Intergalactic He II Absorption at Redshifts $z = 2.3-2.9$: FUSE Observations and Theory

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Abstract. I provide a summary of He II observations (Kriss et al. 2001) of the $z = 2.885$ quasar HE 2347-4342 obtained by FUSE between 1000 and 1187 Å. These data resolve a fluctuating "He II Lyα forest", a discrete set of absorbers that correspond well with Keck observations of the H I Lyα forest. The redshift evolution of He II opacity agrees with theoretical expectations at $z < 2.72$. Between $2.72 < z < 2.90$, the opacity is patchy and increases rapidly, perhaps indicating the onset of He II reionization. Approximately 50% of the He II features have H I counterparts, but a substantial number show no H I absorption, arising perhaps in low-density regions. The column density ratio, $\eta = N(\text{He II})/N(\text{H I})$, ranges from 1-1000, with a mean ($\eta$) $\approx 80$. Ratios $\eta < 100$ are consistent with IGM photoionization by a hard (AGN) spectrum filtered by intergalactic absorption, but regions with $\eta \gg 100$ require additional contributions from starburst galaxies or heavily filtered sources. Perhaps the most amazing features in the data are the small-scale fluctuations in He II opacity, a topic deserving of further investigation.

1 Introduction

In this paper, I report briefly on our recent FUSE observations of the He II Lyα absorption in the intergalactic medium (IGM) toward the $z = 2.885$ quasar HE 2347-4342. Details of these observations and their interpretation are described in the recent Science article by Kriss, Shull et al. (2001). These data show clear fluctuations in the He II absorbers, which have been compared to their counterparts in the H I Lyα forest from Keck data (Songaila 1998). The He II/H I ratio provides a diagnostic of the ionization sources in the IGM; the total amount of He II absorption suggests that some gas exists in low-density portions of the IGM.

Studies of H I and He II absorption in the high-redshift IGM are important probes of structure in the universe, and require observing distant quasars in the rest-frame ultraviolet. The FUSE spectra toward this particular target show substantial line blanketing shortward of the QSO Lyα emission lines of H I at (1215.67 Å)(1 + $z$) and of He II at (303.78 Å)(1 + $z$), which trace both collapsed and uncollapsed portions of the IGM. Both H I and He II are trace "recombination species" in the post-reionization epochs. Based on recent observations, we believe these critical epochs occur at $z = 6.3 \pm 0.1$ (hydrogen) and $z = 2.8 \pm 0.2$ (helium). Theoretical modeling suggests that He II should provide a better tracer of the low-density regions of the IGM, because it is more difficult to photoionize (4 Rydbergs instead of 1 Rydberg) and because He III recombines more rapidly than H II.
2 FUSE Observations

The *Far Ultraviolet Spectroscopic Explorer* (FUSE) science team observed the \( V = 16.1 \) quasar HE 2347-4342 in the 1000 \( \text{Å} \) band at a resolving power of \( R = \lambda / \Delta \lambda \approx 15,000 \). The data came in two separate campaigns, during August 17-24, 2000 (351.7 ksec) and October 11-16, 2000 (249.7 ksec). For each observation, the target was centered in the large (30' \( \times \) 30') apertures. The portions of the observing time obtained during orbital night were 192.6 ksec and 183.6 ksec, respectively. These observations are among the longest obtained with FUSE, owing to the faint flux level of the target, \( F_{\lambda} = 3 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \) near 1200 \( \text{Å} \).

At these faint flux levels, we needed to perform a custom extraction of flux and background level of the 2D data (Kriss et al. 2001). Because FUSE stops at 1187 \( \text{Å} \), just shortward of wavelengths where the continuum becomes unabsorbed in He II \( \lambda 304 \), we obtained near-simultaneous HST/STIS observations using the low-resolution G140L grating. The continuum below 1190 \( \text{Å} \) was extrapolated from the STIS data (1150–3200 \( \text{Å} \)) using a correction for interstellar extinction. Figure 1 shows the LiF portion of the FUSE data longward of 1000 \( \text{Å} \) and binned to 0.05 \( \text{Å} \), a value comparable to the expected line widths of He II absorption lines. One clearly sees a fluctuating opacity in the He II Lyα lines, with a gradual recovery to shorter wavelengths, as expected from photoelectric absorption in an evolving IGM.

Next, we binned the data on a much coarser wavelength grid, corresponding to 5–15 \( \text{Å} \) bins from redshifts \( z = 2.3 – 2.9 \). Figure 2 shows that the average He II line optical depth rises from values just below unity at \( z = 2.3 \) to \( \tau_{\text{HeII}} \approx 1.3 \) at \( z \approx 2.7 \), where it takes a sudden jump to large values between \( 2.72 < z < 2.89 \). The absorption in this interval is patchy, punctuated by two regions with low opacity at \( z = 2.82 \) (1160 \( \text{Å} \)) and \( z = 2.87 \) (1175 \( \text{Å} \)). These two He II “transmission windows” (or opacity gaps) have been studied in great detail with HST/STIS/G140M (about 40 km s\(^{-1}\) resolution) by Smette et al. (2001). These dramatic changes in He II opacity may correspond to denser regions in which helium ionization is incomplete. Certainly they are well above the values expected for a smoothly evolving IGM, in which He II ionization fronts have penetrated the dense gas.
The general trend of He II opacity agrees remarkably well with the theoretical models of Fardal, Giroux, & Shull (1998), which assumed an ionizing background due to quasars alone and adopted a standard IGM opacity model based on Keck H I absorber data. Clearly, something dramatic happened to the IGM along this sightline at \( z > 2.7 \), although one cannot say with certainty whether this sudden increase in absorption is global. It is tempting to associate the drop in He II absorption at \( z < 2.72 \) with the onset of He II reionization, as the ionization fronts from AGN and other sources overlap. Observations of several other sightlines would be useful to gauge the effects of cosmic variance. It now appears likely that FUSE will attempt moderate-resolution observations in cycle 3 of another bright quasar at \( z = 2.63 \).

In the “translucent region” corresponding to \( z < 2.72 \), the FUSE spectrum shows that the opacity is predominantly from discrete absorbers. FUSE has effectively resolved the He II absorption into a He II Ly\( \alpha \) forest, analogous to the H I Ly\( \alpha \) forest studied by high-resolution spectrographs on Keck and VLT. Figure 3 compares both He II (Kriss et al. 2001) and H I absorbers (Songaila, 1998), plotted on an equivalent wavelength scale. Figure 4 shows the range of He II/H I column-density ratios (the parameter \( \eta \)) versus redshift.

Several effects are worth noting in Figures 3 and 4. First, there is generally good agreement between the locations of the strong H I and He II absorbers. Second, the ratio of He II/H I opacities and the inferred ratio of column densities, \( \eta = N(\text{He II})/N(\text{H I}) \), hovers around the standard value \( \eta \approx 100 \) expected for photoionization by a hard ionizing spectrum from AGN (Fardal et al. 1998). Third, we observe many regions of the spectrum with substantial He II absorption but no visible H I opacity. Evidently, one needs to identify additional He II opacity, perhaps in regions corresponding to very low column densities, \( N(\text{H I}) < 10^{12.3} \text{ cm}^{-2} \). Finally, some of the He II absorption appears to have large He II/H I ratios, \( \eta \gg 10^2 \). These regions could be produced by soft ionizing sources (hot stars) or by IGM radiative transfer effects, which can soften the spectrum between 1 and 5 Ryd.

Further analysis of the He II absorption and its small-scale fluctuations is now being performed (Shull, Tumlinson, et al. 2002).

Figure 3: (Top) The He II spectrum toward HE 2347-4342 taken by FUSE. Smooth curve across the top is the extrapolated continuum. Are shaded lightly shows the portion of He II opacity due to absorption features seen in H I absorption seen by Keck. Area shaded more heavily shows portion of opacity due to additional He II features with no H I counterparts. (Bottom) Normalized Keck spectrum (Songaila 1998).
Figure 4: The logarithm of the ratio, $\eta = N(\text{He II})/N(\text{H I})$, of column densities vs. redshift for the absorbers toward HE 2347-4342 (Kriss et al. 2001). These data suggest a range of fluctuations in the ionizing radiation spectrum. The mean value ($\log \eta$) = 1.89 is consistent with a hard (AGN-like) spectrum.

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References