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MINIHALO MODEL FOR THE LOW-REDSHIFT Lyα ABSORBERS REVISITED

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SUMMARY: We reconsider the basic properties of the classical minihalo model of Rees and Milgrom in light of the new work, both observational (on "dark galaxies" and masses of baryonic haloes) and theoretical (on the cosmological mass function and the history of star formation). In particular, we show that more detailed models of ionized gas in haloes of dark matter following isothermal and Navarro-Frenk-White density profile can effectively reproduce particular aspects of the observed column density distribution function in a heterogeneous sample of low- and intermediate-redshift Lyα forest absorption lines.

Key words. quasars: absorption lines – Galaxies: halos – dark matter

1. INTRODUCTION: MINIHALO MODELS

Physical origin of the numerous Lyα absorption systems remains one of the most active field of contemporary astrophysical research. Many models have been proposed (for a brief review see Ćirković 2005), and while the high-redshift absorbers have been successfully incorporated into the general picture of structure formation theories (e.g. Press and Schechter 1974, Bond et al. 1988), the origin of low- and intermediate-redshift absorber population remains mysterious to this day. A substantial fraction of the low-z absorption lines are found to be associated with extended gaseous haloes of normal galaxies (Lanzetta et al. 1995, Chen et al. 1998), but their physical nature still remains elusive. In addition, there are some examples of absorption lines at low z which cannot be associated with any source visible in emission (e.g. Shull et al. 1996).

In the classical minihalo model of 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^{-1}. These would arise from the same process of hierarchical structure formation as normal galaxies, but would never gather sufficient amount of baryons to achieve gaseous densities necessary for star formation (which occurred in normal galaxies). Standard CDM cosmological paradigm predicts a large number of such "failed galaxies" or "dark galaxies" – terms we use here as synonymous with "minihaloes" – and it is not surprising that there has been a recent dramatic surge of interest in their properties and possibilities of observational detection (Hawkins 1997, Trentham et al. 2001). Furthermore, statistics of gravitational lenses provide additional strong support for existence of such dark galaxies (e.g. Jimenez et al. 1997). This prompts our reconsideration of minihalo model for explaining the observed features of low- and intermediate-z Lyα forest lines.

There are some other recent developments suggesting that such revisit would be fruitful. Notably, the research performed on the so-called high-velocity clouds (henceforth HVCs) in recent years seems to support the hypothesis that these objects are remnants from the epoch of the Local Group formation now infalling toward the center of the Milky Way halo (Blitz et al. 1999), contrary to the old ideas about the "galactic fountain". At least some of HVCs could be modern-day equivalents to minihaloes or dark galaxies at higher redshift. In addition to this, all surveys of baryonic matter at low redshift emphasize the necessity of having a convenient reservoir of baryons near individual galaxies and in small groups of galaxies in order to satisfy the constrains from both primordial nucleosynthesis and high-redshift observations and models (e.g. Fukugita and Peebles 2006). All this strongly suggests to us that revisiting the minihalo model, while keeping in mind these new observational and theoretical developments, still has a substantial explanatory potential.

One of the principal aims of any model for the origin of Lyα absorption systems in QSO spectra is to reproduce the column density distribution function (henceforth CDDF). As noted by Rauch (1998) in QSO absorption studies, CDDF occupies the same elevated position as the luminosity function in investigation of galaxy systems and distribution. It is usually assumed that it is expressed as the *differential* distribution function, i.e. the number of Lyα absorbing systems per unit redshift path per unit neutral hydrogen column density as a function of the neutral column density $N_{\rm HI}$. The CDDF is traditionally given in the form (Carswell et al. 1984, Hu et al. 1995)

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

where B and β are positive constants to be fixed by observations in each particular column density and redshift range. The original result of Carswell et al. (1984) was that $B = 1.058 \times 10^{11}$ and $\beta = 1.68 \pm 0.10$ in the column density interval $13 < \log N_{\rm HI} < 15$ cm^{-2}. Newer measurements from the spectra taken with the Keck HIRES suggest the values high-redshift parameters of the Eq. (1) of (Hu et al. 1995, Kim et al. 1997)

$$B = 4.9 \times 10^7, \tag{2}$$

and

$$\beta = 1.46^{+0.05}_{-0.09}. \tag{3}$$

Similar results have been claimed by other researchers. For instance, Press and Rybicki (1993) obtain the best-fit result for the CDDF index

$$\beta = 1.43 \pm 0.04. \tag{4}$$

These results, it should be noted, are obtained by statistical analysis of high-redshift samples of the Lyα forest. For the intermediate redshift sample of Janknecht et al. (2006), $0.5 \leq z \leq 1.9$, which we shall use in the further discussion, the best overall fit is given as

$$\beta = 1.50 \pm 0.45. \tag{5}$$

Subsequently, we compare this result with our redux of the minihalo model, for practical reasons, since in the subsequent work (Lalović and Ćirković 2008, submitted), we analyze the indirect arguments for the validity of minihalo model contained in the same absorption line dataset.

2. THE BASIC MODEL

The density profile and predicted CDDF for gas in hydrostatic equilibrium in spherically-symmetric CDM haloes is determined by the ionization-recombination equilibrium with metagalactic ultraviolet background. The background flux is taken from the comprehensive study of Haardt and Madau (1996). We start from the gas in hydrostatic equilibrium with the underlying CDM density profile described by equations:

$$\nabla p + \rho_{\rm b} \nabla \phi = 0, \tag{6}$$

$$p = R_{\rm m} T \rho, \tag{7}$$

$$\nabla^2 \phi = 4\pi G(\rho_{\rm b} + \rho_{\rm CDM}). \tag{8}$$

Here, $\rho_{\rm b}$ and $\rho_{\rm CDM}$ are physical densities of baryons and CDM particles respectively, p is the pressure (of baryons), ϕ is the Newtonian gravitational potential and $R_{\rm m}$ is the gas constant per mol, defined as

$$R_{\rm m} = \frac{R}{\mu m_{\rm H} N_{\rm A}}. \tag{9}$$

(Here $\mu \approx 1.3$ is the mean molecular mass, N_A is the Avogadro number and m_H is the mass of hydrogen atom.) For the dark matter profile, we use the two standard forms, namely isothermal:

$$\rho_{\rm iso} = \rho_0^{\rm ISO} \frac{r_0^2}{r^2 + r_0^2}, \tag{10}$$

and Navarro-Frenk-White (NFW, Navarro et al. 1996):

$$\rho_{\rm NFW} = \rho_0^{\rm NFW} \frac{r_0^3}{r(r + r_0)^2}. \tag{11}$$

From these equations, we can build a simple model of spherically symmetric minihaloes; for instance, for NFW profile (which is generally considered superior in describing dark matter haloes in normal galaxies and clusters, e.g. Ninković 2007, Kubo et al. 2007) we obtain the equation:

$$\frac{d^2 \ln \rho_{\rm tot}}{dx^2} + \frac{2}{x}\frac{d \ln \rho_{\rm tot}}{dx} + \alpha \rho_0^{\rm b} \rho_{\rm tot} + \alpha \rho_0^{\rm NFW} \frac{1}{x(x+1)^2} = 0, \tag{12}$$

where we have defined dimensionless radius as $x \equiv r/r_0$, total matter density at any point as $\rho_{\rm tot} \equiv \rho_{\rm b} + \rho_{\rm NFW}$ and α is the constant equal to

$$\alpha \equiv \frac{4\pi G r_0^2}{R_{\rm m} T}. \tag{13}$$

On the other hand, for *isothermal profile*, found to be more appropriate here, we have

$$\frac{d^2 \ln \rho_{\rm tot}}{dx^2} + \frac{2}{x}\frac{d \ln \rho_{\rm tot}}{dx} + \alpha\rho_0^{\rm b}\rho_{\rm tot} + \alpha\rho_0^{\rm ISO}\frac{1}{x^2+1} = 0, \quad (14)$$

Using the values for temperature conventionally used for Lyα absorbing gas from analysis of the Doppler parameter distribution ($T = [1-5] \times 10^4$ K), as well as the standard values of core radius ($r_0 = 1-5$ kpc), by numerically solving the Eq. (12) we build a family of models characterized by total baryonic mass of the order of 10^8 M$_\odot$, which is consistent with earlier models (e.g. Chiba and Nath 1997). Several interesting quantities can be computed from this model in order to be compared with the observed data sets of absorption lines; for example, we show the ratio of baryonic to dark matter densities as a function of halocentric radius in Figs. 1 and 2.

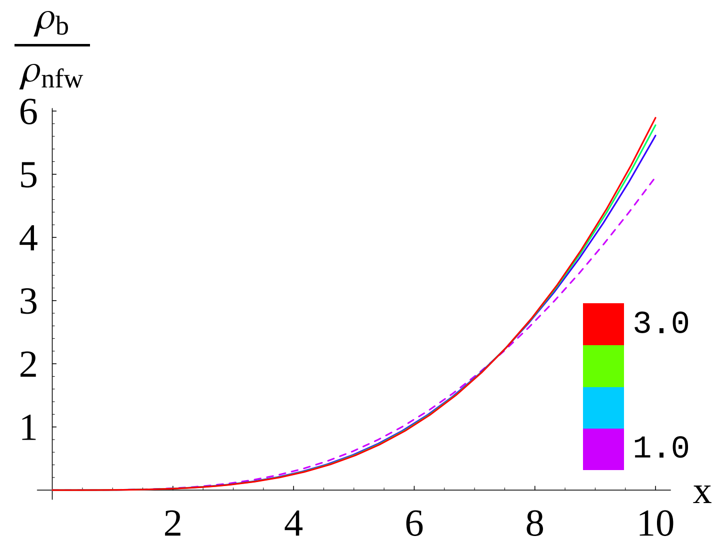

Fig. 1. *The ratio of baryonic to CDM density for various halocentric distances for the NWF density profile for various temperatures. As expected, CDM particles are significantly more centrally concentrated than dissipative baryons. There is no substantial difference between these ratios for variously chosen temperatures of the absorbing gas.*

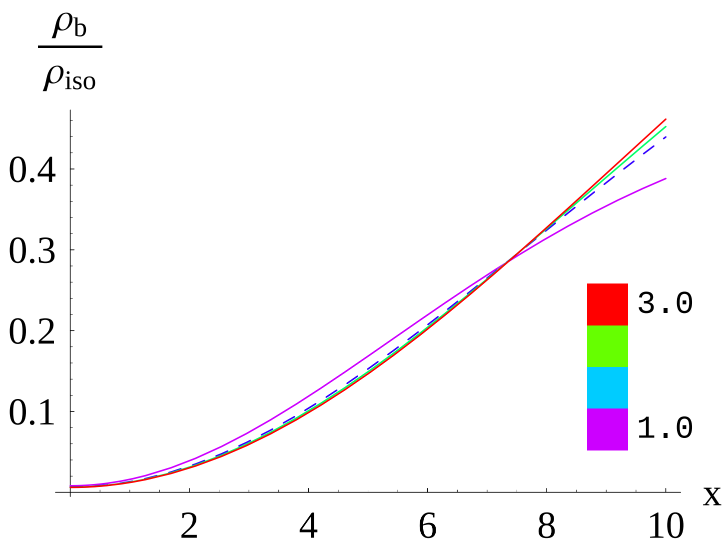

Fig. 2. *The same as in Fig. 1 for an isothermal CDM profile.*

Any such model is constrained by the global relationship between baryonic and dark matter cosmological densities. According to the "new standard" cosmological paradigm, $\Omega_\Lambda \approx 0.72$, $\Omega_{\rm b} \approx 0.05$ and $\Omega_{\rm CDM} \approx 0.23$. Neglecting cosmological bias and other higher-order effects (e.g. feedback of even very sparse star formation), we may assume that the ratio of the total masses of baryons and CDM within any particular minihalo is roughly $\simeq 1/5$. This is consistent with the primordial nucleosynthesis and WMAP constrains (e.g. Bennett et al. 2003), as well as the standard, unbiased galaxy formation scenarios (Press and Schechter 1974, White and Rees 1978).

The temperature range used is based upon the analysis of Doppler parameter distribution of *observed* lines, while the full model to be developed should determine the temperature distribution from the heating-cooling equilibrium, completely analogous to the methods successfully used in modeling interstellar medium in the disk of the Milky Way (e.g. McKee and Ostriker 1977). Since minihaloes are characterized by the absence (or at least strong inhibition) of star formation, after the initial collapse (presumably dominated by shockwave heating) the main heating source is bound to be external ionization. Cooling is a rather sensitive function of metallicity at least up to the threshold of $Z \leq 0.01\ Z_\odot$ (Böhringer and Hensler 1989, Sutherland and Dopita 1993).

3. OPTICALLY THIN MINIHALOES AND CDDF

The equation of ionization equilibrium for optically thin gas reads (e.g. Osterbrock 1989):

$$n_{\rm HI} \int\limits_{\nu_0}^{\infty} \frac{4\pi J_{\nu,z}}{h\nu} \alpha_\nu d\nu = n_{\rm HII}^2 \alpha_{\rm A}({\rm HI}, T), \qquad (15)$$

where the external (metagalactic) ionizing flux $J_{\nu,z}$ is described by the following parametrization ($\alpha_{\rm A}$ is the recombination coefficient for hydrogen plasma):

$$J_{\nu,z} = \left(\tfrac{1+z}{3.5}\right)^{\kappa} 10^{-21} \left(\tfrac{\nu}{\nu_0}\right)^{-\delta} \tfrac{\rm erg}{\rm cm^2\, s\, Hz\, sr},$$
$$\delta = 1.73,\ \kappa = 2,\ \nu_0 = 3.29 \times 10^{15} Hz. \qquad (16)$$

From atomic physics we obtain

$$\alpha_\nu = A_0 \left(\tfrac{\nu}{\nu_0}\right)^{-3} {\rm cm^{-2}},\ A_0 = 6.510^{-18}\ {\rm cm^{-2}};$$
$$\alpha_{\rm A} = 4.18 \times 10^{-13}\ (T = 10^4 {\rm K}). \qquad (17)$$

The integral in this equation is the ionization rate of neutral hydrogen, conventionally written as

$$\Gamma_{\rm HI} = \int\limits_{\nu_0}^{\infty} \tfrac{4\pi J_{\nu,z}}{h\nu} \alpha_\nu d\nu = \tfrac{4\pi A_0}{h} 10^{-21} \left(\frac{1+z}{3.5}\right)^{\kappa} \times \frac{1}{3+\delta} = \begin{cases} 2.89 \times 10^{-13}, & z = 0 \\ 4.68 \times 10^{-12}, & z = 4 \end{cases}. \qquad (18)$$

From (15), (16) and (17) we obtain

$$n_{\rm HI}(r) = \frac{\alpha_{\rm A}}{\Gamma_{\rm HI}}\, n^2(r) = n^2(r) \times \begin{cases} 0.09, & z = 4 \\ 1.45, & z = 0 \end{cases}. \qquad (19)$$

Absorbing column density at the impact parameter ρ is given as

$$N_{\rm HI} = 2 \int\limits_0^{\sqrt{R^2-\rho^2}} n_{\rm HI}(x)\, dx, \qquad (20)$$

where R is the minihalo radius. When the impact parameter is between ρ and $\rho + d\rho$, the probability for the column density to be observed between $N_{\rm HI}$ and $N_{\rm HI} + dN_{\rm HI}$ can be written as

$$P(N_{\rm HI}) dN_{\rm HI} \propto \rho d\rho. \qquad (21)$$

It is only natural to assume that the observed column density distribution is proportional to this probability; consequently, we have

$$\frac{dn}{dN_{\rm HI}} \propto P(N_{\rm HI}) \propto \rho \left(\frac{dN_{\rm HI}}{d\rho}\right)^{-1}. \qquad (22)$$

We present the results in Figs. 3 and 4 for the NFW and isothermal CDM profiles, respectively. We perceive that there is a significant agreement of both models with observations in the intermediate and outer regions of the minihalo. In the innermost region, however, there is a disagreement, which seems significant although the number of data points here is clearly smaller. This discrepancy will be studied in more detail in the course of the future work.

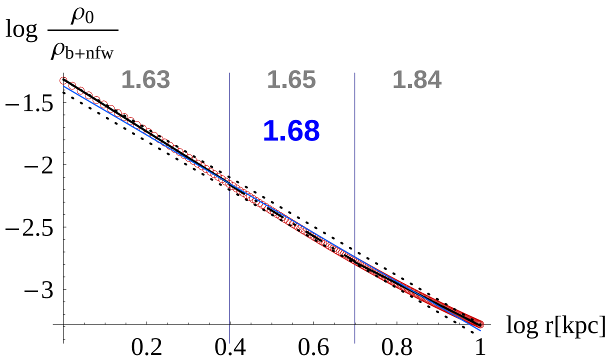

Fig. 3. *Predicted effective density profiles for NFW CDM haloes with the total ratio of baryons to CDM equal to 1:5. Open (red) circles denote numerically solved density of dark matter from Eq. (12). Solid blue line shows the best-fit observational data with* 1σ *error band shown as dotted lines. The effective CDDF index* β *is computed for* $R = 10$ kpc, $\rho_0^{\rm b} \sim 10^{-27}$ g cm^{-3} *and* $T = 3 \times 10^4 K$. *The total baryonic mass of the model minihalo is about* $7.4 \times 10^7\ M_\odot$.

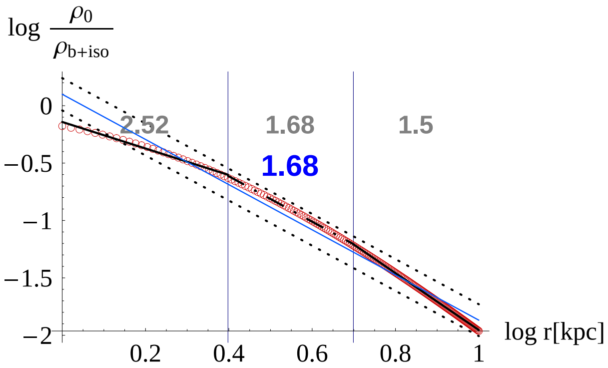

Fig. 4. *The same as in Fig. 3, for an isothermal CDM profile with* $R = 10$ kpc, $\rho_0^b \sim 10^{-27}$g cm^{-3}, *and the same temperature. The total baryonic mass is about* $2.2 \times 10^8\ M_\odot$, *in this case.*

However, the small change in temperature can induce significant changes in fit parameters. As we have mentioned earlier, the acceptable range in temperature is $T = (1-5) \times 10^4$ K, belonging to a thermally stable gas phase (McKee and Ostriker 1977) analogous to the Galactic HII regions. However, due to the optical depth effects, we expect to have different position of ionization-recombination balance. This will result in observation of different power-laws in column density distribution. To illustrate this effect, we have calculated the model with the same initial parameters, all except the temperature.

Although these changes affect the slope significantly, the greatest change comes from the variation of maximal (or cut-off) halo radius – both the slope and the central density vary a lot. For the radius of $R = 100$ kpc, the central density decreases two order of magnitude, which is physically unacceptable. The smaller the radius, the greater is the central density. Hence, if we want to reproduce empirically established densities, $\rho_0^b \in (10^{-27}, 10^{-22})$ g cm^{-3}, we have to decrease the radius from 10 to 5 kpc. The small adjustment of temperature in its range then gives proper densities and slopes. We may conclude that the biggest haloes may go up to 10 kpc in radius, not more, within this model. However, this is a very simple model aimed only at establishing the relationship between the observed CDDF and the density distribution function of the absorber itself.

Apart from this, we are trying to realise which profile of dark matter is in better agreement with observations. For the present, we have a clear indication that β increases towards the core, which means, refering to Figs. 4-5, that *isothermal profile* is more plausible here. Using data set from Janknecht et al. (2006), we reproduced this trend, as shown in the following Figure. The binning is performed with $\Delta N = 0.05$ and more than five points (absorption lines) inside each bin. The number of degrees of freedom is about ten and more, in each range fitted. The fit errors do not exceed 20% of the parameter values.

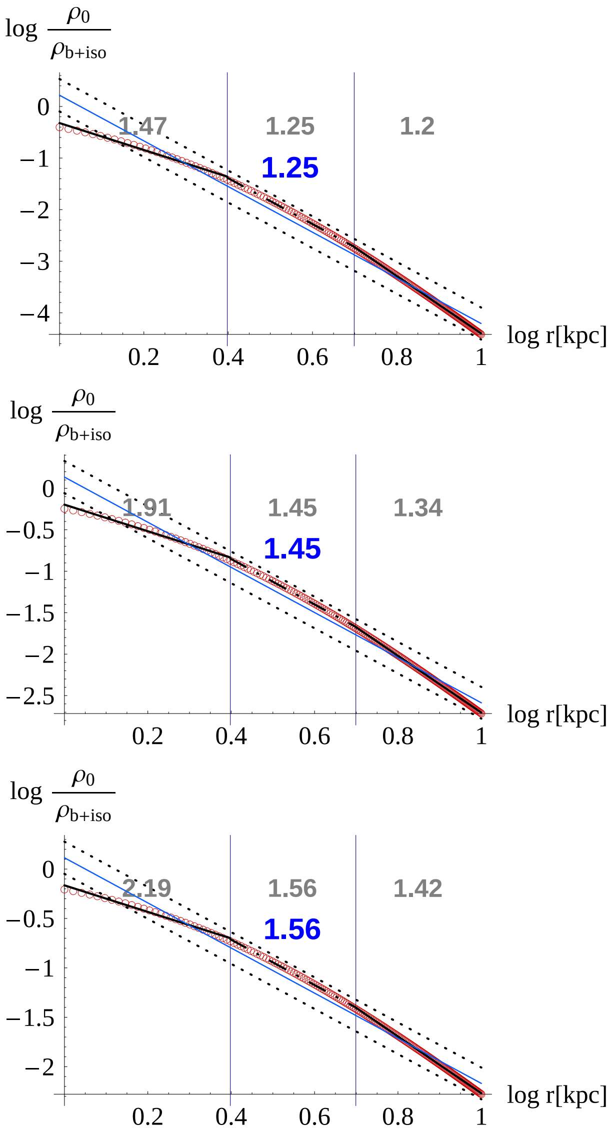

Fig. 5. *Density profiles for isothermal CDM haloes with* $R = 10$ kpc, $\rho_0^b \sim 10^{-27}$g cm^{-3}, *and the temperature taking values of 1, 2 and 2.5* $\times 10^4$ K, *respectively.*

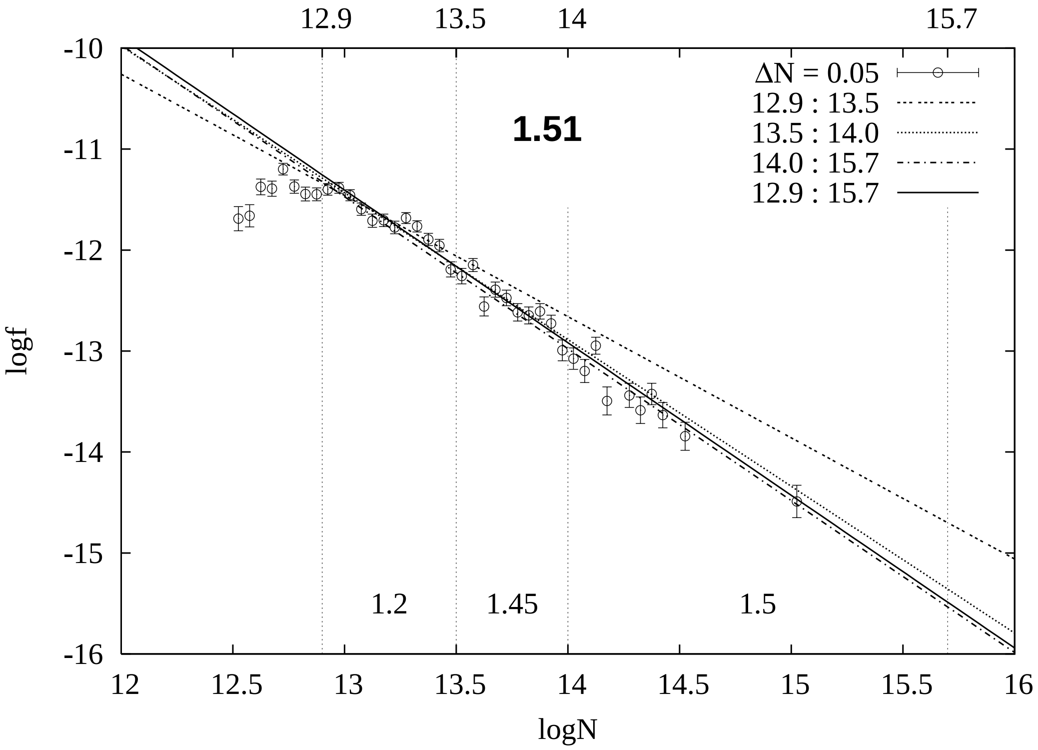

Fig. 6. *As in Figs. 4-5, parameter β is shown here, only in opposite manner, for the logarithm of column density is plotted on the x-axis and since it increases in the inward direction. Different column density regimes are shown by different line types, as shown in the upper right corner.*

4. PROSPECTS FOR FUTURE WORK

In the course of the future work, we shall investigate whether the fine-structure of absorption line samples can be accommodated in the generalized minihalo model. We shall also investigate the third analytical density profile, the one given by Hernquist (1990), which is often used in studies of spherically symmetric system due to its good reproduction of the $R^{1/4}$ law at small distances:

$$\rho(r) = \frac{M}{2\pi}\frac{r_0}{r}\frac{1}{(r+r_0)^3}, \qquad (23)$$

where M is the total mass and r_0 is a scale length. In addition, we shall attempt to answer the crucial question, namely, how big a contribution to the baryonic census can reside in such minihaloes at low redshift. This can be compared with the observed cosmological density fraction

$$\Omega_{\mathrm{Ly}\alpha} = \frac{\mu m_{\mathrm{H}} H_0}{c\rho_{\mathrm{crit}}}\int x^{-1}(N)\, N f(N)\, dN, \qquad (24)$$

where $x \equiv n_{\mathrm{HI}}/n_{\mathrm{H}}$ is the neutral hydrogen fraction. Estimates published thus far obtain wildly varying values, ranging from several times 10^{-9} up to $\simeq 0.04$ (for a recent review, see Stocke et al. 2006), the latter value meaning that practically *all* baryons would reside in absorbing clouds. While that is likely an overestimate, it seems quite plausible that such gas in small groups presents a significant missing baryonic reservoir for complete balancing of the baryonic census (Fukugita et al. 1998). A difficulty which can be envisaged here would be that the ionization source(s) at low redshift are much more heterogeneous and complex to model in comparison with the evolution of metagalactic ionizing background at high-z. In particular, the leakage of ionizing photons from (warped? flaring?) disks of normal spiral galaxies (e.g. Patel and Wilson 1995, Ferguson et al. 1996) can make precise modeling of ionization structure of minihaloes in small groups excessively complex. On the other hand, it would be interesting to redo the calculations of possible recombination flux (Ćirković et al. 1999) for minihaloes at low redshift in this light, in order to see whether new generations of instruments could hope to directly detect these elusive, yet arguably overwhelmingly numerous objects.

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МОДЕЛ МИНИХАЛОА ПРИМЕЊЕН НА Lyα АПСОРБЕРЕ ПРИ НИСКОМ ЦРВЕНОМ ПОМАКУ

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Оригинални научни рад

У овом раду изнова разматрамо основне особине класичног модела минихалоа који су постулирали Rees и Milgrom у новом светлу, како посматрачком ("тамне галаксије" и масе барионских халоа), тако и теоријском (космолошка функција масе и историја формирања звезда). Показано је да детаљнији модели јонизованог гаса у халоима тамне материје, који прате изотермални и Navarro-Frenk-White профил густине, могу репродуковати одређене аспекте посматране расподеле линијских густина у хетерогеном узорку апсорпционих линија Lyα-шуме на ниском и средњем црвеном помаку.