Photoionization Edges of Galaxies and the HI Column Density Distribution

Mark A. Fardal and Philip R. Maloney

JILA/CASA, University of Colorado, Boulder, CO 80309, USA

Abstract. We look for a photoionization feature in the HI column density distribution. Our model assumes the HI lines come from rotationally-supported disks in dark matter potential wells (i.e., galaxies), and the outer edges of these disks are ionized by the metagalactic radiation field. The predicted result is a flattening of the distribution from $N_{\text{HI}} \sim 10^{17.5} \text{ cm}^{-2}$ to $N_{\text{HI}} \sim 10^{20.5} \text{ cm}^{-2}$. Our preliminary results do not show strong evidence for this feature.

1 The Model

The HI distribution in present-day galaxies is observed to cut off very sharply beyond total columns of $\sim 3 \times 10^{19} \text{ cm}^{-2}$. This can be explained by photoionization by a metagalactic ionizing background (Maloney 1993). The column density at which this cutoff should occur is roughly $N_{cr} \sim (\Phi H / \alpha B)^{1/2} \sim 2 \times 10^{19} (\Phi / 10^4)^{1/2} \text{ cm}^{-2}$ for typical galaxies today, where $\Phi$ is the flux of ionizing photons in cm$^{-2}$ s$^{-1}$ and $H$ is the scale height of the galaxy. The rapid decline in $N_{\text{HI}}$ which occurs around $N_{cr}$ will slow when the gas becomes optically thin, i.e., at a neutral column of $\sim 10^{17} \text{ cm}^{-2}$, although this has not yet been observed.

The present-day value for $N_{cr}$ implies an ionizing flux of $\Phi \sim 10^4 \text{ cm}^{-2}$ s$^{-1}$. However, the ionizing background is believed to be about $30-100$ times stronger at $z \sim 2$. Hence we expect a feature in the $N_{\text{HI}}$ distribution starting around $10^{17} \text{ cm}^{-2}$ and extending up to $10^{21} \text{ cm}^{-2}$ or so. Although we have modeled the distribution in the specific context of disk galaxies, this feature is expected in almost any model of the high-$N_{\text{HI}}$ systems.

We assume the total gas column within a galaxy follows a power law, $N_H = 10^{20.2} (R / R_0)^{-\alpha} \text{ cm}^{-2}$. The variable parameters in the model are the flux of ionizing photons $\Phi$, $R_0$, and $\alpha$. We populate the universe at $z \sim 2$ with disk galaxies, drawn from the present-day luminosity function, and calculate their ionization structure. The resulting $N_{\text{HI}}$ distribution is then averaged over random orientations, assuming the disks are thin so that $N_{\text{HI}} \propto \sec \theta$ and the area $\propto \cos \theta$.

We fit this model to the $N_{\text{HI}}$ distribution of Petitjean et al. (1993). The Lyman limit systems from $10^{17.7}$ to $10^{20.5}$ fall into a single bin, which covers the most interesting range in $N_{\text{HI}}$ for the photoionization feature. However, there should still be an offset in the distribution between the systems with $N_{\text{HI}} \lesssim 10^{17} \text{ cm}^{-2}$ and those with $N_{\text{HI}} \gtrsim 10^{20} \text{ cm}^{-2}$.
2 Results

One such fit is shown in Fig. 1. The model is a poor fit ($\chi^2 = 4.2$), although it is a much better fit than a power law over the same range. Most of the discrepancy between the model and the data comes from the region $10^{14.5}$ cm$^{-2}$ to $10^{16}$ cm$^{-2}$, where there is a depression in the data. This feature could result from the overlap of two different populations at $N_{HI} \sim 10^{16}$ cm$^{-2}$. In this case our fit should be restricted to columns above $10^{16}$ cm$^{-2}$, and over this region a simple power law is better than our complicated model.

![Model Photoionization Feature](image)

Fig. 1. Fit (dashed) to column density distribution of Petitjean et al. (1993) (diamonds), with parameters $\Phi = 1.5 \times 10^5$ cm$^{-2}$ s$^{-1}$, $R_0 = 35$ kpc, and $\alpha = 1.3$.

The present lack of evidence for the photoionization feature could mean that $\Phi \leq 3 \times 10^5$. It could also mean that the data poorly constrain the shape of the $N_{HI}$ distribution. In particular, better statistics on the damped Ly$\alpha$ lines would help to constrain or rule out our model.

Acknowledgements. MF thanks the organizers and the CU-Boulder Dean's Small Grant Program for enabling him to attend the conference. This work was supported by NASA grants NAGW-766 and NAGW-1479.

References

On the He II Absorption Towards Q0302-003

Mark A. Fardal, Mark L. Giroux, and J. Michael Shull

JILA/CASA, University of Colorado, Boulder, CO 80309, USA

Abstract. The recent HST observation of the spectrum of the $z = 3.286$ quasar Q0302-003 (Jakobsen et al. 1994) shows an absorption edge at the redshifted wavelength of He II 304 Å. One cannot yet distinguish between contributions from discrete Lyα forest clouds and a smoothly distributed intergalactic medium (IGM). We model the contributions from these sources of He II absorption, including the distribution of line widths and column densities and the "He II proximity effect" from the quasar. Our models include a self-consistent treatment of the He II opacity of the universe as a function of the intrinsic ionizing source spectrum. The He II edge can be fully accounted for by the Lyα forest, for reasonable distributions of line widths and column densities, provided that the ionizing background sources have spectral index $\alpha > 1.9$. Even with some contribution from a diffuse IGM, it is difficult to account for the observed edge with a "hard" source spectrum ($\alpha < 1.3$). The proximity effect will increase the relative contribution of the clouds to $\tau_{\text{He II}}$ near the quasar ($z \approx z_q$). Higher resolution observations that characterize the change in transmission as $z \rightarrow z_q$ would be useful. These same observations may resolve line-free gaps in the continuum and set limits on the diffuse IGM.

1 He II Line Blanketing

To model the absorption from the Lyα forest, we use the distribution in H I column density ($N_{\text{HI}}$) and Doppler width ($b$) of Press & Rybicki (1993). This is a power law between lower and upper limits $N_l$ and $N_u$. We modify the background spectrum to take into account the different opacities at the H and He ionization thresholds. Varying $N_l$ or $N_u$ has a large effect on the line opacity, $N_l$ directly and $N_u$ indirectly by modifying the background spectrum. The $b$ distribution is not very important; a good approximation is to replace $b$ by its mean value.

2 The He II Proximity Effect

The flux from the quasar itself will ionize the gas if it is close enough. For Q0302-003, this should happen around 1280 Å. The opacity from the IGM is inversely proportional to the flux, but the Lyα forest opacity is less sensitive because many of the lines are saturated, the same reason it does not automatically dominate the total opacity in the first place. Possible models for the flux near the He II edge are shown in Fig. 1. Much more sensitive observations could determine the ionizing background using this effect.
3 Results

We require the average transmission from 1250—1300 Å to satisfy \( T < e^{-1.7} \), in accordance with Jakobsen et al.'s 90% confidence limit. When H I GP limits are included, we get limits on the allowed parameter space. If the lines are velocity broadened and/or extend down to \( 10^{12} \) cm\(^{-2} \) they can provide all of the He II opacity, consistent with Madau & Meiksin (1994). The proximity effect tightens the constraint on \( \alpha \) by about 0.2; soft source spectra (\( \alpha > 1.5 \)) are favored. We also suggest the possibility of small gaps between the lines, observable in higher-resolution observations.

![Graph showing transmission and optical depth characteristics.]

**Fig. 1.** Shows the increase in the flux as \( z \to z_\odot \). Two different models with \( T = e^{-2.0} \) are shown. Model 1 (solid) has parameters \( \tilde{\Omega}_{\text{IGM}} = 0.003, N_i = 10^{12}, N_a = 10^{16} \), and velocity-broadened b's. Model 2 (dotted) has \( \tilde{\Omega}_{\text{IGM}} = 0.02, N_i = 10^{13}, N_a = 10^{16} \), and thermal b's. Here \( \tilde{\Omega}_{\text{IGM}} \equiv \pi^{3/2} T_{4}^{-3/16} J_{-21}^{1/2} \Omega_{\text{IGM}} \).

**Acknowledgements.** This work was supported by NASA grants NAGW-766 and NAGW-1479.

**References**