High Precision Analyses of Ly$\alpha$ Damping Wing of Gamma-Ray Bursts in the Reionization Era: On the Controversial Results from GRB 130606A at $z = 5.91$

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Abstract

The unprecedentedly bright afterglow of Swift GRB 130606A at $z = 5.91$ gave us a unique opportunity to probe the reionization era by high precision analyses of the redward damping wing of Ly$\alpha$ absorption, but the reported constraints on the neutral hydrogen fraction ($f_{HI}$) in intergalactic medium (IGM) derived from spectra taken by different telescopes are in contradiction. Here we examine the origin of this discrepancy by analyzing the spectrum taken by VLT with our own analysis code previously used to fit the Subaru spectrum. Though the VLT team reported no evidence for IGM H$\text{I}$ using the VLT spectrum, we confirmed our previous result of preferring non-zero IGM H$\text{I}$ ($f_{HI} \sim 0.06$, when IGM H$\text{I}$ extends to the GRB redshift). The fit residuals of the VLT spectrum by the model without IGM H$\text{I}$ show the same systematic trend as the Subaru spectrum. We consider that the likely origin of the discrepancy between the two teams is the difference of the wavelength ranges adopted in the fittings; our wavelength range is wider than that of the VLT team, and also we avoided the shortest wavelength range of deep Ly$\alpha$ absorption ($\lambda_{\text{obs}} < 8426$ Å), because this region is dominated by H$\text{I}$ in the host galaxy and the systematic uncertainty about host H$\text{I}$ velocity distribution is large. We also study the sensitivity of these results to the adopted Ly$\alpha$ cross section formulae, ranging from the classical Lorentzian function to the most recent one taking into account fully quantum mechanical scattering. It is found that the preference for non-zero IGM H$\text{I}$ is robust against the choice of the cross section formulae, but it is quantitatively not negligible and hence one should be careful in future analyses.

Key words: Techniques: spectroscopic — Gamma-ray burst: individual: GRB 130606A — dark ages, reionization, first stars

1 Introduction

Hydrogen gas in the intergalactic medium (IGM) was reionized at redshifts $z \gtrsim 6$, and it is important to reveal when and how this process occurred quantitatively for better understanding of the formation and evolution of the earliest galaxy populations (Barkana & Loeb 2007; Meiksin 2009; Robertson et al. 2010;...
Fan 2012 for reviews). Gamma-ray bursts (GRBs) are an important probe for the distant universe reaching the epoch of cosmic reionization \( (z \gtrsim 6) \), giving us useful information such as the cosmic star formation rate (see Piran 2005; Mészáros 2006; Zhang 2007; Gehrels et al. 2009 for reviews). When a high precision optical/near-infrared spectrum is taken for a GRB afterglow in the reionization era, light at wavelengths shorter than the redshifted Ly\( \alpha \) is almost completely absorbed by neutral hydrogen in IGM, and so-called Gunn-Peterson troughs appear. Because of the strength of Ly\( \alpha \) absorption, GP troughs give only a weak lower bound for the IGM neutral fraction as \( f_{\rm HI} \equiv n_{\rm HI}/n_{\rm H} \gtrsim 10^{-3} \). However, the shape of redward Ly\( \alpha \) damping wing can be used to further constrain \( f_{\rm HI} \) and hence the reionization history, because IGM H\( \text{I} \) would affect the shape of the wing, in addition to the wing by H\( \text{I} \) in the host galaxy (Miralda-Escude 1998). GRBs have a few advantages against quasars about this test. They are expected to occur in more normal and less dense regions than quasars, and short duration of GRB emission does not affect the ionization status around host galaxies. The simple power-law spectrum of GRB afterglows is suitable for a precise fit to the damping wing shape.

However, use of GRBs for reionization study has been hampered by the low event rate of high-\( z \) GRBs that are bright enough for high precision damping wing analyses. A weak upper bound on IGM H\( \text{I} \) was obtained for GRB 050904 at \( z = 6.3 \) (Kawai et al. 2006; Totani et al. 2006), but meaningful constraints on reionization could not be derived by GRBs at even higher redshifts (Greiner et al. 2009; Patel et al. 2010; Salvaterra et al. 2009; Tanvir et al. 2009; Cucchiara et al. 2011) because of their low signal-to-noise ratio. The discovery of GRB 130606A (Ukwatta et al. 2013; Golenetskii et al. 2013; Castro-Tirado et al. 2013) at \( z = 5.91 \) provided us with the best opportunity so far for this purpose, by its exceptional brightness and relatively low H\( \text{I} \) column density in the host galaxy\(^1\). However, the reported constraints on \( f_{\rm HI} \) using spectra taken by different telescopes are controversial. Chornock et al. (2013) derived an upper bound of \( f_{\rm HI} < 0.11 \) (2\( \sigma \)) using the spectrum taken by Gemini. In contrast, Totani et al. (2014, hereafter Paper I) found a \( \sim 3\sigma \) evidence for IGM H\( \text{I} \) with \( f_{\rm HI} \gtrsim 0.08 \) from the spectrum taken by Subaru. It was argued that the choice of the baseline power-law index \( \beta = -1.99 \) (\( f_\nu \propto \nu^\beta \)) in Chornock et al. is not supported by the observed optical/NIR colors favoring \( \beta \sim -1 \). This has been confirmed by the optical/NIR spectrum by VLT, reporting \( \beta = -1.02 \pm 0.03 \) (Hartoog et al. 2014, hereafter H14).

However, this is not the end of the story. The analysis of the damping wing by H14 using the VLT spectrum found no evidence for IGM H\( \text{I} \), setting an upper limit on \( f_{\rm HI} < 0.03 \) (3\( \sigma \)).

\(^1\) After this event, GRB 140515A was detected at \( z = 6.33 \) and constraints on reionization have been derived (Chornock et al. 2014; Melandri et al. 2015), but the afterglow was not as bright as that of GRB 130606A.

This is statistically inconsistent with the result of our Paper I, indicating the systematic uncertainties in the Subaru/VLT spectra and/or analysis methods. GRB 130606A has proven that a high precision damping wing analysis for GRB spectra in the reionization era is indeed possible, and understanding systematics in such analyses is crucial for future studies using more GRBs at higher redshifts to derive reliable constraints on reionization. Therefore we decided to analyze the VLT spectrum by our own code used for the fitting to the Subaru spectrum in Paper I, to reveal the origin of the discrepant results. This is the primary aim of this work.

Another aim of this work is to examine the effect of adopted formulae for the Ly\( \alpha \) cross section as a function of wavelength. Several different formulae have been used in the literature to calculate the damping wing shape by H\( \text{I} \) in a host galaxy and IGM, including the simplest Lorentzian (or the Voigt profile when convolved with the Gaussian velocity distribution), and the two-level approximation formula by Peebles (1993, hereafter P93). In high precision damping wing analyses, difference of the adopted formulae may result in systematic biases. Here we repeat our analyses using different cross section formulae, including the most recent formula by Bach & Lee (2015, hereafter BL15) that takes into account the fully quantum mechanical scattering based on the second-order time-dependent perturbation theory, and see how the results change.

Unless otherwise stated, we adopt the same model parameter values as those in Paper I. The H\( \text{I} \) column density in the host galaxy, \( N_{\rm HI}^{\rm host} \), is expressed in units of \( \text{cm}^{-2} \).

2 On the Controversial Results between Subaru and VLT

2.1 Comparison between the Subaru and VLT Spectra

First we directly compare the Subaru and VLT spectra of GRB 130606A, which were taken during 10.4–13.2 and 7.2–8.7 hr after the burst, respectively. We use the one-dimensional VLT spectrum and its statistical error, which were reduced by the VLT team and provided to us. The original VLT spectrum has a wavelength binning size of 0.20 Å, which is smaller than 0.74 Å for the Subaru spectrum. To compare the two spectra on the same wavelength grids, the VLT spectrum was converted into that on the Subaru grids. This was done first by associating every VLT grid to the closest Subaru grid, and then by taking the average over the VLT grids associated to a Subaru grid. The two spectra on the same grids are then shown in Fig. 1. The 1\( \sigma \) error at regions without strong airglow emission is typically 1.0% and 1.5% of the continuum level for Subaru and VLT, respectively, on these same wavelength grids. The VLT spectrum shows finer structure because of the better spectral resolution \( (R = \lambda/\Delta \lambda \sim 2200 \text{ and } 8700, \text{ respectively}) \). The ratio of the two spectra is
that the damping wing shape is calculated assuming that IGM of this GRB (Chornock et al. 2013).

In Paper I, we considered two different models for the IGM H1. The 1σ error is shown, but multiplied by a factor of five for presentation purpose. Middle: the same as the top panel but for the VLT spectrum of H14. Here, the VLT spectrum has been converted on the wavelength grids of the Subaru spectrum (see text). Note that the spectral resolution of the VLT spectrum is better than the Subaru even though the wavelength grids are the same. Bottom: the flux ratio of the VLT to the Subaru spectrum.

2.2 Results of the Damping Wing Fits

In Paper I, we considered two different models for the IGM H1 distribution; in one model, the IGM H1 is assumed to extend up to the same redshift as the GRB, i.e., $z_{\text{IGM,u}} = z_{\text{GRB}} = 5.9131$, while in the other model, $z_{\text{IGM,u}}$ is set at 5.83 motivated by a deep GP trough observed at $z = 5.67-5.83$ to the sightline of this GRB (Chornock et al. 2013). It should be noted here that the damping wing shape is calculated assuming that IGM H1 is uniformly distributed with a constant comoving density, which is obviously too simple compared with the expected realistic distribution. Though it is not the purpose of this paper to examine this effect, this should be kept in mind when the implications for reionization are discussed. The best-fit model parameters are $(f_{H1}, \beta) = (0.086^{+0.012}_{-0.011}, -0.93^{+0.04}_{-0.04})$ and $(0.47^{+0.08}_{-0.07}, -0.74^{+0.09}_{-0.07})$ for the former and latter, respectively. The $\chi^2$ difference between the two models is not statistically significant, but both the two models show a $\sim 3\sigma$ statistical preference to the model without IGM H1. It should be noted that some other possibilities of reddening absorption [extinction in the host galaxy or intervening damped Lyα systems (DLAs)] have been ruled out in Paper I.

However, H14 reported $\beta = -1.02 \pm 0.03$ from their optical+NIR spectrum, indicating that the low $z_{\text{IGM,u}}$ model in Paper I is now disfavored. Therefore in this paper we consider only the $z_{\text{IGM,u}} = z_{\text{GRB}}$ model with the power index fixed at $\beta = -1.02$, to compare the Subaru and VLT spectra. Then the model parameters are: the column density of H1 in the host galaxy $N^\text{host}_{H1}$, the 1σ Gaussian velocity dispersion $\sigma_v$ of H1 in the host galaxy, $f_{H1}$ of IGM H1, and the overall normalization factor. The fit results of the host H1 only model ($f_{H1}$ fixed to zero) and the host+IGM H1 model ($f_{H1}$ treated as a free parameter) to the Subaru and VLT spectra are shown in Table 1 and Figs 2 and 3. Here, we used the VLT spectrum converted onto the wavelength grids of the Subaru spectrum as described in the previous section, and exactly the same analysis procedures as Paper I were adopted to the two spectra.

The fit results to the Subaru spectrum with the fixed value of $\beta = -1.02$ are similar to the $z_{\text{IGM,u}} = z_{\text{GRB}}$ model with free $\beta$ reported in Paper I; a non-zero IGM contribution with $f_{H1} \sim 0.06$ is favored than the host H1 only model. The relative flux difference between the two models is only $\sim 0.5\%$ level, but the overall statistical significance is $(\Delta \chi^2)^{1/2} = 3.8\sigma$ thanks to the small statistical error of the spectrum. It should be noted that the errors on the Subaru spectrum are uncorrelated among different wavelength bins and the scatter is consistent with the Gaussian (Paper I). There are 68 data points in the fit, and there are four model parameters in the host+IGM H1 model. The $\chi^2$ value of 80.62 for 68 $- 4 = 64$ degrees of freedom is not unreasonable (8% chance probability of getting a larger value).

The reason why the IGM H1 component improves the fit can be seen in the residuals (normalized by the observed flux error) shown in Fig. 2. The fit residuals of the host only model tend to be positive at longer wavelength range of 8800–8900 Å, but tend to be negative at 8480–8560 Å, indicating that another absorption component is necessary to make the spectrum further

Fig. 1. Top: the Subaru spectrum of the afterglow of GRB 130606A reported in Paper I. The 1σ error is shown, but multiplied by a factor of five for presentation purpose. Middle: the same as the top panel but for the VLT spectrum of H14. Here, the VLT spectrum has been converted on the wavelength grids of the Subaru spectrum (see text). Note that the spectral resolution of the VLT spectrum is better than the Subaru even though the wavelength grids are the same. Bottom: the flux ratio of the VLT to the Subaru spectrum.
redder. It is impossible to do this by increasing the amount of host H\textsc{i}, because it would result in too large absorption in the shortest wavelength range of 8420–8460 Å. Since H\textsc{i} in IGM is more distant from the GRB than H\textsc{i} in the host, the damping wing by IGM H\textsc{i} has weaker wavelength dependence than that by host H\textsc{i} (see Fig. 2 of Paper I). This is the key for the fit improvement by IGM H\textsc{i}. It should also be noted that a reduction of the scatter of residuals by IGM H\textsc{i} is seen in 8420–8460 Å. This indicates that the damping wing shape with IGM H\textsc{i} is in better agreement with the observed data than the host H\textsc{i} only model, giving a further support for the model with IGM H\textsc{i}.

Now we examine the fit results to the VLT spectrum. We confirmed the same result as that to the Subaru spectrum; non-zero IGM H\textsc{i} contribution is favored with the best fit value of $f_{\text{H}\textsc{i}} = 0.087_{-0.014}^{+0.032}$ which is statistically consistent with $f_{\text{H}\textsc{i}} = 0.061_{-0.007}^{+0.007}$ found with the Subaru spectrum. The residuals of the fit to the VLT spectrum in Fig. 3 show the same systematic trend as those of the Subaru fit (in Fig. 2). Therefore the evidence for IGM H\textsc{i} contribution to the observed damping wing reported in Paper I is further strengthened by an independent spectrum taken by VLT. The $\chi^2$ difference implies that the host+IGM H\textsc{i} model is preferred to the host only model with a statistical significance of $11.89^{1/2} = 3.4\sigma$. However, the residuals shown in Fig. 2 are on average significantly larger than the expectation of the Gaussian distribution, suggesting that the errors calculated by the VLT analysis pipeline are underestimated. We discussed about this with the VLT team, and it is most likely because the lower signal-to-noise ratio with respect to the Subaru spectrum makes the systematic noise due to the bright sky emission lines more prominent. The VLT spectrum was taken with an exposure time considerably shorter than that for Subaru, and the air mass was also larger. The median of absolute values of the residuals for the host+IGM H\textsc{i} model is 1.221, while 0.674 is expected for the Gaussian distribution. If we scale the error size by the ratio of 1.221/0.674, the significance is reduced to 1.9\sigma. In this work we do not discuss the statistical significance about the VLT spectrum further.

These results indicate that the discrepant conclusions (evidence for IGM H\textsc{i} by Paper I, while no evidence found by H14) are a result of difference in analysis methods, rather than the systematic difference between the two spectra. Concerning this, we note that the wavelength range fitted by H14, 8406–8462 Å (corresponding to relative velocities of 0–2000 km/s to Ly$\alpha$), is significantly shorter compared with 8426–8900 Å adopted in our Paper I. It should be noted that the evidence for IGM H\textsc{i} in our analysis is found in the spectral shape spanning in the whole wavelength range. Another difference is that we excluded the shortest wavelength range of $\lambda_{\text{obs}} < 8426$ Å. As shown in Fig. 2 of Paper I, the H\textsc{i} absorption in this region is dominated by the host H\textsc{i} rather than the IGM component with $f_{\text{H}\textsc{i}} \sim 0.1$. The observed spectrum rapidly drops with decreasing wavelength at $\lambda_{\text{obs}} < 8426$ Å, making a precise model fitting difficult because of uncertainties about the velocity distribution of H\textsc{i} in the host and spectral resolution. Though the Gaussian velocity distribution has been taken into account for the host H\textsc{i}, such a pure Gaussian distribution is unlikely in a realistic galaxy, as inferred from high resolution spectroscopic studies of DLAs (Wolfe et al. 2005; see also Paper I for more discussion). This is why in Paper I we used only wavelength longer than 8426 Å; this boundary was determined so that the fit result becomes mostly insensitive to the host H\textsc{i} velocity dispersion, $\sigma_v$ (see Table 1).

To test the effect of the wavelength range used, we performed the damping wing fit to the Subaru spectrum with the same wavelength range as H14. Indeed, we found a similar result to H14: the best fit is $f_{\text{H}\textsc{i}} = 0$ with upper bounds of $f_{\text{H}\textsc{i}} < 0.0034$ and 0.088 at 1 and 2\sigma, respectively, $\log_{10} N_{\text{H}\textsc{i}}^{\text{host}} = 19.855_{-0.009}^{+0.009}$, and $\sigma_v = 61.8 \pm 3.3$ km/s. The small error of $\sigma_v$ indicates that the fit in this region is highly sensitive to the host H\textsc{i} velocity distribution, but systematic uncertainty should be large if the distribution is not a simple Gaussian.

| Table 1. The best fit parameters of the fittings to the Subaru and VLT spectra* |
|-------------------------------------------------------------|
| model | $\log_{10}(N_{\text{H}\textsc{i}}^{\text{host}})$† | $\sigma_v$ (km/s)‡ | IGM $f_{\text{H}\textsc{i}}$ | $\chi^2$/§ | $\Delta\chi^2$/§ |
|-------------------------------------------------------------|
| host H\textsc{i} only | 19.877 $^{+0.031}_{-0.015}$ | 0.015 $^{+0.011}_{-0.032}$ | 0.0 $^{+0.009}_{-0.009}$ | fixed to zero | 95.10 $^*$ | 14.48 $^*$ |
| host+IGM H\textsc{i} | 19.768 $^{+0.032}_{-0.032}$ | 0.0 $^{+0.007}_{-0.007}$ | 0.061 $^{+0.007}_{-0.007}$ | 80.62 $^*$ | - |
| fit to the VLT spectrum | | | | | |
| host H\textsc{i} only | 19.806 $^{+0.019}_{-0.016}$ | 0.0 $^{+0.007}_{-0.007}$ | 0.0 $^{+0.007}_{-0.007}$ | fixed to zero | 292.57 $^*$ | 11.89 $^*$ |
| host+IGM H\textsc{i} | 19.621 $^{+0.009}_{-0.007}$ | 0.0 $^{+0.007}_{-0.007}$ | 0.087 $^{+0.017}_{-0.017}$ | 280.68 $^*$ | - |

*The fit results for the Ly$\alpha$ damping wing models including only H\textsc{i} in the host galaxy (“host H\textsc{i} only”) and including host plus IGM H\textsc{i} (“host+IGM H\textsc{i}”, with IGM H\textsc{i} extending up to the redshift of the GRB). The quoted errors are statistical 1\sigma.
† The neutral hydrogen column density in the GRB host ($N_{\text{H}\textsc{i}}^{\text{host}}$) in units of cm$^{-2}$.
‡ The survey range of $\sigma_v$ (1\sigma of the Gaussian velocity distribution of host H\textsc{i}) is limited to 0–100 km/s, motivated from the observed widths of the metal absorption lines (Paper I).
§ The number of data points is 68.
$^*$ The $\chi^2$ excess of the host H\textsc{i} only model against the host+IGM H\textsc{i} model.
3 Testing Different Lyα Cross Section Formulae

In Paper I we used the two-level approximation formula of P93 for the Lyα cross section as a function of wavelength. In the calculation of the damping wing by IGM H₁, we further used the analytic formula of Miralda-Escude (1998), which also assumes the P93 formula and uses an approximation valid when the frequency is far from the resonance (4π|ν−να| ≫ Γα) to make the analytic integration possible, where Γα = 6.262 × 10⁸ s⁻¹ is the damping constant of Lyα. Though this approximation is very good (corresponding to |λ−λα|/λα ≫ 2.02 × 10⁻⁸) for the practical damping wing analysis, we revised our code to numerically integrate the IGM damping wing, to calculate it for arbitrary formulae of Lyα cross section.

Here we test three different formulae of Lyα cross section: the Lorentzian, the classical Rayleigh scattering formula, and the fitting formula of BL15 taking into account the quantum mechanical scattering effect, in addition to the P93 formula used in Paper I. (See BL15 for the exact expressions of these formulae.) Fig. 4 shows the change of H₁ optical depth as a function of wavelength for different formulae, using the best-fit parameters of the host+IGM H₁ model to the Subaru spectrum of GRB 130606A. The change relative to the Lorentzian becomes larger with increasing wavelength, reaching 10–20% at 8900 Å. The Rayleigh and P93 formulae result in smaller optical depth, but the BL15 formula larger, compared with the Lorentzian. Then we repeated our damping wing fitting analysis on the Subaru spectrum for the host H₁ only and host+IGM H₁ models, and χ² are presented in Table 2. The best-fit value of fH₁ changes by less than 8%. The BL15 formula results in the smallest significance of the statistical preference for the non-zero fH₁ to the host H₁ only model, but still it is larger than 3.1σ.

4 Discussion and Conclusions

This paper investigated the origin of the discrepant results about the constraint on IGM H₁ fraction from Lyα damping wing
Fig. 3. The same as Fig. 2, but for the VLT spectrum converted onto the wavelength grids of the Subaru spectrum.

Table 2. The best fit parameters in the fittings with different Lyα cross section formulae.

| cross section formula | $\log_{10}(N_{HI}^{\text{host}})$ | $\sigma_v$ (km/s) | $f_{\text{HI}}$ | $\chi^2$ | $\Delta\chi^2$ |
|-----------------------|----------------------------------|------------------|-------------|---------|-------------|
| host HI only model    |                                  |                  |             |         |             |
| Lorentzian            | $19.869^{+0.010}_{-0.010}$       | $0.0^{+0.0}_{-0.0}$ | fixed to zero | 91.81   | 10.74       |
| Rayleigh              | $19.875^{+0.010}_{-0.010}$       | $22.1^{+6.1}_{-2.1}$ | fixed to zero | 94.21   | 13.50       |
| Peebles               | $19.877^{+0.008}_{-0.015}$       | $0.0^{+8.9}_{-0.0}$ | fixed to zero | 95.10   | 14.48       |
| Bach & Lee            | $19.866^{+0.009}_{-0.009}$       | $0.0^{+6.5}_{-0.0}$ | fixed to zero | 90.66   | 9.88        |
| host + IGM HI model   |                                  |                  |             |         |             |
| Lorentzian            | $19.755^{+0.033}_{-0.033}$       | $100.0^{+100.0}_{-100.0}$ | $0.057^{+0.0012}_{-0.007}$ | 81.07   | -           |
| Rayleigh              | $19.765^{+0.033}_{-0.033}$       | $54.6^{+45.4}_{-54.6}$ | $0.060^{+0.008}_{-0.007}$ | 80.71   | -           |
| Peebles               | $19.768^{+0.032}_{-0.012}$       | $62.0^{+38.0}_{-62.0}$ | $0.061^{+0.007}_{-0.007}$ | 80.62   | -           |
| Bach & Lee            | $19.751^{+0.029}_{-0.029}$       | $100.0^{+100.0}_{-100.0}$ | $0.056^{+0.011}_{-0.006}$ | 80.78   | -           |

*The fitting results of the host HI only and host+IGM HI models for the Lyα damping wing, using the Subaru spectrum. See also Table 1 for more explanations.
analyses of the Subaru and VLT spectra for GRB 130606A at $z = 5.913$. Direct comparison between the two spectra does not show any systematic difference on the overall shape in the wavelength range of 8426–8900 Å used in Paper I. We repeated exactly the same analysis as Paper I for the VLT spectrum converted onto the wavelength grids points of the Subaru spectrum, and confirmed our previous result of more than 3σ statistical preference for non-zero contribution from IGM H I with $f_{HI} \sim 0.05-0.1$ (assuming uniform distribution of IGM H I up to the redshift of the GRB). The absorption by IGM is dominated by H I within $\Delta z \sim 0.1$ from the upper redshift bound ($z_{IGM, u} = z_{GRB}$), corresponding to a proper distance of $\sim 6$ Mpc. The host H I only model is disfavored because of the systematic trend of fit residuals (positive at 8640–8900 Å, while negative at 8450–8560 Å) indicating that another absorption component is necessary to make the spectrum redder, in addition to H i in the host galaxy. This trend has been confirmed also using the VLT spectrum.

Therefore we consider that the discrepant results were obtained because of different analyses methods. H14 adopted the wavelength range of 8406–8462 Å, which overlaps only with the shortest part of the range adopted by us in Paper I, and H14 also included the deep Lyα absorption region down to the resonant Lyα wavelength (8406 Å). In Paper I we excluded the wavelengths shorter than 8426 Å because this region is highly sensitive to the velocity distribution of H i in the host galaxy, which is rather uncertain and unlikely to be a pure Gaussian. Indeed, we found a result consistent with H14 (i.e., no evidence for non-zero $f_{HI}$) when we adopted the same wavelength range as H14.

Finally, we examined the robustness of these results against the adopted Lyα cross section formulae, by testing the Lorentzian, Rayleigh scattering formula, and the latest BL15 fitting formula taking into account a fully quantum mechanical scattering effect, in addition to the Peebles’ two-level approximation formula used in Paper I. We found that the preference for the non-zero $f_{HI}$ is robust against the difference of these formulae. The BL15 formula results in the lowest statistical significance, but still it is greater than 3.1σ and the best-fit $f_{HI}$ changes at most 8%. However this effect is quantitatively not negligible, and one must be careful about the Lyα cross section formulae in future studies.

These results demonstrate that high precision Lyα damping wing analyses of high-z GRB afterglows are a powerful approach to measure IGM H I fraction, which is sensitive to a small value of $f_{HI} \sim 0.05$. The same results were obtained by the two spectra taken by the two different telescopes, when the model fitting method is the same, indicating that the systematic uncertainty of the spectral measurement can be controlled to allow discrimination of sub-percent level relative flux change in the spectral shape. However, a high precision fitting is easily affected by systematic uncertainties about the fitting methods, especially the wavelength range. Therefore one must be very careful to minimize the systematic uncertainties, e.g. by checking the sensitivity of the results to the adopted wavelength ranges and other model parameters.

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References

Bach, K., & Lee, H.-W. 2015, MNRAS, 446, 264 (BL15)
Barkana, R., & Loeb, A. 2007, Rep. Prog. Phys., 70, 627
Castro-Tirado, A. J., et al. 2013, arXiv:1312.5631
Chornock, R., et al. 2013, ApJ, 774, 26
Chornock, R., Berger, E., Fox, D. B., et al. 2014, arXiv:1405.7400
Cucchiara, A., et al. 2011, ApJ, 736, 7
Fan, X. 2012, Research in Astronomy and Astrophysics, 12, 865
Gehrels, N., Ramirez-Ruiz, E., & Fox, D. B. 2009, ARA&A, 47, 567
Golenetskii, S., et al. 2013, GRB Coordinates Network, 14808
Greiner, J., et al. 2009, ApJ, 693, 1610
Hartoog, O. E., Malesani, D., Fynbo, J. P. U., et al. 2014, arXiv:1409.4804
(H14)
Kawai, N., et al. 2006, Nature, 440, 184
Meiksin, A. A. 2009, Reviews of Modern Physics, 81, 1405
Melandri, A., Bernardini, M. G., D'Avanzo, P., et al. 2015, arXiv:1506.03079
Mészáros, P. 2006, Reports on Progress in Physics, 69, 2259
Miralda-Escude, J. 1998, ApJ, 501, 15.
Patel, M., Warren, S. J., Mortlock, D. J., & Fynbo, J. P. U. 2010, A&A, 512, L3.
Peebles P. J. E., 1993, Principles of Physical Cosmology. Princeton Univ. Press, Princeton, NJ (P93)
Piran, T. 2005, Reviews of Modern Physics, 76, 1143
Robertson, B. E., Ellis, R. S., Dunlop, J. S., McLure, R. J., & Stark, D. P. 2010, Nature, 468, 49
Salvaterra, R., et al. 2009, Nature, 461, 1258
Tanvir, N. R., et al. 2009, Nature, 461, 1254
Totani, T., et al. 2006, PASJ, 58, 485
Totani, T., Aoki, K., Hattori, T., et al. 2014, PASJ, 66, 63 (Paper I)
Ukwatta, T. N., et al. 2013, GRB Coordinates Network, 14781
Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861
Zhang, B. 2007, Chinese Journal of Astronomy and Astrophysics, 7, 1