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MINIHALO MODEL OF THE LYMAN-ALPHA FOREST IN A NEW LIGHT

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Abstract. We show that some observational properties of low- and intermediate-redshift Lyman-alpha forest clouds, e.g., the column density distribution function may be explained in more details by the classical minihalo model postulated by Rees. In addition, we propose a simple way of estimating the quantity of baryons residing in absorbing clouds in arbitary redshift range, unlike the estimates based only on the observed forest lines.

1. INTRODUCTION

Physical origin of the numerous Lyα absorption systems seen in spectra of all known QSOs remains one of the most active fields of contemporary astrophysical research. Many models have been proposed, but the origin of low- and intermediate-redshift absorber population remains mysterious to this day. In the classical minihalo model by Rees (1986) and Milgrom (1988), absorption is caused by neutral hydrogen fraction of the gas confined by gravitation in dark matter haloes with corresponding circular velocities $V_c < 50$ km/s. One of the principal aims of any model is to reproduce the column density distribution function (CDDF), that is considered an equivalent to the luminosity function of galaxies.

2. COLUMN DENSITY DISTRIBUTION FUNCTION

The CDDF function is usually given as

$$f(N_{\rm HI}) = \mathbb{B}_{\rm HI} N_{\rm HI}^{-\beta}, \qquad (1)$$

where $\mathbb{B}_{\rm HI}$ and β are positive constants to be fixed by observations in each particular column density and redshift range. The empirical results differ slightly due to the epoch and column density range used to establish the law (1).

2. 1. HIGH REDSHIFT RANGE

Carswell et al. (1984) found $\beta = 1.68 \pm 0.10$ in the range $13 < \log N_{\rm HI}$ [cm^{-2}] < 15 . Results obtained by Keck HIRES in the high redshift range gave a bit lower value of this parameter (Hu et al., 1995; Kim et al., 1997): $\beta = 1.46 \pm 0.09$. Press and Rybicki (1993) as the best fit give a value of $\beta = 1.43 \pm 0.04$, and Kim et al. (2002) at $< z >= 3.8$ found $\beta = 1.44 \pm 0.03$, in the column density range $13 < \log N_{\rm HI}$ [cm^{-2}] < 17.

2. 2. LOW- AND INTERMEDIATE-REDSHIFT RANGE

Penton et al. (2000) obtained $\beta = 1.72 \pm 0.06$ in the range $12.5 < \log N_{\rm HI}$ [cm^{-2}] < 14.0 and Janknecht et al. (2006) found $\beta = 1.59 \pm 0.02$, for $0.5 \leq z \leq 1.9$, in the column density interval $12.9 \leq \log N_{\rm HI}$ [cm^{-2}] ≤ 17.2.

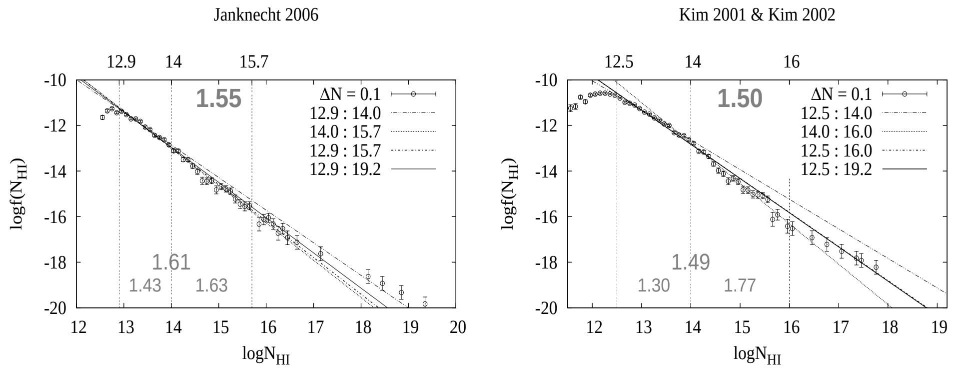


Figure 1: Column density distribution functions for the two samples investigated (Kim et al., 2001 together with Kim et al., 2002, labeled as Kim 2001 and Kim 2002 in the figure; Janknecht et al., 2006, labeled as Janknecht 2006). Best fits in different column density ranges (listed in the upper right corner of each panel) determine the parameter β.

Some straightforward conclusion could be the decrease in the power-law exponent with the redshift, due to increase of extragalactic ionizing flux since the equation of ionization equilibrium for optically thin gas (Osterbrock, 1989) relates total density of hydrogen ($n_{\rm H}$) to its neutral fraction ($n_{\rm HI}$) like:

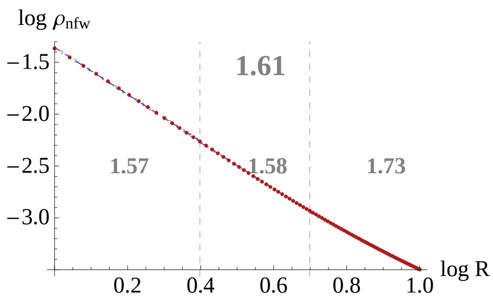
$$n_{\rm H}^2 = \frac{1}{\alpha_A}\frac{4\pi}{h}\left(\frac{1+z}{3.5}\right)^{\kappa} 10^{-21}\frac{A_0}{3+\delta}\; n_{\rm HI} = \frac{\Gamma_{\rm HI}}{\alpha_A} n_{\rm HI}, \qquad (2)$$

where α_A is ionization and $\Gamma_{\rm HI}$ is recombination coefficient. Another conclusion would be the increase in power law index throughout the absorber. We tested isothermal, Navarro-Frenk-White (Navarro et al., 1996) and Hernquist (Hernquist, 1990) dark matter profiles. For all models we obtained decrease in parameter β with redshift. For isothermal profile (Fig. 2(c)) we obtained decrease in parameter β *throughout the absorber*, that agrees well with observations (Fig. 1). On the other hand, there are individual cases (individual LOS) where the other two profiles (Fig. 2(a), 2(b)) should be considered (where β increases). However, on the average there seems to be more isothermal-like absorbers.

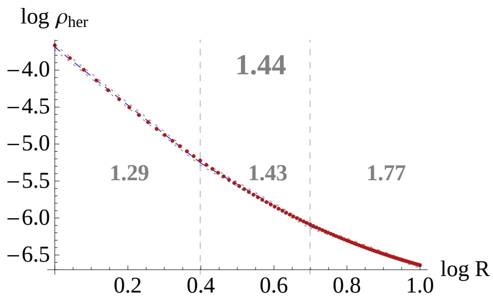
3. $\Omega_{\rm Ly\alpha}$ VALUE

Further, there is a way we could theoretically constrain the contribution to baryons residing in such minihaloes at low redshift. This can be compared with the observed cosmological density fraction

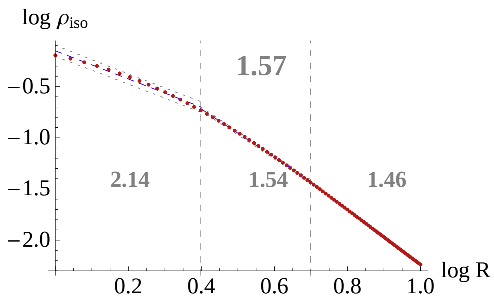
$$\Omega_{\rm Ly\alpha} = \frac{\mu m_{\rm H} H_0}{c\rho_{\rm crit}} \int x^{-1}(N_{\rm HI}) N_{\rm HI} f(N_{\rm HI}) dN_{\rm HI}, \qquad (3)$$



(a) Navarro-Frenk-White profile



(b) Hernquist profile



(c) isothermal profile

Figure 2: Different dark matter profiles calculated for $n_{\rm HI} = 10^{-6}$ cm^{-3}, $T = 10^4$ K and $z = 1$. Parameter β is indicated between grid lines taken at 2.5 and 5 kpc, and the upper value is the best fit for the whole range from 1 to 10 kpc.

where $x = n_{\rm HI}/n_{\rm H}$ is the neutral hydrogen fraction. Estimates published thus far obtain wildly varying values, ranging from several times 10^{-9} up to ≈ 0.04, the latter value meaning that practically *all* baryons would reside in absorbing clouds.

If we assume that dark matter profile follows some kind of power law γ, the connection between absorber density and CDDF can be established through absorbing column density, defined at the impact parameter r as

$$N_{\rm HI}(r) = \int_r^R n_{\rm HI}(r')dr' \Rightarrow \; N_{\rm HI}(r) = \mathbb{C}\left(\frac{r}{R}\right)^{-2\gamma+1} \quad \left(\mathbb{C} = \frac{\alpha_A/\Gamma_{\rm HI}}{2\gamma-1} r_0^{2\gamma} n_0^2 R^{-2\gamma+1}\right), \tag{4}$$

where R is the minihalo radius, r_0 core radius, n_0 core density and $n_{\rm HI}(r')$ is the neutral density fraction per mass related to the overall density trough the equation of ionization equilibrium for optically thin gas (2).

When the impact parameter is between r and r+dr the probability for the column density to be observed between $N_{\rm HI}$ and $N_{\rm HI} + dN_{\rm HI}$ is $P(N_{\rm HI})dN_{\rm HI} \propto r dr$. It is only natural to assume that the observed column density distribution is proportional to this probability; consequently, we have

Table 1: Calculated $\mathbb{B}_{\rm HI}$ and $\Omega_{{\rm Ly}\alpha}$ for all dark matter profiles for $R = 5$ kpc.

model	$n_{\rm HI}$ (cm^{-3})	β	$\log \mathbb{B}_{\rm HI}$	T_4	$\Omega_{{\rm Ly}\alpha}$
isothermal	10^{-5}	1.54	7.16	1.2	0.0047
Navarro-Frenk-White	10^{-5}	1.56	7.53	2.0	0.0044
Hernquist	10^{-5}	1.55	7.27	2.7	0.0046

$$\frac{d\mathcal{N}}{dN_{\rm HI}} \propto P(N_{\rm HI}) \propto r \left(\frac{dN_{\rm HI}}{dr}\right)^{-1} \propto N_{\rm HI}^{-(2\gamma+1)/(2\gamma-1)} \equiv \mathbb{B}_{\rm HI} N_{\rm HI}^{-\beta} \Rightarrow \beta = \frac{2\gamma+1}{2\gamma-1} \, . \quad (5)$$

There is a way even to calculate the constant $\mathbb{B}_{\rm HI}$ using (4), which means that our estimate of $\Omega_{{\rm Ly}\alpha}$ is completely independent on data. Combining equation of ionization equilibrium (2) with assumption on probability distribution, we obtain:

$$\mathbb{B}_{\rm HI} = \frac{2}{2\gamma-1} \left(\frac{2\alpha_A n_0^2 r_0^{2\gamma}}{(2\gamma-1)\Gamma_{\rm HI} R^{2\gamma-1}} \right)^{2/(2\gamma-1)} . \quad (6)$$

Now we can compare this result with observational data of Janknecht et al. (2006) in the redshift range $0.57 < z < 1.91$. The overall fit gives $\beta = 1.55 \pm 0.02$ and $\log \mathbb{B}_{\rm HI} = 8.7 \pm 0.3$. Using the same value of power law index, we can estimate the value of $\Omega_{{\rm Ly}\alpha}$ for different model neutral central densities, i.e. $n_{\rm HI} \in (10^{-6}, 10^{-3})$ cm^{-3}.

The best match we get for model parameters listed in Table 1. Lyα contribution ($\Omega_{{\rm Ly}\alpha}$) is near the upper limit consistent with nucleosynthesis theory. All profiles are very sensitive to the change of temperature, that causes a degeneracy to be resolved using realistic temperature profile (calculated from heating and cooling equilibrium, not a constant as it is taken within these simple models).

Acknowledgments

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