1. INTRODUCTION

Recent hydrodynamic simulations of large-scale structure formation in cold dark matter (CDM)-dominated cosmologies (e.g., Cen et al. 1994; Zhang, Anninos, & Norman 1995; Hernquist et al. 1996; Theuns et al. 1998) have been able to naturally reproduce the Lyα forest. These simulations have been remarkably accurate in reproducing the column density and Doppler width distribution as well as evolutionary properties seen in the Lyα forest of real QSO spectra (e.g., Kirkman & Tytler 1997; Lu et al. 1996).

Early attempts to model the Lyα absorption lines considered pressure-confined clouds (Sargent et al. 1980; Ostriker & Ikeuchi 1983) inside a hot intergalactic medium (IGM). Other ideas used dark matter minihalos to gravitationally confine the Lyα clouds (Rees 1986). In these models, a Voigt profile naturally arises from a Maxwellian thermal distribution or Gaussian turbulent motion of the gas. This lead to the fitting of Voigt profiles to the data, a method now generally used to analyze the complex blended features seen in the high-resolution Keck spectra (e.g., Kirkman & Tytler 1997).

The numerical simulations have brought about a paradigm shift in our understanding of the IGM. No longer is the Lyα forest viewed as many isolated objects within a hot tenuous IGM; rather, it is seen as the density fluctuations of the IGM itself caused by gravitational collapse into a network of sheets and filamentary structures (sometimes described as a fluctuating Gunn-Peterson effect after Gunn & Peterson 1965). The observed spectrum is thus described by the temperature, and velocity of the gas at all points along the line of sight, and the absorption lines that make up the forest are caused by extended overdensities rather than discrete clouds.

This change in our understanding of the IGM has called into question the justification behind Voigt profile fitting. In recent years, dramatic improvements in the resolution and signal-to-noise ratio (S/N) of data has lead to complex blends of Voigt profiles in order to fit the absorption features. Problems due to the somewhat arbitrary number of components and the non-uniqueness of the fitted solutions have become apparent. Now the simulations have shown that the physical interpretation of the solutions themselves are in doubt. Despite this, there is little direct evidence that the Lyα forest line profiles are significantly different from Voigt profiles. Many absorption lines appear to have remarkably Gaussian velocity distributions, especially at lower redshifts where blending is less of a problem. On the other hand, non-Gaussian features could as well be attributed to blends of two or more Voigt profiles as to an intrinsically non-Voigt distribution.

Outram, Chaffee, & Carswell (1999) proposed a method to detect departures from Voigt profiles of the absorption lines in a statistical way. They applied it to the Lyα forest spectrum of GB 1759+7539, but detected no significant evidence of non-Voigt profiles. In this Letter, we develop the method proposed by Outram et al. In the next section, we discuss the signature of non-Voigt profiles in Lyα forest spectra and present details of the method to detect it. Then we apply this method to simulated forest spectra to show that the profiles seen in hydrodynamic simulations are indeed statistically non-Voigt, before finally discussing the implications of this result.

2. DETECTING NON-VOIGT PROFILES

If the Lyα forest is now viewed as density fluctuations within the IGM, then what does this imply about the physical nature of Lyα absorbers? Typical systems have column densities of around $13.0 < \log N(H) < 14.0$ (in units of $\text{cm}^{-2}$). Observations of quasar pairs have shown that these systems can be very large, of the order of 500 kpc across (Dinshaw et al. 1994). They are therefore highly ionized and hence contain a significant fraction of all the baryons at $z = 3$, yet they are only slightly overdense ($\rho_0 \sim 1–10$) compared to the mean baryonic density. Although a large variety of structures are seen in the simulations, they tend to have a flattened geometry in the form of “pancakes” or filamentary structures. They are unlikely to
be virialized objects and are probably transient density fluctuations undergoing gravitational collapse in one direction, while still expanding with the Hubble flow in others (Haehnelt 1996).

The individual absorption profiles depend on the orientation and exact geometry of that system and may well be asymmetric. In general, though, if \( \text{Ly} \alpha \) absorbers are in a state of collapse, then the bulk motion and compressional heating of the gas should lead to broad non-Maxwellian wings (Rauch 1996; Nath 1997). Equally, if the absorber is extended in space and undergoing Hubble expansion along the line of sight, then the line profile would also deviate from that predicted by the simple model.

The expected shape of a typical absorption line from such objects is shown in Figure 1. The central core is that of a log \( N(\text{H} \, \text{i}) = 13.0 \), \( b = 20 \) km s\(^{-1} \) absorption line, with broad non-Maxwellian wings due to infalling gas. When a spectrum is fitted with Voigt profiles, these wings may be (1) fitted by a single broad, low \( N(\text{H} \, \text{i}) \) component, (2) fitted by two low \( N(\text{H} \, \text{i}) \) components, on either side of the main line, or (3) simply not fitted at all. Rauch (1996) considered the first of these possibilities, searching for broad lines fitted simultaneously in redshift space with narrower ones. He looked at both real and simulated data for an anticorrelation of Doppler parameters for profile pairs at small separations, detected a positive signal in both data sets, and concluded that there was evidence of a departure from Voigt profiles.

In order to investigate the line profiles further, we estimate the departures from the Voigt profile in absorption lines using the following method. First, for the spectrum in question, Voigt profiles are fitted to all absorption features. Since we are looking for departures from Voigt profiles in stronger lines, the raw spectrum is divided by an artificial spectrum made by inserting the Voigt profile fits on the continuum. The obvious thing to do is to divide through by the fitted Voigt profiles, only leaving any non-Voigt residuals in the spectrum. However, this is complicated by the fact that many of these residuals will have been fitted themselves, using a blend of low column density lines with high or low Doppler width, and therefore the non-Voigt signal could be removed as well. In an attempt to overcome this, all the systems with log \( N(\text{H} \, \text{i}) < 12.5 \) are left in for the examples here, although the precise limit can be any desired. Although this leaves in many randomly distributed small absorption features together with the non-Voigt residuals of removed systems, the final step is then to co-add many of the absorption systems whose Voigt core had been divided out. Any signature of a non-Voigt profile should be reinforced with this stacking, whereas randomly distributed small absorption lines should be averaged away if enough lines are stacked.

The expected residuals using this method depend on how many components are used to fit the non-Voigt wings. The general shapes can be seen in Figure 2. If the solid profile shown in Figure 1 is fitted by a single Voigt profile, which is then divided out, then the residual expected is the solid curve in Figure 2. As expected, there are dips due to the two wings, and inside these are two peaks due to the fact that the Doppler width of the fitted Voigt profile is forced to be wider than that of the core. If one or two extra lines are fitted to the wings, then the residuals would look like the dotted and dashed curves, respectively, in Figure 2. When stacking hundreds of lines, a combination of all three effects would be expected, and the ratio of each would depend on the S/N of the data and the fitting criteria used. The randomly distributed small lines would also have an effect: depressing the entire spectrum by about 0.5%. Within about 20 km s\(^{-1} \) of the absorption-line center (1215.60–1215.74 Å), the division to remove the profile core becomes uncertain, especially for the higher column density lines, for which the residual signal is near zero. However, since we are looking for a signal in the wings as opposed to the core, this region was ignored for the analysis.
3. SIMULATED Lyα FOREST PROFILES

In order to test this idea further, we used artificial spectra taken from Theuns et al. (1998). The spectra were created using a simulation code based on a combination of a hierarchical particle-particle-particle-mesh scheme for gravity and smoothed particle hydrodynamics (SPH) for gas dynamics. The simulations assume a standard adiabatic, scale-invariant CDM cosmology ($\Omega = 1$, $\Omega_m = 0$, $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\sigma_8 = 0.7$, $\Omega_b = 0.05$). A box size of $5.5 \text{ Mpc}$ was used, with $64^3$ SPH and an equal number of dark matter particles. Finally, the assumed background radiation spectrum was half the amplitude of the spectrum computed by Haardt & Madau (1996). For further details, refer to Theuns et al. (1998), in which this simulation is named A-5-64. Theuns et al. tested the convergence of this simulation by comparing it to a similar run with even higher numerical resolution (A-2.5-64). They concluded that the A-5-64 run is very close to convergence and that conclusions drawn from this simulation are reliable.

We took the absorption spectra computed from 128 different lines of sight through the box at redshift $z = 3$. Each spectrum was convolved with a Gaussian profile with FWHM = 7 km s$^{-1}$, and Gaussian noise was added with standard deviation $\sigma = 0.02$ (S/N = 100 for pixels at the continuum) to mimic spectra observed using the HIRES spectrograph on the Keck Telescope. The spectra were wrapped around to enable fitting of features that were otherwise close to the edge of the region.

Voigt profiles were fitted, using a $x^2$ minimization technique, to the absorption features in order to determine the redshifts, column densities, and Doppler widths of the Lyα absorption lines using an automated version of the software package VPFIT (Webb 1987; Rauch et al. 1992).

When comparing simulated data to observed spectra, one of the major problems to be overcome is that of continuum fitting. The simulated spectra show typically around 1%--2% zero-order absorption, which would be removed by the continuum fitting procedure for real data. This is usually done by using low-order polynomial fits to apparently unabsorbed parts of the spectrum. The regions over which the continuum is fitted are typically many times the size of a simulated spectrum. In an attempt to overcome this problem and treat the simulated data in a similar manner to real data, VPFIT has been developed to simultaneously fit a linear multiplicative factor to the initial assumed continuum (unity for the simulations) during the $x^2$ minimization procedure. The continuum was lowered by an average of 1.6% during the fitting of the artificial spectra.

The spectra were then divided through by the profiles of the stronger fitted lines [$\log N(\text{H I}) > 12.5$], leaving the residuals due to weaker lines in. Care was taken to give zero weight to those regions in which the residual flux was below 20% and to correct the errors for the other regions accordingly.

The resulting residual spectra were co-added, weighted according to variance, and centered on the rest wavelength of the removed Voigt profile absorption lines with parameters $13.0 < \log N(\text{H I}) < 14.0$ and $15.0 < b < 60.0$ km s$^{-1}$. The result, with 235 lines stacked, can be seen in Figure 3.

If a line profile was indeed narrow in the center, but with broader-than-Maxwellian wings, the residual profile after fitting with a Voigt profile then dividing through by this fit would be as shown by the smooth curve in Figure 3 [modeled by a $b = 20$ km s$^{-1}$, $\log N(\text{H I}) = 13.0$ line with broader wings simulated by a coincident $b = 60$ km s$^{-1}$, $\log N(\text{H I}) = 12.0$ line]. This pattern seems to follow that seen in the residual spectrum remarkably well. The dips at 1215.50 and 1215.85 Å and the peaks at 1215.55 and 1215.85 Å are similar to those predicted by the model curve. The entire spectrum has been depressed by about 0.5% due to the small [$\log N(\text{H I}) < 12.5$] features not removed, and these could also explain the small irregularities away from the line center. These irregularities would be expected to diminish as more lines are stacked. Were the profiles of the absorption features intrinsically random blends of Voigt profiles, then no such residual features would be expected in the co-added spectrum. This is therefore clear evidence of intrinsic departures from the Voigt profile in the simulated spectra.

FIG. 3.—Co-added residual spectrum obtained by stacking the residuals from 235 Lyα lines, taken from simulated spectra at $z = 3$, with $13.0 < \log N(\text{H I}) < 14.0$ and $15.0 < b < 60.0$, after first removing all fitted Voigt profiles with $\log N(\text{H I}) > 12.5$. The region from 1215.60–1215.74 Å is uncertain due to the division and hence has been left out. The resulting S/N of the remaining spectrum is 680. The overlying curve shows a simulated non-Voigt residual.

4. DISCUSSION

The next step is to apply this method to real data in order to determine whether the non-Voigt absorption profiles are a simulated phenomenon or a real physical property of the absorbers. The stacked residual spectrum in Figure 3 was created using 235 separate lines at S/N = 100. This is of the same order as the number of observed lines in a single high-quality Keck spectrum, and so a result should be easily achievable. Care would need to be taken to remove regions in which heavy-element absorption is detected, and the continuum should be treated in a similar manner in order to produce a fair comparison. The latter would mean fitting the spectrum in very small chunks ($\sim 500$ km s$^{-1}$), simultaneously introducing a local fit to the continuum in a similar manner to that described above. The S/N of the spectrum is also important as it could change the way that the residuals are fitted and hence the resulting residual profiles, as discussed above.

It has been noted that the absorption-line profiles of individual systems in simulated spectra often appear to have broad wings or asymmetries, signifying a non-Voigt profile (e.g.,...
Dave et al. 1997). Rauch (1996) showed that pairs of lines with small separations have anticorrelated Doppler widths, suggesting that the Voigt profile decompositions are not actual blends. We have introduced a method to test whether or not the line profiles in the Lyα forest are intrinsically non-Voigt. A similar technique was applied to GB 1759+7539 (Outram et al. 1999) with no sign of any signal. However, a much more extended sample is needed, with care paid to continuum uncertainties before the results can be compared. If wings are found in the real data, it will provide a powerful confirmation of the SPH models. If they are not, then they provide a crucial test and we need the modelers to think again.

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