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ON THE TOTAL ABSORPTION CROSS-SECTION OF GALAXIES. II. THE CASE OF Λ COSMOLOGIES AND COVERING FACTOR VARIATION

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SUMMARY: In this work we expand the previous discussion of the plausibility of hypothesis of origin of the Lyα forest absorption systems in haloes of normal galaxies in connection with the *HubbleDeepField* (HDF) data. It is shown that simplistic approach to absorption cross-sections of galaxies with no luminosity scaling is in strong violation of empirical statistics up to redshift of $z \sim 3.5$. Realistic variation of the covering factor in order to account for its increase in the inner parts of observed haloes leads to even bigger discrepancy. Cosmologies with finite cosmological constant are briefly discussed and compared to $\Lambda = 0$ case. Ways to improve agreement with observational data are indicated. This problem is highly illustrative of the basic tenets of modern observational cosmology.

1. INTRODUCTION

The question of absorption cross-section of normal galaxies is one of great importance in several respects. It will serve as a good method of delineation between extended galactic haloes and ambiental intergalactic medium, which fills most of the universe. Improved knowledge on absorbing gas would enable obtaining empirical data on dynamical and chemical evolution of galaxies and/or galactic progenitors. It will solve one of the outstanding problems of astrophysics and cosmology: the mystery of origin of the narrow Lyα "forest" lines observed in spectra of all known quasars (e.g. Bahcall and Spitzer 1969; Bahcall *et al.* 1992; Shull 1995; Lanzetta *et al.* 1995). Finally, baryonic cosmological mass-density parameter Ω_b (equal to the ratio od density of baryonic matter to the closure density) is very hard to establish without knowing at least approximate amount of gas associated with normal field galaxies or small groups (Bristow and Phillipps 1994; Fukugita, *et al.* 1998).

In this work, we shall extend a simple and attractive way of applying basic physical principles in dealing with relevance of the absorption cross-section of normal galaxies to the problem of origin of Lyα forest which was presented in Ćirković *et al.* (1997, hereafter Paper I). To find a way out of the cosmological quandary, it is necessary that several astrophysical disciplines join forces and various recently obtained or refreshed data (deep sky surveys, absorption statistics, thermal instabilities, luminosity function of galaxies, etc.) find place in a unified framework.

Essentially, we would like to test a hypothesis put forward almost thirty years ago by Bahcall and

Spitzer (1969), that absorption lines seen in spectra of distant quasars arise in interceptions of the line of sight to the source by numerous extended haloes of intervening galaxies. From the work of Lanzetta et al. (1995) and Chen *et al.* (1998, hereafter CLWB) we know that at low and intermediate redshifts ($z \leq 1$), the average absorption cross-section corresponds to geometrical cross-section with radius for a typical L_* galaxy equal to $R_0 = 174^{+38}_{-25} h^{-1}$ kpc (h being the Hubble constant in units of 100 km s^{-1} Mpc^{-1}). There are other recent data on QSO absorption line systems pointing out in the same direction (Bechtold and Yee 1995; Bowen, *et al.* 1996), as well as attractive theoretical models (Mo 1994; Srianand and Khare 1994). The interesting question is applicability of that result to general universe, at least up to redshift between 3 and 4, where absorption systems are now regularly detected.

2. A SIMPLE MODEL

> *Quia frustra fit per plura quod potest equaliter per pauciona.*
>
> William of Ockham

As described in some more detail in the Paper I, a simple model with constant sizes of absorbers predicts significantly more absorption lines than actual observations reveal. The total number of predicted absorption lines up to redshift z is equal to

$$N_{\rm tot}(z) = \frac{\langle\kappa\rangle \pi}{4} \int\limits_0^z n(z)\Theta^2(z)\, dz, \tag{1}$$

where $\langle\kappa\rangle$ is the covering factor averaged over the size of absorbing area, $n(z)$ is the galaxy surface density (Lanzetta *et al.* 1996), and $\Theta(z)$ is the solid angle of an absorbing galactic halo located at redshift z. Obviously, this quantity depends on the cosmological parameters Ω and Λ (dependence on H_0 fortunately cancels out). We use the following notation: Ω is the total cosmological density parameter, which can be written as

$$\Omega = \Omega_m + \Omega_\Lambda, \tag{2}$$

Ω_m being mass-density, and $\Omega_\Lambda \equiv c^2\Lambda/(3H_0^2)$ effective cosmological vacuum-energy density. The points on the solid line in Fig. 1 represent the values of $N_{\rm tot}$ for constant unity covering factor and Einstein-de Sitter universe with $\Omega = \Omega_m = 1$, for many decades considered the best and most viable cosmological model. Error bars plotted are 1σ uncertainties.

Recently, a mounting evidence has appeared in favor of the finite cosmological constant, both in connection with the solution to the age problem (e.g. Reiss *et al.* 1998; Roos and Harun-or-Rashid 1998), and as best-fit model for new observations (e.g. Perlmutter *et al.* 1998). In addition, it seems that inflationary model, and other contemporary developments in quantum cosmology favor the residual non-zero Λ (Martel *et al.* 1998). This motivates us to consider the effect of non-zero cosmological constant on this problem and to calculate $N_{\rm tot}$ for such cases.

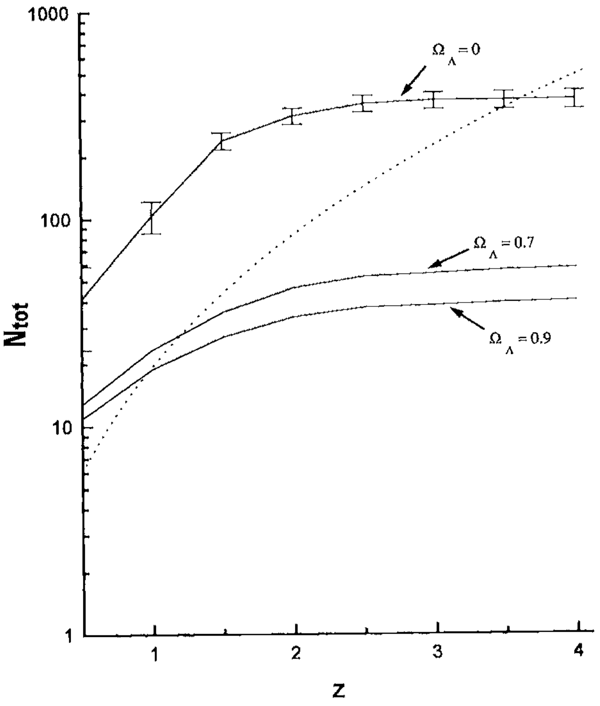

Fig. 1. *The number of predicted absorption lines* $N_{\rm tot}$ *as a function of redshift* z*, for the cases of Einstein-de Sitter universe with* $\Omega_\Lambda = 0$ *(solid curve with 1σ error bars), as well as the cases* $\Omega_\Lambda = 0.7$ $\Omega_m = 0.3$ *and* $\Omega_\Lambda = 0.9$, $\Omega_m = 0.1$. *Comparison with the empirical data derived from absorption statistics (dotted curve) is also given. We notice that the discrepancy with the observational data is smaller in case of these cosmological models, than in Einstein-de Sitter space. All curves are plotted for the unity covering factor.*

The angular size distance for Λ-cosmologies is (in the case of flat universe, $\Omega_m + \Omega_\Lambda = 1$) is given as (e.g. Carroll *et al.* 1992)

$$d_A = \frac{d_M}{1+z}, \tag{3a}$$

and

$$H_0 d_M = \int_0^{z_1} [(1+z)^2(1+\Omega_m z) - z(2+z)\Omega_\Lambda]^{1/2}\, dz \equiv I. \tag{3b}$$

The angle $\Theta(z)$ of an object of size D at redshift z is then given as

$$\Theta(z) = \frac{DH_0}{2c}\frac{1+z}{I} \tag{4}$$

In eqs. (3a) and (3b), d_M is the proper motion distance, as defined, for example, in Carroll *et al.*

(1992), and $D = 2R$ is physical diameter of the object. The eq. (7) of Paper I gives the general expression for the number of absorbing lines created by an ensemble of objects spanning angles $\Theta(z)$ and having redshift surface densities $n(z)$. Predictions for $\Omega_\Lambda = 0$, $\Omega_m = 1$ case are given in Paper I. Here, we compare it with two cases with finite cosmological constant. The results are shown for unity covering factor in the Fig. 1, for favored case $\Omega_\Lambda = 0.7$ and a rather extreme case $\Omega_\Lambda = 0.9$, the latter being interesting for its theoretical possibility of accounting for **all** matter in the universe in the form of baryons, i.e. no exotic dark matter necessary.

3. EMPIRICAL DATA POINTS AND COVERING FACTOR VARIATION

In figures 1 and 2, we have also shown the empirical results on the redshift distribution of the QSO absorption lines, which are usually approximated as (Bahcall *et al.* 1992; Storrie-Lombardi *et al.* 1994; Shull 1995; Kim *et al.* 1997)

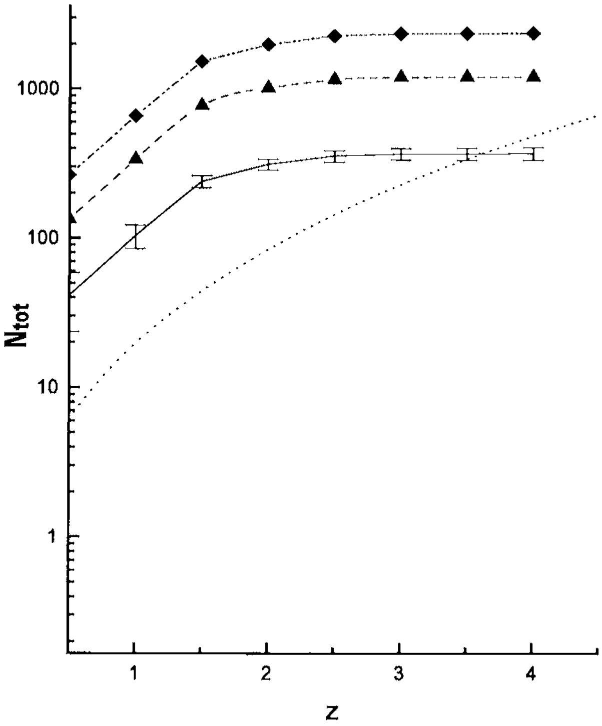

Fig. 2. *The number of predicted absorption lines N_{tot} in Einstein-de Sitter universe (solid line) as a function of redshift z shown with cases of non-uniform covering factor reaching unity at larger galactocentric distances (filled triangular and diamond-shaped points), as described in the text.*

$$\frac{dN}{dz} = N_0(1+z)^\gamma, \tag{5}$$

where N_0 is the comoving density of absorbers at present epoch ($z = 0$), and index γ is characterizing evolution of the cloud population. Therefore, the total number of absorption lines observed at redshifts up to z is equal to

$$N^{\mathrm{e}}_{\mathrm{tot}}(z) = \int\limits_0^z N_0(1+z)^\gamma dz = \frac{N_0}{\gamma+1}\left[(1+z)^{\gamma+1} - 1\right], \tag{6}$$

where the superscript "e" denotes **empirically** established value. Using recent results (Kim *et al.* 1997), suggesting $N_0 = 6.89$ and $\gamma = 2.41 \pm 0.18$, we have constructed dotted curve shown in Figs. 1 and 2. We notice clear discrepancy between empirical values and results of our simple model, in the sense that the model predicts systematically more absorption lines than it is observed, up to redshifts of $z \sim 3.5$ ($\Omega_m = 1$ model) or $z \sim 1.3$ (1.1) for models with cosmological constant density $\Omega_\Lambda = 0.7$ (0.9). Clearly, the inclusion of the cosmological term significantly decreases the total absorption cross-section of galaxies.

It should be emphasized that such a point of intersection is generally expected, even if the amplitude of theoretical prediction is significantly changed by luminosity scaling (see below). Namely, at higher redshifts at least two additional factors come into play:

- Even the HDF is not necessarily deep enough to be completely faithful representative of local galaxy density, and will thus systematically underestimate the galaxy surface densities.
- Galaxies may not be completely formed at those early epochs, or may be still in the stage of subgalactic fragments for which the low-redshift cross-sections (as well as luminosity functions!) certainly does not apply.

The discrepancy becomes even worse if we consider variation of the covering factor κ with impact parameter (i.e. galactocentric radius in spherical model). There is some evidence to the effect that in the inner parts of the galactic haloes (where metal-line absorption and Lyman limit systems are supposed to arise) gas is highly clumped, and $\kappa \sim 10$. This can be seen, for example, in complicated velocity substructure of many metal absorbers when observed with the highest available resolutions, like that on Keck HIRES spectrograph. If we denote characteristic size of that inner ("core") region with a and assume simple "step" profile:

$$\kappa(\rho) = \begin{cases} 10 & \rho \le a \\ 1 & a < \rho \le R_0 \\ 0 & \rho > R_0 \end{cases} \tag{7}$$

The mean value within R_0 is obtained as

$$\langle\kappa\rangle = 9\frac{a}{R_0} + 1. \tag{8}$$

If we take the core radius to be about the size inferred from metal-line observations (e.g. Steidel *et al.* 1994) $a \sim 40\,h^{-1}$ kpc, we get $\langle\kappa\rangle \approx 3.25$ and the predicted number of absorption lines is represented by triangular points in the Fig. 1.

On the other hand, we may assume an exponential model for the covering factor in the form

$$\kappa(\rho) = K \exp\left(-\frac{\rho}{a}\right), \tag{9}$$

where ρ is changing from 0 to R_0, and the boundary condition $\kappa(R_0) = 1$ immediately implies $K = \exp(R_0/a)$. On the other hand, the requirement $\kappa(\rho < a) \sim 10$ translates into approximate relation $a \approx R_0/3$, which is greater, but still similar to the actually inferred sizes of inner halo regions. This model for the covering factor gives $\langle\kappa\rangle \sim 6$. The predicted number of absorbers along the line of sight is represented by filled-diamond points in the Fig. 2. This is done for the $\Omega = \Omega_m = 1$ case.

4. DISCUSSION

Results in the Figures 1 and 2, in spite of their crudeness, again emphasize the basic conclusion of our Paper I, showing frequently quoted argument against galactic origin of Lyα forest clouds that there is too few galaxies to account for all Lyα absorbers to be wrong. It is interesting to note that introducing significant cosmological constant reduces the discrepancy of predicted and empirically established number of absorbers, and that in the plausible complete model of the total absorption cross-section of gas in the universe this factor has to be taken into account, especially in the light of impending accurate determination of cosmological parameters (Perlmutter *et al.* 1998).

The main cause of unrealistically high results in both figures, though, is not taking into account luminosity scaling of absorption properties. It is well-established in the case of metal line systems, and it is quite reasonable to expect Lyα forest clouds to behave similarly. The best available sample of low-redshift absorbers suggests that values of parameters in Holmberg-type scaling

$$R = R_0 \left(\frac{L}{L_*}\right)^{-\alpha} \tag{10}$$

are $R_0 = 174^{+38}_{-25}\, h^{-1}$ kpc, and $\alpha = 0.37 \pm 0.11$ (CLWB). In this case, correct total prediction for number of absorption lines in the universe up to redshift z is (for $\Omega = \Omega_m = 1$ cosmology)

$$N_{\rm tot}(z) = \frac{\kappa\pi}{4}\frac{R_0^2 H_0^2}{c^2}\left(\frac{10800}{\pi}\right)^2 \int\limits_0^z \frac{(1+z)^3}{(\sqrt{1+z}-1)^2} \left[\int\limits_{L_{\min}}^{L_{\max}} \left(\frac{L}{L_*}\right)^{-2\alpha} \varphi(L) dL\right] dz, \tag{11}$$

where $\varphi(L)$ is the universal luminosity function (LF) of normal galaxies (Schechter 1976; Bingelli *et al.* 1988; Willmer 1997). Recently, great progress was made in establishing the values of LF parameters in those parts of the spectrum in which they have not been well known for a long time, especially in near-infrared bands (e.g. Gardner *et al.* 1997), which are of the greatest importance for purposes of counting significantly redshifted objects. In the forthcoming paper, we shall calculate the values of the integral in the eq. (11) and show that it reasonably well reproduces empirical data on absorption lines at low and intermediate redshift, when observational (finite equivalent widths, etc.) and theoretical (mergers, late structure formation, etc.) constraints are taken into account (Fernández-Soto *et al.* 1997). In the same time, we shall devote more attention to similar analysis of recently obtained NTT SUSI Deep Field (Giallongo *et al.* 1998; Samurović and Ćirković 1998), as well as to expectations from the Southern Hubble Deep Field images (Sealey *et al.* 1998), to be obtained later this year. Results obtained from the international project MDS (Medium Deep Survey) will also be examined.

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О ТОТАЛНОМ АПСОРПЦИОНОМ ПОПРЕЧНОМ ПРЕСЕКУ ГАЛАКСИЈА. II. СЛУЧАЈ КОСМОЛОГИЈА СА КОСМОЛОШКОМ КОНСТАНТОМ

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Оригинални научни рад

У овом раду проширујемо ранију дискусију хипотезе о пореклу Лајманове шуме апсорпционих система у халоима нормалних галаксија, а у вези са подацима из Хабловог дубоког поља (HDF). Може се показати да је наивни приступ апсорпционим попречним пресецима галаксија, без скалирања са луминозношћу, у изразитој супротности са емпиријским статистикама све до црвеног помака од $z \sim 3,5$. Реалистичко варирање фактора покривања да би се репродуковало његово увећање у унутрашњим областима халоа води до још веће дискрепанције. Космологије са коначном вредношћу космолошке константе су укратко размотрене и упоређене са случајем $\Lambda = 0$. Указано је на путеве којима се може поправити слагање са посматрачким подацима. Овај проблем је изузетно илустративан у погледу примене основних поставки савремене посматрачке космологије.