum attenuation factor of 40, Loeb et al. (2004) find a mild constraint ($x_{\rm H\,I} < 0.4$), and, allowing for a smaller maximum attenuation factor of 15, Ricotti et al. (2004) find a stronger constraint that is alleviated to allow a neutral universe only if $R_s > 5$ (comoving) Mpc. Our results here appear to be consistent with these findings. Gnedin & Prada (2004) have emphasized that a fraction of Lyα galaxies at $z = 10$ could escape strong attenuation because of variations along our line of sight in the shape and size of H II regions that surround individual sources at $z = 10$. In our treatment, we have utilized both the shape and attenuation of the observed line, and we reach a unique set of conclusions. In particular, we find that the rather unexpected asymmetry of the line with more transmission on the blue side of the line may be indication that the galaxy has a recessional velocity relative to the surrounding gas. We find that the Lyα-emitting galaxy with a recessional velocity 35 km s^{-1} would make the observed line profile much more probable (by a factor of 4–5) than without. Consequently, with such a preferred kinematic situation, we find that no strong constraint can be placed on $x_{\rm H}$ at $z = 10$, given other uncertainties.

If our interpretation of the Lyα emission-line profile is correct, we can deduce that at any redshift there should be a trend: the fraction of symmetric Lyα emission lines should decrease with increasing Lyα emission-line width. In addition, bright Lyα emitters with symmetric profiles may be signposts of groups and clusters of galaxies, within which they can acquire velocities comparable to larger than their line widths. We also note that a velocity dispersion of, say, 65 km s^{-1} for the larger group of galaxies implies a common dark halo mass of $2 \times 10^{10}\ M_\odot$ at $z = 10$, and we find, using the halo mass function from Jenkins et al. (2001), that there should indeed be

$\sim$1 such halos in the comoving volume of $\sim$20 Mpc^3 probed by P04 between $9 < z < 11$.

The expected surface density of dark matter halos between redshifts $z = 9$–11 with mass $5 \times 10^8\ M_\odot$ (the minimum halo mass for the galaxy itself inferred by P04) is estimated to be $\sim$0.03 arcsec^{-2}. Thus, it should not be a great surprise to find one galaxy strongly lensed in a targeted search behind a rich cluster whose Einstein ring size is of order of several arcsec. However, the inferred large intrinsic abundance of galaxies is still surprising when the implied near-IR counts are compared to observations (Ricotti et al. 2004). It will be highly desirable to enlarge the sample of such galaxies in the future, for a better estimate of their space density, as well as to acquire better statistics on constraints for the neutral fraction in the IGM.

6. CONCLUSIONS

We considered the implications of the detection of the highly attenuated Lyα emission line from a candidate $z = 10$ galaxy with apparently more transmission on the blue side. Normally, one would expect to have more flux on the red side rather than the opposite as observed, because of enhanced resonant absorption on the blue side by residual hydrogen. The likelihood of observing such a line is then formally quantified. We find that the observed line profile is inconsistent with the galaxy being embedded in a fully neutral intergalactic medium (IGM) with no recessional peculiar velocity relative to the surrounding absorbing gas at 95.0%–98.8% confidence level.

Having considered all likely factors and remedies, we suggest that the mostly likely solution to obtain such a line profile is that the emitting galaxy is receding relative to the surrounding absorbing gas by a velocity of at least 35 km s^{-1}. Such a moderate receding velocity improves the likelihood of the observed line by a factor of 4–5 so that the observed line is inconsistent with theory at less than 74.0%–95.6% confident level. Thus, while the difficulties and challenges associated with such observations are formidable, it is not a great surprise, in principle, to be able to detect galaxies with such Lyα emission lines at high redshift. However, with the required recessional velocity, this galaxy does not place a strong constraint on the ionization state of the IGM, given various uncertainties in the current data and lack of handle of the intrinsic absorption. A fully neutral universe, while not preferred, is still consistent with the observation.

A moderate increase in the sample size of such high-redshift galaxies will be highly valuable in statistical inferences for the ionization state of the IGM, based on the systematic dependence of the line properties on redshift and luminosity (Haiman 2002; Rhoads & Malhotra 2002). More urgent is to obtain a higher quality spectrum to better characterize the line profile, because the observed line width is not much larger than the instrument PSF and because the accuracy in the characterization of the line profile is severely limited by the number of pixels resolving the line. Although major improvements may have to await *JWST*, higher resolution spectra, by a factor of 2, should be possible to obtain with Keck and/or VLT.

We thank James Rhoads for useful conversations and the authors of P04 for providing the line profile and instrument response in electronic form. We thank the referee for many excellent suggestions that help clarify many issues concerning the uncertainties of the line profile. We gratefully acknowledge financial support by NSF through grants AST 03-07200 and AST 03-07291 (to Z. H.) and AST 02-06299 and AST 04-07176 (to R. C.), and by NASA through grants NAG5-13381 (to R. C.) and NAG5-26029 (to Z. H.).

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