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ON THE TOTAL ABSORPTION CROSS-SECTION OF GALAXIES

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SUMMARY: In this work we shall sketch a further piece of evidence for the plausibility of hypothesis of galactic origin of Ly-α forest absorption systems. Two basic premises of our discussion are (1) HDF redshift surface densities in the redshift interval $0 < z < 6$; and (2) validity of low-redshift results on redshift coincidences, showing average absorption cross-section corresponding to radius of $160h^{-1}$ kpc for L^* galaxies. Low-redshift analysis also showed covering factor nearing unity, which will be used and discussed in further considerations. Semantic problems concerned with the interpretation of galaxy absorption cross-section are discussed in some details, and importance of distinction between size of the absorbers and absorption coherence length is emphasized. It is shown that HDF data predict huge number of absorption systems, in fact much larger than observed, which shows frequently quoted argument that the number of galaxies is insufficient to account for all absorption lines to be wrong. Road to achieving higher compatibility with the empirical statistics is shown to lie in applying the luminosity scaling, possibly with cut-off. This is significant for recent attempts to explain the association of the Ly-α forest systems with normal galaxies.

1. INTRODUCTION

The question of absorption cross-sections of normal galaxies is one of great importance in several respects. It will serve as a good method of delineation between extended galactic halos and ambiental intergalactic medium (IGM). Improved knowledge on absorption in galaxies would enable obtaining empirical data on dynamical and chemical evolution of galaxies and/or galactic progenitors. Finally, baryonic cosmological mass-density parameter Ω_b is very hard to establish without knowing at least approximate amount of gas associated with normal galaxies.

From the work of Lanzetta *et al.* (1995, hereafter LBTW) we know that at low redshifts ($z \leq 1$), average absorption cross-section corresponds to purely geometrical cross-section with radius for a typical L^* galaxy equal to $160h^{-1}$ kpc (h is the dimensionless Hubble constant, defined by relation $H_0 = 100h$ km s^{-1}Mpc^{-1}). There are other data on QSO absorption line systems pointing out in the same direction. Now, interesting question is applicability of that result to general universe, at least up to redshift between 3 and 4, whereat absorption systems are now regularly detected. In order to calculate total absorption cross-section of normal galaxies, it is necessary to establish two facts: (1) the total number of galaxies in visible universe up to given redshift, and (2) scaling of absorption cross-section of each individual galaxy with its various properties: luminosity, morphological type, redshift (epoch) etc. Since our knowledge is vastly deficient to solve the full problem, we shall try to point out some great simplifications which can be reasonably made at present in order to make the topic more tractable.

Problem (1) became solvable (at least approximately) with the advent of *Hubble Deep Field* (HDF) analysis (Lanzetta, Yahil & Fernández-Soto 1996, hereafter LYF), which establishes redshift **surface densities** of normal galaxies at crude grid of redshift points. Although the interval $\Delta z = 0.5$ is very large, these are by far the best data, and probably the only ones available for this kind of research at present and in the near future. Thus, we intend to use photometric redshift determination by LYF in order to determine number-density of possible absorbers. Surface densities quoted in LYF are available only to 28th magnitude in 8140 Angström band, but the number density can, in principle, be extrapolated to even fainter magnitude. Since it is necessary to apply galaxy luminosity function (LF) of some sort in order to account for luminosity scaling of the absorption properties, extrapolation with the same LF is warranted, but in the first approximation, we shall regard the LYF surface densities as representative of a complete sample of galaxies up to given redshift.

As for (2), our knowledge is still very far from complete in order to directly express the dependence of absorption cross-section of galactic halos with other galactic properties. The only dependence firmly established is weak scaling with luminosity in case of metal-line systems (see below). So far, data indicate no difference with respect to morphological type, and the data are in principle insufficient to establish any systematic evolutionary effect, i.e. any scaling of absorption cross-section with redshift. The remaining possibility, which we take in further discussions, is to take into account only luminosity scaling (first approximation), after we showed that constant cross-section ("zeroth approximation") gives unrealistic results.

2. NOTES ON THE METHODOLOGY

It is very important to emphasize the difference between **intrinsic size** of the absorbers and characteristic **coherence length** for the absorption. Only the latter is an observable quantity (as far as the totality of available absorption studies is concerned). Claims made in the literature concerning measurement of size of absorbers, using either close pairs of background sources or multiple images of a single, gravitationally lensed source, are a sort of *quid pro quo*, since they do not make distinction between size and coherence length, thus making a mistake which is not only semantical. We shall denote a spatial extent of a single, contiguous absorber whose internal structure is, from the point of view of absorption studies, unimportant, as the absorber's size. On the other hand, if one observes coherent absorption over some angular extent, corresponding length is the coherence length for absorption. The difference is very profound if one considers, for example, two-phase halo models of Ly-α absorbers (e.g. Mo & Miralda-Escudé 1996). In such models, the size of a halo (~ 100 kpc) corresponds to coherence length; intrinsic size of the individual absorber (i.e. cloud of cold phase embedded in hot halo) is much smaller, probably only ~ 1 kpc.

Coherent absorption is not absolutely coherent: splittings of the order of several tens or even more than 100 km/s are observed (Bechtold et al. 1994; Dinshaw et al. 1995). In our view, this is further indication that the absorption does not arise in a single physical entity, but in the aggregate of objects strongly clumped (or clustered) about a central redshift. That is what is expected from the halo models, where entire ensemble of the absorbers is located at basically the same redshift – the redshift of the galaxy itself – and velocity dispersion is similar to the one characteristic for intragalactic objects, i.e. less than or equal to the rotational velocity of the galaxy ($V_c =$ const.). Although the exact motion of halo clouds is subject to poorly known phenomena, like galactic magnetic field in the halo, it can not, for simple physical reasons (Mo & Miralda-Escudé 1996), surpass the rotational velocity, and taking into account the projection along the line of sight, small-scale velocity splittings may be explained. In this way, the interpretation of empirical data as **the coherence length** is quite plausible. What makes the distinction somewhat blurred and confusing is **the large covering factor** within the coherence length of absorbing complexes. If we define the covering factor as the number of occasions the line of sight to QSO penetrating a cold cloud (where the absorption is to be expected), averaged over sufficiently large sample, it seems that it is greater than or equal to 1 in all parts of the volume spanned by coherence length. This follows from low-redshift observations (LBTW), and agrees well with galactic halo models, with the proviso that in inner parts of the halo (say, inner 30 - 50 kpc), covering factor may be much larger, on the order of 10. There are some observational indications to confirm such view (Lanzetta, private communication).

In further discussion we shall assume constant covering factor $\kappa \sim 1$. A detailed and sophisticated model of galactic halo gas is necessary for determination of exact dependence of the covering factor on other galactic properties, a model which, unfortunately, still does not exist.

3. A SIMPLE CALCULATION

Angular size of an object of proper diameter D at redshift z is given by the general relativistic formula (see, for example, Weinberg 1972)

$$\Theta = \frac{DH_0}{4c} \frac{(1+z)^2\Omega^2}{\frac{\Omega z}{2} + \left(\frac{\Omega}{2} - 1\right)\left(\sqrt{1+\Omega z} - 1\right)} \qquad (1)$$

for any given set of cosmological parameters H_0 and Ω. For the Einstein-De Sitter universe ($\Omega = 1$), which we shall hereafter only consider, this reduces to

$$\Theta = \frac{DH_0}{2c} \frac{(1+z)^{\frac{3}{2}}}{\sqrt{1+z} - 1}. \qquad (2)$$

In this world-model, an ensemble of absorbers of constant proper size D, located at redshift z give rise to total absorption cross-section equal to

$$\Sigma(z) = \sigma(z) n(z), \qquad (3)$$

where $\sigma(z)$ is the cross-section of each individual absorber, and $n(z)$ is the density of absorbers at redshift z, defined as the number of absorbers per (arc min)^2. What is interesting, though, is **the total number of absorptions up to redshift** z, which is given as

$$\Sigma_{\rm tot} = \int_0^z \Sigma(z) dz = \int_0^z \sigma(z) n(z) dz. \qquad (4)$$

This is, in principle, observable quantity, and any value obtained from the model may be tested against empirical data. In the spirit of the discussion above, we shall use geometric cross section corrected for the covering factor variation as

$$\sigma(z) = \kappa \frac{\pi \Theta^2(z)}{4}, \qquad (5)$$

Here, $\kappa = $ const. is the covering factor of the absorbers. Note that this is simplification of general formula

$$\sigma(z) = \int dL \int d\psi \sigma'(z, L, \psi), \qquad (6)$$

where the luminosity dependence is pointed out, and all other possibly relevant parameters are lumped together into a multidimensional variable ψ, while integration is carried over the relevant regions of parameters space (for luminosity, this is, in principle, over all possible luminosities, from 0 to ∞, but in practice this reduces only to the interval of applicability of the luminosity function used in calculation; see below for further discussion).

From equations (4) and (5), we obtain

$$\Sigma_{\rm tot} = \frac{\kappa\pi}{4} \int_0^z n(z) \Theta^2(z) dz. \qquad (7)$$

Since galaxy surface density $n(z)$ is available only in very crude discrete intervals, it is necessary to go from integration to summation. Also, we should substitute eq. (2) for angular size in Einstein-de Sitter model, thus obtaining

$$\Sigma_{\rm tot} = \frac{\kappa\pi}{4} \sum_{z_i} n(z_i) \left(\frac{DH_0}{2c} \frac{(1+z_i)^{\frac{3}{2}}}{\sqrt{1+z_i} - 1} \frac{10800}{\pi} \right)^2. \qquad (8)$$

Here, summation is carried out over upper bounds of redshift intervals $\Delta z = z_i - z_{i-1}$, up to the redshift of the background source. The factor $(10800/\pi)$ is included in order to enable surface densities to be expressed in (arc min)$^{-2}$.

It is important to realize the significance of equation (8). It gives a very important prediction: the number of absorption lines in spectrum of any background QSO as a function of observable surface densities and assumed absorption diameter and covering factor (both of which may be observable quantities in the low redshift limit of the theory). Here, both κ and D may be functions of redshift (epoch), luminosity or any other set of parameters. Supposing that they are constants, $\kappa = 1$ and $D \equiv D_0 = 2R_0 = 2 \times 160 h^{-1}$ kpc, we obtain numerical relation

$$\Sigma_{\rm tot} = 0.026 \sum_{z_i} n(z_i) \frac{(1+z_i)^3}{\left(\sqrt{1+z_i} - 1\right)^2}. \qquad (9)$$

(We note that delicate dependence on the exact value of Hubble constant fortunately cancels out.) Numerical calculation with LYF surface densities gives following results for sources located at fiducial redshifts:

Table 1. Dependence of the total number of absorptions, $\Sigma_{\rm tot}$ on the redshift z, and the estimate of the error of $\Sigma_{\rm tot}$

z	$\Sigma_{\rm tot}$	$\delta\Sigma_{\rm tot}$
0.5	41.1	17.7
1.0	103.4	18.2
1.5	238.4	22.3
2.0	312.0	27.7
2.5	355.5	31.6
3.0	367.7	33.2
3.5	369.3	35.3
4.0	371.2	36.8

4. DISCUSSION AND PROSPECTS

The result in Table 1, in spite of its crudeness, shows that the frequently quoted argument against galactic origin of Ly-α forest clouds that there is too few galaxies to account for all Ly-α forest absorbers is simply wrong. The best available sample of galaxies strongly testifies against it.

The cause of unrealistic result in Table 1 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 Ly-α forest clouds to behave similarly. It is accurate enough to express luminosity dependence of characteristic absorption radius as

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

where $R_0 = 160h^{-1}$ kpc for Ly-α forest absorption, and $\alpha > 0$ is the exponent for luminosity scaling. The same expression applies to all sorts of absorption systems; for metal line systems, for example, $R_0 = 30h^{-1}$ kpc, $\alpha = 0.3$ (Steidel 1993). Newer work (Chen *et al.* 1997) emphasizes similar values of α for the entire sample of absorbers (dominated, of course, by Ly-α forest): $\alpha = 0.32 \pm 0.12$. Under the assumption of $\alpha = 0.3$, correct total absorption cross-section up to given redshift is

$$\Sigma_{\rm tot} = \frac{\kappa\pi}{4} \frac{R_0^2 H_0^2}{c^2} \left(\frac{10800}{\pi} \right)^2 \int_0^z \frac{(1+z)^3}{(\sqrt{1+z}-1)^2} \left[\int_{L_{\rm min}}^{L_{\rm max}} \left(\frac{L}{L_*} \right)^{-2\alpha} \varphi(L) dL \right] dz, \qquad (11)$$

where $\varphi(L)$ is the universal luminosity function (LF) of normal galaxies. In further work, we shall show that the application of Schechter LF (Schechter 1976)

$$\varphi(L) = \varphi_* \left(\frac{L}{L^*} \right)^{-\gamma} e^{-\frac{L}{L^*}} \qquad (12)$$

in which values of parameters may vary in different methods (e.g. Willmer 1997) as:

$$(-1.11 \pm 0.08 \lesssim \gamma \lesssim -1.70 \pm 0.05) \qquad (13)$$

and

$$(-19.17 \pm 0.08 \lesssim M^* \lesssim -19.55 \pm 0.05), \qquad (14)$$

may lead towards important conclusions about the total number of absorptions.

The other important problem to be addressed in further study is morphological segregation of galaxies. According to present results, there is no certain difference in absorption properties of spiral and elliptical galaxies at high redshift. On the other hand, it is quite obvious that profound differences in structure of gas and stars in these two types of systems must be accounted for if we are ever to glimpse a unified picture of evolution of baryonic content of the universe. The dependence of absorption cross-section on morphological type may not necessarily be accounted for in such a simple manner as luminosity scaling in the equation (10) – or some analogous relation for the covering factor κ – although such approximation would be immensely useful. In any case, it is our hope that further investigations in this direction may result in unusually deep and fruitful insights in the basic questions of our universe.

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О ТОТАЛНОМ ПОПРЕЧНОМ ПРЕСЕКУ ЗА АПСОРПЦИЈУ ГАЛАКСИЈА

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У раду је дат део доказа о веродостојности хипотезе о галактичком пореклу Лајман алфа апсорпционих система. Две основне премисе у нашој дискусији су следеће: (1) Површинске густине према HDF-у (Хабловом дубоком пољу) у областима црвеног помака $0 < z < 6$ и (2) оправданост резултата за мале црвене помаке који показују да просечни апсорпциони попречни пресек одговара радијусу од $160h^{-1}$ kpc за L^* галаксије. Анализа за мале црвене помаке такође показује да је фактор покривања приближно јединица, што смо и користили у нашој расправи. У раду су такође дискутовани семантички проблеми који се односе на интерпретацију попречног пресека галактичке апсорпције, као и важност разликовања величине апсорбера и апсорпционе кохерентне дужине, што је посебно наглашено. Показано је HDF подаци предвиђају велики број апсорпционих система, у ствари много већи од онога који је посматран, што говори о томе да често цитирани аргумент који каже да је број галаксија недовољан да објасни све апсорпционе линије погрешан. Показано је да пут ка постизању веће сагласности са емпиријском статистиком лежи у примени скалирања луминозности, вероватно са прекидом. Ово је значајно за недавне покушаје објашњавања повезаности система Лајман алфа шума са нормалним галаксијама.