Ω_{baryon} and the geometry of intermediate-redshift Lyman α absorption systems

Michael Rauch[1] and Martin G. Haehnelt[2]

[1] *Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101, USA*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85748 Garching bei München, Germany*

ABSTRACT

Estimates of Ω_{baryon} from primordial nucleosynthesis, together with standard assumptions about the ionization state of low column density Lyα forest clouds, can be used to determine an upper limit for the cloud thickness along the line of sight. This upper limit provides significant constraints on the axial ratio of the absorbers and on the overall fraction of the baryonic matter contained in these objects if the recently measured large values for their transverse size are representative. The absorbers have to be considerably flattened structures and may possibly contain a substantial fraction of the baryonic matter at high redshift.

Key words: quasars: absorption lines – large-scale structure of Universe.

1 INTRODUCTION

Recently it has been emphasized (Petitjean et al. 1993; Meiksin & Madau 1993; Shapiro, Giroux & Babul 1994) that low column density Lyα absorption systems ($10^{13} \leq N \leq 10^{15}$ cm^{-2}) may contain a substantial fraction of the baryonic Ω, if the clouds are highly ionized.

Aside from the intrinsically interesting question of whether the baryons reside predominantly in the intergalactic medium (including Lyα clouds) or in galaxies, the maximum amount of baryonic matter that can be accommodated in Lyα clouds may provide useful constraints on the geometry of these objects (Rauch & Haehnelt 1994).

2 THEORY AND DISCUSSION

The baryonic fraction of the closure density in the clouds at intermediate and high redshifts can be computed from the neutral hydrogen (H I) column density distribution function (CDDF), $f(N)$, as described e.g. by Wolfe (1993),

$$\Omega_{\text{Ly}\alpha} = \frac{\mu m_H H_0}{c \rho_{0\,\text{crit}}} \int_{N_1}^{N_2} x^{-1}(N)\, N f(N)\, dN, \tag{1}$$

where N and x are the neutral hydrogen column density and the ratio of neutral-to-total hydrogen, respectively. H_0 and $\rho_{0\,\text{crit}}$ are the Hubble constant and the critical density at the present epoch. μm_H is the mean molecular weight. We adopt the usual power-law fit to the lower column density range (between $N_1 = 10^{13}$ and $N_2 = 10^{15}$ cm^{-2}), $f(N) = BN^{-\beta}$, with $B = 4.9 \times 10^7$ and $\beta = 1.46$, as given by Hu et al. (1995) for $q_0 = 0$, and integrate between column densities N_1 and N_2.

Assuming that the neutral fraction x of hydrogen is determined by photoionization equilibrium, we have

$$x = 3.9 \times 10^{-6} \left(\frac{T}{3 \times 10^4}\right)^{-0.35} \left(\frac{I}{10^{-21}}\right)^{-0.5}$$
$$\times \left(\frac{N}{10^{14}}\right)^{0.5} \left(\frac{D}{100\,\text{kpc}}\right)^{-0.5}, \tag{2}$$

where T is the gas temperature in K, I is the intensity of the ionizing UV background in units of erg Hz^{-1} sr^{-1} s^{-1} cm^{-2} (for the adopted fiducial value, see Lu, Wolfe & Turnshek 1991, and references therein), N is the H I column density in cm^{-2}, and D is the thickness of the cloud (or the path length of our line of sight through it).

To proceed further, we have to make some assumptions about the effective thickness D. It may depend on the H I column density N of the cloud, but without detailed modelling we can only speculate how. We represent D as a power law in N and consider three cases to demonstrate that our conclusions depend only weakly on what is assumed here (the power-law dependence is not intended to correspond to a concrete physical model):

(A) $D = D_0 = \text{constant}$, \hfill (3)

(B) $D = D_0 \left(\dfrac{N}{10^{14}}\right)$, \hfill (4)

and

(C) $D = D_0 \left(\dfrac{N}{10^{14}}\right)^{-1}$, \hfill (5)

where D_0 is a fiducial thickness which we will express below in units of 100 kpc.

Using case (A) in equation (1) we obtain, for the baryonic Ω,

$$\Omega_{\text{baryon}} \approx 0.036 \, h_{75}^{-1} f_{\text{Ly}\alpha}^{-1} \left(\frac{T}{3 \times 10^4}\right)^{0.35} \left(\frac{I}{10^{-21}}\right)^{0.5} \left(\frac{D_0}{100 \text{ kpc}}\right)^{0.5}.$$

(6)

Here $f_{\text{Ly}\alpha}$ is the fraction of baryons contained in Lyα absorption systems, and h_{75} is the Hubble constant in units of 75 km s^{-1} Mpc^{-1}. Cases (B) and (C) give $\Omega_{\text{baryon}} \approx 0.047$ and 0.043, respectively, with the same scaling in T, I and D_0. These Ω-values have to be compared with the range permitted by primordial nucleosynthesis arguments,

$$0.018 \leq \Omega_{\text{nuc}} h_{75}^2 \leq 0.027$$

(7)

(Walker et al. 1991). The nucleosynthesis upper limit on Ω then implies an upper limit on the size of the absorber along the line of sight,

$$D \leq 56 \, h_{75}^{-2} f_{\text{Ly}\alpha}^2 \left(\frac{T}{3 \times 10^4}\right)^{-0.7} \left(\frac{I}{10^{-21}}\right)^{-1} \text{ kpc}.$$

(8)

Together with the transverse sizes derived from absorption towards neighbouring QSO images, we can obtain an *upper limit on the typical axial ratio D/L (the ratio of thickness D to transverse length L) of the clouds:* $\Omega_{\text{nuc}} \leq 0.027 \, h_{75}^{-2}$ implies, for the most conservative case (A),

$$D/L \leq 0.056 \, h_{75}^{-2} f_{\text{Ly}\alpha}^2 \left(\frac{T}{3 \times 10^4}\right)^{-0.7} \left(\frac{I}{10^{-21}}\right)^{-1} \left(\frac{L}{1 \, h_{75}^{-1} \text{ Mpc}}\right)^{-1}.$$

(9)

Two recent measurements for quasar pairs with 1.4-arcmin and 9.5-arcsec separation, respectively, indicate transverse 'cloud diameters' (or coherence lengths) of order 1.2 h_{75}^{-1} Mpc for absorbers in the redshift range $0.5 \leq z \leq 0.9$ (Dinshaw et al. 1995), and 360 h_{75}^{-1} kpc or larger at redshift ~ 1.8 (Bechtold et al. 1994; Dinshaw et al. 1994). Here $q_0 = 0$ was assumed. These values are significantly larger than the lower limits obtained by Smette et al. (1992, 1995) from absorption of multiple QSO images of gravitationally lensed quasars with considerably smaller separation.

These results suggest that low column density Lyα absorption systems belong to *significantly flattened* structures, even if the fraction of all baryons contained in these systems is close to one [cf. Barcons & Fabian (1987), who proposed flattened absorbers for quite different reasons].

If this is correct, the actual size estimates should be even larger because the values quoted above were derived assuming spherical objects. Flattened structures seen at random aspect angles will have to be larger to subtend the same absorption cross-section, so the estimated diameters for $q_0 = 0$ become 1.7 h_{75}^{-1} Mpc $(0.5 \leq z \leq 0.9)$ and 500 h_{75}^{-1} kpc $(z \sim 1.8)$, respectively.

How are our conclusions affected if transverse cloud sizes change with time? The size estimates for $z \sim 1.8$ (Bechtold et al. 1994) and $z \sim 0.8$ (Dinshaw et al. 1995) may indicate that the typical transverse size of the absorbers is getting larger with time. Possible explanations include an expansion of the individual absorber (at least along the transverse direction),

or formation of absorbers with increasing transverse sizes towards lower redshifts, as expected in a hierarchical structure formation scenario. A direct comparison of the two estimates implies an evolution of transverse size roughly according to $(1 + z)^{-2.7}$. In view of the large errors of both estimates, such a comparison should be treated with caution. Nevertheless, extrapolation to a typical absorber redshift in the sample used to determine the CDDF ($z \sim 2.8$) would give a size of $L \sim 200$ kpc for disc-like absorbers. Even when adopting this unfavourable case, together with the extreme assumption that all baryons are contained in Lyα absorption systems, we find that the axial ratio D/L is required to be less than 0.25.

Note that so far we have assumed ionization number equilibrium, but *not* thermal equilibrium. Introduction of the additional constraint of thermal equilibrium would allow us to use the measured width of the absorption lines to obtain a second independent lower limit on the characteristic density and thus an upper limit on the characteristic thickness and axial ratio of the clouds (see e.g. Donahue & Shull 1991; Hu et al. 1995). At present, however, it is not at all clear whether heating by photoionization leads to thermal equilibrium. This uncertainty is mainly due to the lack of a reliable estimate of the characteristic density of the clouds. If the density of the clouds is only moderately enhanced compared with the mean baryonic density, as suggested in currently favoured models for the Lyα absorption systems (Cen et al. 1994), time-scales for photoionization heating and recombination and line cooling are longer than the Hubble time. The temperature of the clouds will then not be determined by photoionization equilibrium, but it will depend on dynamical processes like adiabatic cooling/heating, the spectrum responsible for the reionization of the intergalactic medium and the time elapsed since the gas was reionized (Miralda-Escudé & Rees 1994). However, the assumption of total (thermal and ionization) equilibrium would only strengthen our point: with the fiducial values for T, I and N adopted here and assumptions for the heating and cooling processes as in Donahue & Shull (1991), the equilibrium thickness of the cloud would be only of order 100 pc (Hu et al. 1995). One should note here, however, that the exact value will depend very sensitively on the details of the assumptions for the relevant cooling and heating processes and the spectrum of the ionizing background. Work by Cowie, Songaila & Kim (1995) and Hu et al. (1995), based on limits on the relative strengths of C IV, C II, Si II and N V (as indicators of the ionization state), suggests that the ionized fraction of the gas may indeed be compatible with a thermal equilibrium model, and we may take this as independent evidence in favour of flattened absorbers.

Can we escape the conclusion that Lyα clouds are considerably flattened? If our assumptions about the values of the ionizing background radiation, the nucleosynthesis Ω_{baryon} and the recent estimates of the transverse size are correct, we can think of clumping only as a potential way to increase the neutral fraction while keeping the overall geometry approximately spherical. Then the individual clumps or cloudlets would have to be confined, presumably in the hot external medium of a (galactic) halo which itself is being kept in place by gravity, a model investigated most recently for low-redshift absorption systems by Mo (1994). However, the cloudlets would have to be numerous and of

low mass to explain the observed covering factor of order unity. It seems difficult to understand how such cloudlets would form, given the high Jeans mass in such an environment. Furthermore, the velocity structure seen in high-resolution Lyα forest studies indicates multiple-component structure only on a velocity scale of a few tens of km s^{-1} (e.g. Cowie et al. 1995; Dinshaw et al. 1994), less than expected for haloes with galactic or even larger dimensions. Another potential difficulty of the halo picture concerns the confinement itself: assuming a virialized structure with virial velocities of a few tens of km s^{-1}, the confining halo gas would hardly be hotter than the cloudlets to be confined. Unlike in the case of Mg II absorption systems at low redshift (e.g. Bergeron & Boissé 1991), it seems therefore implausible that small absorbing gas clumps in a quasi-spherical halo are an explanation for the large observed absorber sizes at intermediate redshift.

3 CONCLUSIONS

We have used the assumption that intermediate-redshift Lyα forest absorbers are in photoionization equilibrium with the UV background radiation, together with limits on Ω_{baryon} derived from primordial nucleosynthesis and recent detections of common absorption on large scales, to show that these absorbers are likely to be *significantly flattened* structures, with axial ratios of possibly less than 1/10. The recent large size estimates can be reconciled with highly ionized gas in photoionization equilibrium if they measure mostly the transverse extent of flat gaseous structures with a large covering factor. The picture of Lyα forest absorbers as flattened structures is consistent with the conclusions of Cen et al. (1994) and Petitjean, Mücket & Kates (1995), who find that simulations of gravitational collapse in the Universe create filamentary or sheet-like structures giving rise to absorption phenomena very similar to the Lyα forest. It also ties in nicely with the results obtained by Bechtold et al. (1994) and Dinshaw et al. (1994, 1995), who find small velocity differences among the common absorption-line pairs in their double QSO spectra. In fact, the large transverse size estimates and our result, if correct, do not uniquely distinguish between the existing models (pressure confinement, cold dark matter gravity confinement) discussed

earlier for intergalactic clouds; they suggest, however, that most Lyα forest systems, at least at high redshift, do not arise in quasi-spherical structures.

REFERENCES

Barcons X., Fabian A. C., 1987, MNRAS, 224, 675
Bechtold J., Crotts A. P. S., Duncan R. S., Fang Y., 1994, ApJ, 437, L83
Bergeron J., Boissé P., 1991, A&A, 243, 344
Cen R., Miralda-Escudé J., Ostriker J. P., Rauch M., 1994, ApJ, 437, L9
Cowie L. L., Songaila A., Kim T.-S., Hu E. M., 1995, AJ, 109, 1522
Dinshaw N., Foltz C. B., Impey C. D., Weymann R. J., Chaffee F. H., 1994, ApJ, 437, L87
Dinshaw N., Impey C. D., Foltz C. B., Weymann R. J., Morris S. L., 1995, Nat, 373, 223
Donahue M., Shull J. M., 1991, ApJ, 383, 511
Hu E. M., Kim T.-S., Cowie L. L., Songaila A., Rauch M., 1995, AJ, submitted
Lu L., Wolfe A. M., Turnshek D. A., 1991, ApJ, 367, 19
Meiksin A., Madau P., ApJ, 412, 34
Miralda-Escudé J., Rees M. J., 1994, MNRAS, 266, 343
Mo H. J., 1994, MNRAS, 269, L49
Petitjean P., Webb J. K., Rauch M., Carswell R. F., Lanzetta K., 1993, MNRAS, 262, 499
Petitjean P., Mücket J. P., Kates R. E., 1995, A&A, 295, L9
Rauch M., Haehnelt M. G., 1994, paper presented at the ESO Workshop on QSO Absorption Lines, Garching, 1994 November, in press
Shapiro P. R., Giroux M. L., Babul A., 1994, ApJ, 427, 25
Smette A., Surdej J., Shaver P. A., Foltz C. B., Chaffee F. H., Weymann R. J., Williams R. E., Magain P., 1992, ApJ, 389, 39
Smette A., Robertson J. G., Shaver P. A., Reimers D., Wisotzki L., Köhler Th., 1995, A&A, in press
Walker T. P., Steigman G., Schramm D. N., Olive K. A., Kang H. S., 1991, ApJ, 376, 51
Wolfe A. M., 1993, Ann. NY Acad. Sci., 688, 281