IMPLICATIONS OF THE \textsc{Ly}α EMISSION LINE FROM A CANDIDATE Z=10 GALAXY

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Submitted to ApJ

ABSTRACT

The recently discovered \( z = 10 \) galaxy (Pello et al. 2004) has a strong \textsc{Ly}α emission line that is consistent with being surprisingly symmetric, even given the relatively poor quality of its spectrum. The blue wing of a \textsc{Ly}α 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 \textsc{Ly}α emitting sources at lower redshifts (\( 3 < z < 6.7 \)). Absorption on the blue side of the line of the Pello et al. source could be reduced if the intergalactic medium (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 \textsc{Ly}α emitting gas be receding relative to the surrounding gas with a velocity of \( \gtrsim 35 \) km/s, a large velocity that is plausible only if the galaxy is part of a larger system (group of galaxies) with a velocity dispersion \( \gtrsim 35 \) km/s. We find that with this velocity shift, the observed strength and shape of the line is still 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 \textsc{Ly}α emitters with broader lines would exhibit stronger asymmetry than fainter ones. Bright galaxies with symmetric \textsc{Ly}α lines may be signposts for groups and clusters of galaxies, within which they can acquire random velocities comparable to or larger than their linewidths.

Subject headings: cosmology: theory - galaxies: formation - early universe

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 \( z = 15 - 25 \) (Kogut et al. 2003) for (at least) a significant redshift interval. This is somewhat contradicted by the third observational line of evidence of the intergalactic medium 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.

\textsc{Ly}α 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 \textsc{Ly}α 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 2003). In practice, the expectation is that strong conclusions cannot be drawn from a single galaxy. For example, the relatively strong \textsc{Ly}α 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 2003).

The recent claim of the detection of a \textsc{Ly}α 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 Letter, we examine both the observed shape and overall attenuation of the detected \textsc{Ly}α line, in models where the line is processed through the IGM. We find that in order to achieve the observed symmetry of the \textsc{Ly}α line profile, the emitting gas in the galaxy must be receding faster than the surrounding gas by at least 35 km/s. 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 \( \Lambda \)CDM with \((\Omega_\Lambda, \Omega_m, \Omega_b, h) = (0.7, 0.3, 0.04, 0.7)\).

2. THE OBSERVED \textsc{Ly}α EMISSION LINE

We first consider a characterization of the symmetry of the observed \textsc{Ly}α 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 2003); this expectation is borne out by \textsc{Ly}α emitting sources detected at lower redshifts, nearly all of which show such asymmetry when at high enough spectral S/N (Rhoads et al. 2003; Shapley et al. 2003; Trager et al. 1997). In contrast, Figure 5a of P04 reveals that the line is nearly symmetric, with perhaps 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 \textsc{Ly}α 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 \( \sigma(b_1), \sigma(b_2), \ldots , \sigma(r_1), \sigma(r_2) \ldots \). In this case, we can obtain the mean value and the
uncertainty of the line asymmetry parameter $R$ by usual error propagation as follows:

$$\langle R \rangle = \frac{b_1 + b_2 + \ldots + b_N}{r_1 + r_2 + \ldots + r_N}$$

(1)

and

$$\sigma(R)^2 = \frac{\sigma(b_1)^2 + \sigma(b_2)^2 + \ldots + \sigma(b_N)^2}{(r_1 + r_2 + \ldots + r_N)^2} + \ldots$$

(2)

$$\ldots + \ldots \sigma^2(R) = \sigma(r_1)^2 + \sigma(r_2)^2 + \ldots + \sigma(r_N)^2$$

(3)

In the emission line spectrum displayed in Figure 5a of P04, there are six pixels with $S/N > 1$, with the apparent line center defined to lie at the center of the pixel. We therefore break the central pixel into half, and consider $b_1 = 0.35, b_2 = 0.75, b_3 = 1.25,$ and $b_4 = 0.8,$ and $r_1 = 0.8, r_2 = 1.4,$ and $r_3 = 0.6$, where the fluxes are quoted for pixels in order of increasing wavelength, and in units of $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. We take the noise to be a constant in each full pixel $\sigma(b_1) = \sigma(b_2) = \sigma(b_3) = \sigma(b_4)$, $\sigma(r_1) = \sigma(r_2) = 0.2$, and we lower its value by a factor of $\sqrt{2}$ for the central half-pixels, $\sigma(b_5) = \sigma(r_3) = 0.14$. We find

$$R = 1.12 \pm 0.05.$$  

(4)

Assuming the flux in each pixel is a normally distributed random variable, we find that the line significantly close to being symmetric, and, in fact, appears to have an asymmetry with more flux on the blue side of the line, which is the opposite of the expectations. For the sake of concreteness, in the rest of this paper, we will require $0.9 < R < 1.3$. Taking the data at face value, this corresponds to a $\sim 4\sigma$ statistical confidence limit on this ratio. However, we note that the observed line is only marginally resolved, with its width only approximately 40% larger than the spectral resolution (P04). We briefly examine the extent to which convolving the emission line with the instrumental response (approximately described by a 60 km/s Gaussian) reduces the asymmetry. As an example, we adopt a Ly$\alpha$ line, assumed to be described by a Gaussian with a width of 50 km/s, but with the blue flux suppressed by a factor of $\exp(-\alpha \Delta \lambda^2)$. Here $\Delta \lambda$ is the offset from the Lyman $\alpha$ wavelength, and $\alpha$ is a constant chosen such that the line has an asymmetry of $R = 0.90$. We find that when this line is convolved with the PSF, the asymmetry is degraded and somewhat symmetrized to $R = 0.92$. However, we also find that the effect of the convolution depends strongly on the otherwise poorly known intrinsic line width and shape. Thus, in order to decide whether the emission line of the P04 galaxy candidate is indeed as symmetric as it appears at the current, low spectral S/N and resolution, it would be highly desirable to repeat this type of analysis with a higher quality spectrum, when available.

3. TRANSMISSION OF THE LY$\alpha$ 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 $\lambda_{\text{obs}} = \lambda_s(1+z_s)$, is given by $\tau(\lambda_{\text{obs}}, z_s) = \int_{z_s}^{\infty} dz \frac{\rho_H(z) \sigma_{\text{IC}}(\lambda_{\text{obs}}/1+z)}{c dt/dz}$, where $c dt/dz$ is the line element in the assumed $\Lambda$CDM cosmology, $n_H$ is the neutral hydrogen density, and $\sigma_{\text{IC}}$ is the Ly$\alpha$ absorption cross-section at $\lambda_{\text{obs}}/(1+z)$. There are two separate contributions to the optical depth from within $(z_i < z < z_s)$ and outside $(z < z_i < z_s)$ 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 $R_H[z]$ 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 $\sigma_{\text{IC}}$. Outside the Strömgren sphere the IGM is assumed to have a neutral fraction $x_H$ with mean density.

Inside the HII region, the neutral hydrogen density is calculated assuming photoionization equilibrium, with a gas temperature of $T = 10^4$ K. We assume a log-normal distribution for the gas density and compute the effective opacity $\tau_{\text{eff}} = -\ln(\exp(-\tau_H))$, where the brackets denote averaging over the probability distribution of $\tau_H$. 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 $C = (n_H^2/[n_H^2])$ in the range $1 < C < 1000$ due to 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 log-normal form for the density distribution is not critical for our results. Nevertheless, to explicitly check the validity of the assumption of a log–normal density PDF, we derive the PDF directly from a hydrodynamic simulation (see Cen et al. 2004 for details). We find that the adopted log-normal 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.

4. RESULTS

We use a fiducial model to find the attenuation of the Ly$\alpha$ 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 $x_{HI}$. The fiducial model we adopt has the following parameters: $z_s = 10.00175$ (source redshift); SFR $= 3 M_{\odot}/yr$ (or $N_s = 1.1 \times 10^{53}$ ionizing photons per second, corresponding to a usual Salpeter IMF); $\Delta v_i = 70$ km/s (intrinsic linewidth, equivalent to FWHM= 4.4 Å); $t_{\text{esc}} = 0.50$ (escape fraction of ionizing radiation); $t_e = 10^8$ yrs (age of the source); $\Delta v = 0$ km/s (velocity offset of line relative to its surrounding absorbing gas); $x_H = 1$ (neutral fraction in IGM outside HII region); and a log-normal 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 1. 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 $(1-f_{\text{esc}})$ 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 when comparing our results to the ratio of the SFR inferred from the line and the continuum, the line attenuation has to be multiplied by the factor $(1-f_{\text{esc}})$ of the ionizing photons that do not escape from the galaxy and hence contribute to powering...
the Lyα emission line is large. We find that the width would have to exceed $\sim 1000$ km/s. This is in clear conflict with the observed linewidth of $< 200$ km/s. (3) The star formation rate of the galaxy is high, reducing the neutral fraction inside the HII region. We find that a 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 HII region produced by other sources, which are not detected. None of these options appears to be physically plausible, except (4), which may require a more detailed discussion. For (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 which 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 to pack all of these galaxies into a region of comoving size of $\lesssim 150$ 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 HII region. Figure 2 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. Essentially, 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.

Let us now examine the possibility of having such a recessional velocity. First, the possibility that the Lyα emitting gas in the galaxy has a recessional velocity of $> 35$ km/s 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. However, this solution is probably not viable, because outflowing gas is expected to 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 linewidths. Higher redshift Lyα emitters at $z = 5 - 6$ all seem to show asymmetric Lyα line profiles (Rhoads et al. 2003), although the existence of winds is not yet observed.

Second, we consider the possibility that the galaxy itself has a recessional velocity of $> 35$ km/s relative to the ambient IGM. Using linear theory, we find that the r.m.s. bulk velocity of a sphere of radius of 0.5 Mpc is 65 km/s at $z = 10$ in the standard LCDM model (Spergel et al. 2003), whereas the velocity dispersion inside such a sphere is only 6.6 km/s, which is much smaller than the required 35 km/s 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 35km/s 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 non–linear system, with a velocity dispersion of $\geq 35$km/s. In that case, the galaxy can be moving at $\geq 35$km/s relative to the surrounding gas. In addition, the presence of other, undetected galaxies would somewhat further help create a larger HII 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).

The need for this recessional velocity from the line symmetry alone raises the question: Can we place interesting constraints on the ionization state of IGM? Figure 3 shows the emission line profile for two cases with different neutral fractions for the IGM. While the adopted $f_{\text{esc}} = 0.5$ is close to maximizing the transmitted line flux, we note that the Ly$\alpha$ line may have suffered additional obscuration by, for example, dust in the emitting galaxy. The combined uncertainty in $f_{\text{esc}}$ and intrinsic absorption weakens the constraint on $x_{\text{HI}}$. With $x_{\text{HI}} = 1$ we find that the overall attenuation due to combined IGM and residual Ly$\alpha$ scattering is $\lesssim 70$ (for $\Delta v \geq 35$km/s), which is consistent with the upper limit of 100 of P04. An 80% neutral IGM produces a total attenuation (including the factor of $1 - f_{\text{esc}} = 0.5$) of $\lesssim 30$, reasonably close to the mid–range of 40 quoted by P04. However, if the intrinsic absorption including dust were 80%, and if the Ly$\alpha$ line to continuum ratio is at the low end of range (0.05) quoted by P04, then $x_{\text{HI}} \leq 0.2$ would be preferred.

In conclusion, we find that if one allows a total attenuation of 60, then no strong constraint can be placed on $x_{\text{HI}}$. Tighter constraints can only be made possible with (1) more accurate calibrations of star formation rates using Ly$\alpha$ emission and UV continuum, and/or (2) a greatly improved knowledge of the intrinsic absorption of Ly$\alpha$ emission and UV continuum. For example, if one can independently put a upper bound on the combined absorption by all other sources on the Ly$\alpha$ line, one may be able to place a lower bound on $x_{\text{HI}}$, in addition to an upper bound, given that the observed line to continuum ratio is quite small.

5. DISCUSSION

Following the announcement of the $z = 10$ candidate galaxy, several recent works (Loeb, Barkana, & Hernquist 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 ($x_{\text{HI}} < 0.4$) 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 $R_c > 5$ (comoving) Mpc. Our results here appear to be consistent with these findings. Gnedin & Prada (2004) have emphasized that a fraction of Ly$\alpha$ galaxies at $z = 10$ could escape strong attenuation due to variations along our line of sight in the shape and size of HII 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 symmetry of the line requires that the galaxy has a recessional velocity of $\geq 35$km/s relative to the surrounding gas. Consequently, we find that no strong constraint can be placed on $x_{\text{HI}}$ at $z = 10$ given the uncertainties.

If our interpretation of the Ly$\alpha$ emission line profile is correct, we can deduce that at any redshift there should be a trend: the fraction of symmetric Ly$\alpha$ emission lines should decrease with increasing Ly$\alpha$ emission line width. In addition, bright Ly$\alpha$ emitters with symmetric profiles may be signposts of groups and clusters of galaxies, within which they can acquire velocities comparable to to larger than their linewidths. We also note that a velocity dispersion of, say, 65 km/s 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 $5 \times 10^9 M_\odot$ (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.
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Fig. 3.— The top panel shows the case with $x_{\text{HI}} = 1$ and $\Delta v = 35\text{km/s}$, and the bottom panel with $x_{\text{HI}} = 0.8$ and $\Delta v = 35\text{km/s}$. In each panel the dotted curve shows the Ly\text{\textalpha} 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 panel) and 30 (bottom panel) as opposed to 100 in the $\Delta v = 0$ model (Figures 1, 2). We further note that for $x_{\text{HI}} = (0.6, 0.17)$ the attenuation becomes (13,3), respectively (not shown in the figure).

6. CONCLUSIONS

We considered the implications of the detection of the symmetric, highly attenuated Ly\text{\textalpha} emission line from a candidate $z = 10$ galaxy. We find that the observed symmetry of the Ly\text{\textalpha} emission line can be accounted for if the emitting galaxy is receding relative to the surrounding absorbing gas by a velocity of at least $35\text{km/s}$. Such a relative velocity is mostly plausibly achieved if this detected galaxy is a member of a larger system with a velocity dispersion in excess of $35\text{km/s}$. 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 Ly\text{\textalpha} 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 in the short term is to obtain a higher quality spectrum to better characterize the line profile.

We thank James Rhoads for useful conversations, and the authors of P04 for providing the line profile and instrument response in electronic form. We gratefully acknowledge financial support by NSF through grants AST-03-07200 and AST-03-07291 (to Z.H.) and AST-0206299 (to R.C.), and by NASA through grant NAG5-13381 (to R.C.).

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