The effects of an ionizing background on the HI column density distribution in the local Universe

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ABSTRACT

Using data on the HI column density distribution in the local Universe, \( f(N_{HI}) \), in this paper we show how to determine \( g(N_H) \), the distribution of the total gas (HI+HII) column density. A simple power law fit to \( f(N_{HI}) \) fails due to bendings in the distributions when \( N_{HI} < 10^{20} \text{ cm}^{-2} \) and H is no longer fully neutral. If an ultraviolet background is responsible for the gas ionization, and \( g(N_H) \propto N^{-\alpha}_H \), we find the values of \( \alpha \) and of the intensity of the background radiation which are compatible with the present data. The best fitting values of \( \alpha \), however, depend upon the scaling law of the gas volume densities with \( N_H \) and cannot be determined unambiguously. We examine in detail two models: one in which the average gas volume density decreases steadily with \( N_H \), while in the other it stays constant at low column densities. The former model leads to a steep power law fit for \( g(N_H) \), with \( \alpha \simeq 3.3 \pm 0.4 \) and requires an ultraviolet flux larger than what the QSOs alone produce at \( z = 0 \). For the latter \( \alpha \simeq 1.5 \pm 0.1 \) and a lower ionizing flux is required. The ambiguities about the modelling and the resulting steep or shallow \( N_H \) distribution can be resolved only if new 21-cm observations and QSOs Lyman limit absorbers searches will provide more data in the HI-HII transition region at low redshifts. Using the best fit obtained for higher redshift data we outline two possible scenarios for the evolution of gaseous structures, compatible with the available data at \( z \sim 0 \).

Subject headings: diffuse radiation — galaxies: evolution — galaxies: ISM — intergalactic medium — quasar: absorption lines

1. Introduction

The HI column density distribution of intergalactic gas clouds, \( f(N_{HI}) \), is determined at high redshifts through the analysis of QSO absorption spectra. The detection of Lyman
continuum absorption and of Lyα absorption lines between us and the QSOs has been used to derive $f(N_{HI})$ from $N_{HI} \simeq 10^{12.5}$ cm$^{-2}$ to $N_{HI} \simeq 10^{21.5}$ cm$^{-2}$ (?, e.g.)[pet93,rau98,sto00]. Attempts have been made to fit $f(N_{HI})$ over many decades of $N_{HI}$ with a simple power law. However, it is more physically meaningful to expect a power law behavior for $g(N_H)$, the total (neutral+ionized) column density distribution. In fact, due to drastic changes in the hydrogen ionization fraction when the gas becomes optically thin to photons above 13.6 eV, breaks in $f(N_{HI})$ appear for $N_{HI} \sim 10^{18}-10^{20}$ cm$^{-2}$, where a small decrease of $N_H$ corresponds to a rapid change in $N_{HI}$. A more appropriate approach is to compare the observed $f(N_{HI})$ to the $N_{HI}$ distribution function derived from an assumed $g(N_H)$, after ionization changes corrections have been applied. This method has been used by Corbelli et al. (2001) to derive the slope of $g(N_H)$, assumed to be $\propto N_H^{-\alpha}$, and the ionization conditions of the gas at redshifts $z \sim 2–3$. Since the frequency of intervening absorption systems is high at these redshifts, it has been possible to limit the analysis to high column density absorbers, using data relative to (mostly neutral) Damped Lyα absorption systems, and to (mostly ionized) Lyman limit systems. A comparison of models for dark matter confined systems with the observed $f(N_{HI})$ led to values of $\alpha > 2$ for $z \sim 2–3$; an extrapolation of this power law distribution towards systems of lower column density, the Lyα forest, gives reasonable fits for $N_{HI} > 10^{15}$ cm$^{-2}$.

At lower redshifts the number density of absorption systems is much lower and the poor statistics based on Lyman limit and Damped Lyα alone does not allow a determination of the distribution function $g(N_H)$. At zero redshift however these studies can be complemented with detailed observations of 21-cm emission line radiation from nearby galaxies. 21-cm emission data have the advantage of leaving small uncertainties on $N_{HI}$, while saturated Lyman limit breaks in QSOs spectra give only lower limits on the intervening $N_{HI}$ (?, e.g.)for a correct statistical treatment of such measurements[ban01]. If 21-cm observations are sensitive enough to HI column densities where the hydrogen gas is mostly ionized in the presence of a UV radiation field, then we could use these data to infer $g(N_H)$ and the intensity of the ionizing background radiation in the local Universe, which is not directly observable. Similarly, the observed sharp drop of the HI column density in the outer disk of two nearby spiral galaxies, M33 and NGC3198, interpreted as an HI-HII transition zone, made possible an estimate of the UV ionizing flux at $z = 0$ (Corbelli & Salpeter 1993; Maloney 1993). The known dark matter content of these galaxies, inferred from the gas kinematics, reduced the associated uncertainties. In this paper we shall give additional evidence for a UV ionizing background in the local Universe using the shape of the observed $f(N_{HI})$. We derive power law fits to $g(N_H)$ which reproduce $f(N_{HI})$ quite well over many orders of magnitude, after ionization corrections have been applied. We underline the observations needed in the future to reduce the ambiguities in modeling the ionization corrections and the resulting best fitting
values of \( g(N_H) \). We briefly discuss two different evolutionary scenarios for gaseous structures in the Universe, both compatible with the present data.

2. The \( N_{HI} \) distribution function at \( z = 0 \)

At low redshifts there are two different sets of data which can be used to derive \( f(N_{HI}) \):

- Ly\( \alpha \) absorption lines and Lyman breaks observed in QSOs spectra. The Hubble Space Telescope (HST) has provided good quality data for low redshift absorption systems. Penton et al. (2000) and Shull (2001) have analyzed HST/FUSE data for redshifts \( z < 0.1 \) and \( N_{HI} < 10^{17} \text{ cm}^{-2} \). Weymann et al. (1998) have analyzed data for \( N_{HI} < 10^{16.5} \text{ cm}^{-2} \) in a broader redshift range \( z < 1.3 \) and found a weak evolution in the number of absorbers per unit redshift. As Penton et al. (2000) have already pointed out there is good agreement between the \( N_{HI} \) distributions derived from the two sets of data and therefore we limit ourselves to the Weymann et al. (1998) data, shown in Figure 1(a). For higher column densities \( f(N_{HI}) \) at \( z \approx 0 \) is evaluated from the Lyman limit and Damped Ly\( \alpha \) data collection of Bandiera & Corbelli (2001) over the redshift interval \( 0 \leq z < 1.3 \), taking into account the mild evolution of Lyman limit systems (Corbelli et al. 2001).

- 21-cm maps of nearby galaxies and the \( HI \) mass function. 21-cm observation of the \( HI \) gas in nearby galaxies with high resolution and sensitivity provide data on \( d\Sigma(N_{HI}) \), the galaxy differential cross section for a given range of \( N_{HI} \), averaged over all inclinations. This information, acquired for galaxies of different \( HI \) masses and coupled with the \( HI \) mass function, \( \Phi(M_{HI}) \), gives \( f(N_{HI}) \):

\[
f(N_{HI}) = \frac{\int_{M_{HI}}^{M_{HI}^{\text{max}}} \Phi(M_{HI}) d\Sigma(N_{HI}, M_{HI}) dM_{HI}}{(H_0/c) dN_{HI}}
\]

In order to determine \( f(N_{HI}) \) across the region where the hydrogen becomes mostly ionized, observations should be sensitive to column densities down to \( \sim 3 \times 10^{18} \text{ cm}^{-2} \). Recently the \( HI \) Parkes All Sky Survey (HIPASS) together with the Australia Telescope Compact Array (ATCA) has provided good quality data for \( \Phi(M_{HI}) \) and for \( d\Sigma(N_{HI}, M_{HI}) \) (Ryan-Weber et al. 2001). Fitting the data with a Schechter function (Schechter 1976), the resulting \( \Phi(M_{HI}) \) has a characteristic \( HI \) mass value \( M^* = 1.14 \times 10^{10} \text{ M}_\odot \), a faint end slope \( \alpha = 1.52 \), and a normalization \( \theta = 0.0032 \) (Kilborn 1999, 2000). Similar values have been obtained recently also by Rosenberg & Schneider (2001). We use this mass function in the following analysis and consider 6 mass bins of equal width across the range \( 7.5 < \log(M_{HI}/\text{M}_\odot) < 10.5 \). Ryan-Weber et al. (2001) have evaluated \( d\Sigma(N_{HI}, M_{HI}) \) for two \( M_{HI} \) ranges: for \( 10^{7.5} < M_{HI} < \)}
10^8 M_⊙ and for 10^{10} < M_{HI} < 10^{10.5} M_⊙. In the literature there are furthermore two galaxies which have been mapped in great detail down to a low surface density: M33 and NGC3198. We compute dΣ for these galaxies as orientation averages of the face on cross sections, obtained from the deconvolution of the observed N_{HI} radial profiles with the best fitted tilted ring model (Begeman 1989; Maloney 1993; Corbelli & Salpeter 1993; Corbelli & Salucci 2000). The HI mass of M33 is \sim 2.7 \times 10^9 M_⊙ for a distance of 0.84 Mpc and that of NGC3198 is \sim 5 \times 10^9 M_⊙ for a distance of 9.4 Mpc. Data on these two galaxies can therefore be used for dΣ(N_{HI}, M_{HI}) in the two mass bins spanning 10^9 < M_{HI} < 10^{10} M_⊙. In order to estimate dΣ for 10^8 \leq M_{HI} \leq 10^9 M_⊙, where we have no data, we have averaged the values on the adjacent M_{HI} bins.

\( f(N_{HI}) \), as derived from equation (1), is plotted in Figure 1(b). The ATCA data (Ryan-Weber et al. 2001), as well as the M33 and NGC3198 data, show the “footprint” of ionization. While in 21-cm emission maps the ionization has the effect of giving a sharp drop to the radial decline of N_{HI}, in the distribution function this translates into a plateau where the H I-H II transition occurs. When the gas becomes mostly ionized, at lower N_{HI} values, \( f(N_{HI}) \) rises again but it is offset with respect to the neutral side and has a slope which depends on how the H I/H II ratio varies with N_H (Corbelli et al. 2001). Figure 1(b) shows that this is indeed the behavior of \( f(N_{HI}) \), even though the sum over different mass bins may have smoothed somewhat the H I-H II transition (if the gas vertical stratification depends on the galaxy mass).

3. From the shape of \( f(N_{HI}) \) to the total gas distribution

In order to evaluate \( f(N_{HI}) \) over the range \( 10^{14} \leq N_{HI} < 6 \times 10^{20} \text{ cm}^{-2} \) in the local Universe we select QSOs absorption data for \( N_{HI} < 5 \times 10^{17} \text{ cm}^{-2} \) and 21-cm emission data at higher \( N_{HI} \). We exclude both the very low column density Lyα forest, since it may not be associated with denser structures, and the very high column density data, because star and molecular gas formation might have reduced the original H I column density. While simple power law fits to \( f(N_{HI}) \) fail we will show in what follows that a power law for the total hydrogen distribution can instead well fit all the data displayed in Figure 2. As in Corbelli et al. (2001) we derive a theoretical \( f(N_{HI}) \) after applying the \( N_H - N_{HI} \) conversion relation to an assumed power law distribution for the total gas column density, \( g(N_H) = K N_H^{-\alpha} \). The use of 21-cm data eliminates the problem of having large errors in \( N_{HI} \) in the region where Lyman limit systems become saturated and therefore we can safely use \( f(N_{HI}) \) binned over small \( N_{HI} \) intervals. We consider two possible \( N_H - N_{HI} \) conversion models for \( 10^{14} \leq N_{HI} < 6 \times 10^{20} \text{ cm}^{-2} \):

\(-a\) the model used by Corbelli et al. (2001) to fit the data on Lyman limit and Damped
Lyα systems, as described in their Section 3, extended to lower column density systems. This model is valid for a dark matter confined gas with ionization fractions which increase steadily as the total gas column density decreases.

-(b) the model used by Corbelli et al. (2001) only for $N_H \geq N_*$; for $N_H < N_*$ we keep constant the H ionization fraction, equal to that reached for $N_H = N_*$. A constant ionization fraction for $N_H < N_*$ is achieved if the average gas volume density stays constant as $N_H$ decreases below $N_*$. A constant gas volume density might imply either that a constant external pressure is confining the gas or that dark matter and turbulence are distributed in such a way as to give a gas vertical dispersion which does not depend on the gas column density.

For both (a) and (b) we find the best fitting value of $\alpha$ and of $J_L/\eta_0$. This is the ratio between the intensity of the background flux at 912 Å normalized to $10^{-22}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$, and the gas compression factor $\eta_0$ due to gravity from matter other than the gas (e.g., dark matter). The constant $\eta_0$ adds to the gas self gravity in vertical scale height expression (Corbelli et al. 2001):

$$\frac{1}{h^2} = \frac{16G^2M_g^2}{c_s^4} \left(1 + \frac{\eta_0 c_s^2}{\tilde{c}_s^2}\right)$$

where $M_g$ is the total mass surface density per cm$^{-2}$ of gas, $c_s$ is the thermal sound speed and $\tilde{c}_s$ is the value of $c_s$ for $T = 10^4$ K. For model (a) the minimum value of $\chi^2$ (1.3) corresponds to $\alpha = 3.32$ and to $\log J_L/\eta_0 = -0.25$. The 3-σ uncertainties on $\alpha$ are $\pm 0.4$, on $\log J_L/\eta_0$ are $\pm 0.6$. An $\alpha = 3$ power law is therefore compatible with the data. This is important since there have been often claims that $f(N_{HI})$ for disk like structures should follow an $N_{HI}^{-3}$ power law (Milgrom 1988), but $f(N_{HI})$ observed in galaxies strongly deviates from this law (Zwaan et al. 1999). This is not surprising since it is $g(N_{HI})$ which should eventually scale as $N_{HI}^{-3}$ for disk like systems, and we have shown that for model (a) the present data are compatible with this law. For model (b) the best fit gives $\alpha = 1.47 \pm 0.1$, $\log J_L/\eta_0 = -1.85 \pm 1$, and $\log N_*/$cm$^{-2} = 19.4 \pm 0.4$. This model fits the data better than model (a) with 0.5 being the minimum $\chi^2$ value.

The resulting $f(N_{HI})$ are shown in Figure 2 together with the data used for the $\chi^2$ minimization. Both best fitting models reproduce rather well also the high and low column density QSO’s absorption data, not used for the fit, but shown in the Figure as well. A pure power law with no ionization corrections fails since it gives a minimum $\chi^2 \sim 10$. Unfortunately the present data are not sufficient to discriminate between (a) and (b) type of model. This is mostly due to the lack of data around $N_{HI} \simeq 10^{18}$ cm$^{-2}$ and to the uncertainties on the conversion of atomic hydrogen gas into other baryonic forms at very
high column densities. In these two regions (a) and (b) model predictions for \( f(N_{HI}) \) differ substantially.

The two best fitting power laws for \( g(N_H) \) imply a quite different degree of ionization and therefore different total gas densities in the local Universe. For model (a) most of the gas resides in low column density absorbers; H neutral fractions are of order 0.002 for \( N_{HI} \approx 10^{17} \text{ cm}^{-2} \) and are as low as \( 10^{-5} \) for \( N_{HI} \approx 10^{14} \text{ cm}^{-2} \). The total gas density (H+He) predicted by this distribution for \( 10^{14} \leq N_{HI} \leq 10^{22} \) gives \( \Omega_g h_{50}(z = 0) \approx 0.01 \) with a 3\( \sigma \) range of 0.005 – 0.025. Model (b) instead predicts a lower total density of gas in the same range of \( N_{HI} \): \( \Omega_g h_{50}(z = 0) \approx 10^{-3} \) with a 3\( \sigma \) range of 0.001 – 0.005.

4. Discussion

We now discuss the best fitting power laws for \( g(N_H) \) derived in the previous Sections, taking into account the known limits on the UV ionizing background flux at \( z = 0 \), the limits on the density of baryonic matter, \( \Omega_b \), and the total gas column density distribution obtained for QSOs absorbers at \( z \sim 2 – 3 \) by Corbelli et al. (2001). Limits on the intensity of the UV ionizing background at \( z = 0 \) rely on several indirect techniques such as those based on the detection of a sharp cutoff in the HI surface density of outer disks of nearby galaxies (Corbelli & Salpeter 1993; Maloney 1993; Dove & Shull 1994), on searches for Hα emission from outer disks or from intergalactic HI clouds (Donahue et al. 1995; Madsen et al. 2001; Weymann et al. 2001), on measurements of column densities of metal species in intergalactic HI clouds (Tumlinson et al. 1999). The range \( J_L \approx 0.1 – 0.4 \) is consistent with the above limits as well as with the determination of the UV ionizing background from the QSOs luminosity function, even considering possible additional contributions of photons escaping from star forming galaxies (Haardt & Madau 1996; Shull et al. 1999). Measurements of the proximity effect for \( z < 1 \) have been reported (Kulkarni & Fall 1993; Pascarelle et al. 2001; Scott et al. 2001) but the resulting ionizing background intensity, \( J_L \approx 0.01 – 4 \), is highly uncertain due to possible clustering of the Ly\( \alpha \) forest around QSOs and to a possible evolution over the used \( z \) range. The total density of baryonic matter can be inferred from deuterium abundances, \( \Omega_b h_{50}^2 \approx 0.02 \) (Burles et al. 2001; O’Meara et al. 2001). For a Universe with \( \Omega_L = 0.7 \) and \( \Omega_M = 0.3 \) this \( \Omega_b \) value limits the power law index of the total gas column density distribution derived by Corbelli et al. (2001) at higher redshifts to values \( \alpha < 3 \). The extrapolation of the same power law towards the Ly\( \alpha \) forest requires however that ionization conditions of the gas stay constant for \( N_{HI} < 10^{15} \text{ cm}^{-2} \) at these redshifts i.e. for \( N_H \approx 2.5 \times 10^{19} \text{ cm}^{-2} \). In the following we shall assume that the gas distribution at \( z \sim 2 – 3 \) is well described by the Best-Fit 1 model of Corbelli et al. (2001) (\( \alpha = 2.7, \eta_0 = 12.5, \log J_L/\eta_0 = -0.35 \), see
If today the gas is distributed according to the best fitting model (a), with $\alpha \simeq 3.3$, the limits on $J_L$ and on $\Omega_\delta$ at $z = 0$ force the gas compression factor to be $\eta_0 < 3$. According to this model the following evolutionary scenario might hold: because changes in time of the ionization conditions of the gas are mild, the average gas compression factor should decrease with time in order to balance the decrease of $J_L$. If the dark matter is confining and compressing the gas then today’s systems have on average a lower dark matter density than systems at earlier times. The alternative would be to invoke a steadily increasing turbulence which lowers the effective compression $\eta_0$, or additional ionization sources in the surroundings of gaseous clouds. The power law index for the total gas column density distribution from $z \sim 2.5$ to $z \sim 0$ becomes slightly steeper and now it is compatible with a disk-like geometry. For model (a) the gas associated with the Ly$\alpha$ forest clouds is, even today, the dominant reservoir of baryonic matter in the Universe.

The best fitting model (b) at $z \sim 0$ implies a constant hydrogen neutral fraction, of order 0.05, for $N_{HI} \lesssim 10^{18}$ cm$^{-2}$. The power law index for $g(N_H)$ in this case is $\alpha \simeq 1.5$ and $J_L/\eta_0 \simeq 0.01$. In order to explain the flattening of the power law index for $g(N_H)$ with time, we invoke a scenario in which low column density structures collapse towards the center or merge to form higher column density structures. If $\eta_0$ is constant through the evolution of the Universe, the required ionizing background radiation at $z = 0$ would equal that estimated by Haardt & Madau (1996) for QSOs as primary sources of ionizing photons. If the external pressure is responsible for confining the gas and keeping constant the ionizing fraction at low column densities, the inferred value of $P_{ext}$ is also constant through redshifts and is $P_{ext}/(\text{cm}^{-3} \text{K}) \simeq \eta_0 \simeq 10$ (Charlton et al. 1994; Corbelli & Salpeter 1995). This excludes that $P_{ext}$ is dominated by a diffuse and pervasive intergalactic medium since this is expected to decrease with time. However, the merging or the collapse of low column density structures is likely to trigger star formation and outflows of hot gas into the intergalactic medium; this hot gas at temperatures $T \sim 10^5$–$10^7$ K would be the likely confining medium of low column density Ly$\alpha$ clouds and it would contribute mostly to the density of baryonic matter in the Local Universe (Fukugita et al. 1998; Cen & Ostriker 1999; Dave et al. 2001; Tripp 2001).

In this paper we have shown that ionizing radiation affects the neutral gas distribution in the local Universe and that any attempt to fit $f(N_{HI})$ with a simple power law across the HI-HII transition region ($10^{17} < N_{HI} < 10^{20}$ cm$^{-2}$) can lead to misleading results. A power law distribution for the total gas column density instead fits the data reasonably well, from the Ly$\alpha$ forest to the high gas column density in galaxies. Additional 21-cm data, as well as new Lyman limit searches at low redshifts, are needed to implement the knowledge
of $f(N_{HI})$ in this delicate region and draw a more definite conclusion on the slope of the total gas column density distribution. Furthermore, if 21-cm data are analyzed in detail to constrain the gas and dark matter distribution in outer disks, one can assign a more definite value to the gas compression and picture a unique evolutionary scenario for the gas distribution and the UV ionizing background in the Universe.

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Fig. 1.— (a) $f(N_{HI})$ from QSO Ly$\alpha$ and Lyman continuum absorption data at low redshifts. Ly$\alpha$ forest data from Weymann et al. (1998) are shown as filled triangles while data for Lyman limit and Damped Ly$\alpha$ systems from our collection are shown as open dots. (b) $f(N_{HI})$ from 21-cm data at $z = 0$ (see text for details).
Fig. 2.— The two theoretical $f(N_{HI})$ which best fit the data for $10^{14} < N_{HI} < 6 \times 10^{20} \text{ cm}^{-2}$, shown in the Figure with simple crosses. The continuous line is derived from a total gas distribution function with $\alpha = 3.32$ using the ionization model $(a)$ with $\log J/\eta_0 = -0.25$. The dashed line is derived from a total gas distribution function with $\alpha = 1.47$ using the ionization model $(b)$ with $\log J/\eta_0 = -1.9$ and $N_* = 2.5 \times 10^{19} \text{ cm}^{-2}$. The high and low column density data shown with filled dots have not been used for the fit.