The Full Re-Ionization of Helium

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Abstract. Observations of resolved HeII Lyman alpha absorption in spectra of two QSO’s suggest that the epoch of helium ionization occurred at \( z \approx 3 \). Proximity zones in the spectra of the quasars \( z = 3.18, 3.285 \) at 304 Å resemble Stromgren spheres, suggesting that the intergalactic medium is only singly ionized in helium. We present models of the proximity effect which include the full physics of the ionization, heating and cooling and an accurately simulated inhomogeneous gas distribution. In these models the underdense intergalactic medium is heated to at least 10,000-20,000 K after cooling to as low as a few 1000K due to cosmological expansion, with higher temperatures achieved farther away from the quasar due to absorption-hardened ionizing spectra. The quasars turn on for a few \( \times 10^7 \) years with a fairly steady flux output at 228 Å comparable to the 304 Å flux output directly observed with HST. The recoveries in the spectra occur naturally due to voids in the IGM and may provide a fairly model-independent probe of the baryon density.

In the last few years it has become possible to observe details of absorption by singly ionized helium. The observations combine new information about the history of quasars, intergalactic gas, and structure formation. These phenomena can be disentangled with detailed quantitative models of the situation which we briefly describe here. Theoretical treatments of some of the effects modeled here were given by Zheng and Davidsen (1995), Croft et al. (1997), Miralda-Escudé et al. (1996), Zhang et al. (1998) and Fardal, Giroux and Shull (1998).

Early observations of the helium II Lyman alpha absorption spectral region included the quasars Q0302-003 \( (z=3.285, \text{Jakobsen et al. 1994}) \), HS 1700+64 \( (z=2.72, \text{Davidson et al. 1996}) \) and PKS 1935-692 \( (z=3.18, \text{Tytler & Jakobsen 1996}) \). Higher resolution (GHRS) observations of Q0302-003 (Hogan, Anderson & Rugers 1997) and HE 2347-4342 \( (z=2.885, \text{Reimers et al. 1997}) \) revealed structure in the absorption which could be reliably correlated with HI absorption. The most recent published observations of PKS 1935-692 with STIS (Anderson et al. 1998) yield particularly good zero level estimates important for estimating the optical depth \( \tau \). Taken together, these data now appear to be showing the cosmic ionization of helium by quasars.
FIGURE 1. Observations of the HeII forest of PKS 1935-692 by Anderson et al. (1998) overlaid with a redshift-matched HI spectrum (dotted). The shelf structure in the GHRS (dashed)/STIS (solid) HeII spectra is best explained as the second-ionization of helium in the zone near the quasar. The flux recovers due to a void in the IGM at $\approx 1247\,\text{Å}$. A similar pattern is found in the two other higher-$z$ HeII quasars.

All of the objects show absorption with $\tau > 1$ at redshifts lower than the quasar. For the higher redshift QSO’s Q0302-033 and PKS 1935-692 (shown in Figure 1) there is a clear shelf of $\tau > 1.3$ in a wavelength region of order 20 Å in observed wavelength blueward of the quasar emission line redshift, dropping to a level consistent with zero flux or $\tau > 3 - 4$ beyond that. Anderson et al. conclude from these observations that gas initially containing helium as mostly HeII is being double-ionized in a region around the quasars. The lack of a strong emission line for HeII Lyman alpha suggests that ionizing flux is escaping so that the 228 Å flux may be similar to a simple power-law extension of the observed 304 Å rest frame flux. Hogan et al. used this to estimate the time required for quasars to create the double-ionized helium region to be 20 Myr for a 20 Å shelf (dependent on the Hubble parameter, spectral hardness, cosmology, baryon density and the shelf size).

The features present in HeII Lyman alpha spectra are reflected in the HI Lyman alpha forest for these quasars. Attempts to model the HeII absorption with line systems detected in HI suggest that low column HI absorbers, difficult to differentiate from noise in HI spectra, provide a substantial contribution to the HeII absorption. Typically, in the shelf region, the ratio of HeII to HI ions is of order 20 or more, rising to at least 100 farther away (The cross-section for HeII Lyman alpha absorption is 1/4 that of HI). A dominant feature in PKS 1935-692 and HE 2347-4342 is a void in the HeII absorption near the apparent edge of the HeIII bubble with corresponding voids in the HI spectra.

To interpret the rich datasets we are constructing models which include a realistic inhomogeneous distribution of gas as well as the relevant gas and radiation physics. We measured density and temperature along lines of sight through a SPH/N-body cosmological simulation (Wadsley & Bond 1998, CDM, $\Omega_b = 0.05$, $h = 0.5$) to use for modelling the radiative transfer of 54.4eV radiation from a newly turned on
quasar. Very small systems produce significant HeII absorption features, prohibiting using large, poor resolution simulations. We generated the long line of sight by bouncing a ray inside a 5 Mpc comoving diameter typical, mean density simulation. There is thus no independent long wavelength structure in the spectra.

The quasar flux used was the power-law extension to 228 Å of the observed 304 Å rest frame flux of PKS 1935-692. There is only significant continuum absorption by HeII when it is the dominant form of helium. We track the radiation above 54.4eV (the ionization energy of HeII to HeIII) in 100 frequency bins. This is important because the ionization cross-section for falls off strongly with frequency as \( \nu^{-3} \). The radiation field thus becomes harder as it is absorbed moving away from the quasar.

The gas density was fixed at each point and hydrodynamic motions ignored, appropriate because of the rapid onset of ionization compared to hydrodynamical timescales. Non-equilibrium energy and ionization equations are evolved with all the heating, cooling and ionization processes required for a zero metallicity intergalactic medium: ionization heating, cosmological expansion, compton, bremsstrahlung, line cooling, radiative recombination, photoionization and collisional ionization. Shocks are a possible heating source but the time scales are sufficiently short that heating associated with bulk ionization is dominant.

We treated several lines of sight from the simulation and varied the flux history and baryon density. For a given baryon density, the key parameters are the integrated total luminosity from the quasar, determining the bubble size, and the flux level for the last few times \( 10^6 \) years (the recombination time) before the observation is taken, determining \( \tau \).

A typical model spectrum is shown in Figure 2. The basic features of the observed proximity shelves are straightforward to reproduce. To get substantial recovery \((\tau << 1)\) in the spectrum a combination of a high flux and an empty void is required. Voids on the edge of the proximity shelf occur with sufficient frequency in the simulations that the ubiquity in the observations is not surprising. The 10,000-20,000K heating in the medium is greater away from the quasar (lower panel in Figure 2). The recombination rate goes as \( \sim T^{-0.7} \) and thus distant voids are made emptier. This heating and ionization extends beyond the visible shelf by around 30% beyond which even harder photons get absorbed.

The time-averaged quasar fluxes could be substantially different from those observed. Quasars are known to vary by a factor of two over a period of years and the response times are order of \( 10^5 \) years. Observational bias favours selection of quasars currently at the bright end of their intrinsic variability. There is a trade off so that a higher flux can be used with a corresponding increase in the baryon density. Shelves resembling the real data can be constructed by suitably adjusting the lifetime and recent flux. If quasars are rare density peaks, the mean density nearer quasars is higher which will increase \( \tau \) near the quasar and improve the model fit. However the density in void regions is seldom less than \( \sim 0.1 \) times the cosmological mean and thus we do not have the freedom to increase the universal baryon fraction without raising the ionizing flux to compensate, lest the optical depth in the voids become too high. The voids might therefore offer a relatively
FIGURE 2. Simple model with PKS 1935-692 flux level at 228 Å and 35 Myr lifetime. Simulated spectra: GHRS (dashed), STIS (solid), HI (dotted) and HI optical depth times 25 (thin solid). The shelf and recovery resemble those found in the real data, but the Gunn-Peterson edge is not as pronounced; this can be fixed by allowing for quasar variability. The temperature before and after turn-on is shown in the lower panel; note the rise in temperature away from the quasar, especially the order-of-magnitude increase in the voids. The heated zone extends well beyond the edge of the detectable HeIII bubble.

model-insensitive constraint on mean baryon density.

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FIGURE 3. Model with PKS 1935-692 flux level at 228 Å and 50 Myr lifetime with last 20 My at 1/10 the observed flux. The curves represent the same quantities as in Figure 2. Note that the shelf is better reproduced with this choice of parameters. The void near 1240 Å is not as pronounced. The intrinsic variability of quasars allows for some flux variation; but a better way to make the model match that data is to include the density enhancement in the zone surrounding the quasar density peak to increase the shelf optical depth. The void is sufficiently far from the quasar to be outside the local density enhancement for reasonable models of the density peak that produced the quasar host. This void is at a density 0.11 times the mean which is close to the rough lower limit of 0.1 times the mean. This universal lower limit combined with more detailed modelling currently underway will provide a constraint on the mean baryon density.