The Gunn-Peterson effect and the Lyman alpha forest

Sergei A. Levshakov\(^1\) and Wilhelm H. Kegel\(^2\)

\(^1\)Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-01, Japan and
Department of Theoretical Astrophysics, A. F. Ioffe Physico-Technical Institute,
194021 St.Petersburg, Russia

\(^2\)Institut für Theoretische Physik der Universität Frankfurt am Main, Postfach 11 19 32,
60054 Frankfurt/Main 11, Germany

14 October 1997

**ABSTRACT**

We show that spatial correlations in a stochastic large scale velocity field in an otherwise smooth intergalactic medium (homogeneous comoving density) superposed on the general Hubble flow, may cause a 'line-like' structure in QSO spectra similar to the population of unsaturated Ly\(\alpha\) forest lines which usually are attributed to individual clouds with \(10^{11} \lesssim N_{\text{HI}} \lesssim 5 \times 10^{13} \text{ cm}^{-2}\). Therefore there is no clear observational distinction between a diffuse intergalactic medium and discrete intergalactic clouds. It follows that the HI-density in the diffuse intergalactic medium might be substantially underestimated if it is determined from the observed intensity distribution near the apparent continuum in high resolution spectra of QSOs. Our tentative estimate implies a diffuse neutral hydrogen opacity \(\tau_{\text{GP}} \sim 0.3\) at \(z \sim 3\) and a current baryon density \(\Omega_{\text{IGM}} \simeq 0.08\), assuming a Hubble constant \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\).

**Key words:** line : formation – line : profiles – quasars : absorption lines.

The intergalactic medium [IGM] may be probed by observing absorption features in the spectra of QSOs. The continuum on the blue side of the HI Ly\(\alpha\) emission line is expected to be depressed as compared to that on the red side, since Ly\(\alpha\) absorption in the diffuse intergalactic medium leads to an apparently continuous absorption due to the general cosmological expansion (Scheuer 1965, Gunn & Peterson 1965). If this effect can be measured accurately, it allows in principle to estimate the intergalactic density of neutral hydrogen, \(n(\text{HI})\).

In their original paper Gunn & Peterson [GP] estimated the depression in the spectrum
of 3C9 to be of the order of 40 per cent and \( n(\text{HI}) \) to be of about \( 6 \times 10^{-11} \text{ cm}^{-3} \) at \( z = 2 \). This low value of \( n(\text{HI}) \) is usually taken as an indication for a very high degree of ionization of the IGM.

However, the measurement of the true depression caused by the smoothly distributed intergalactic hydrogen is hampered by numerous absorption lines blueward of the Ly\( \alpha \) emission line, which make it difficult to locate the continuum level correctly and to remove the contribution to the depression from individual absorbers accurately. There have been suggested a few methods to overcome this problem and to measure the diffuse neutral hydrogen absorption (for a review see e.g. Fang & Crotts 1995). The conclusion is that either ‘there is no evidence for any Gunn-Peterson effect up to the highest redshifts observable in quasar spectra’ (Giallongo et al. 1995), or that \( \tau_{\text{GP}} = 0.115 \pm 0.025 \) at \( z \simeq 3.4 \) (Fang & Crotts 1995). In any case the effect is small, indicating a very low density of neutral hydrogen in the diffuse intergalactic medium.

It is worth pointing out that in quantitative estimates the IGM is usually considered as a thermal gas and the possible influence of a hydrodynamical velocity field superposed on the general Hubble flow is ignored. Commonly the individual Ly\( \alpha \) lines being interpreted as arising in discrete intergalactic clouds at different redshifts are evaluated by means of a Voigt profile fitting analysis (see e.g. Lu et al. 1996). In this procedure there are three free parameters, the column density \( N_{\text{HI}} \), the Doppler parameter \( b \), and the redshift \( z_a \), to be determined from the observational data. Implicitly it is also assumed that any hydrodynamical velocities within the individual clouds may be accounted for in the \textit{microturbulent} approximation in which any bulk motions are treated as completely uncorrelated (i.e. the velocity correlation length \( l_0 \equiv 0 \)).

Thus, in the standard analysis it appears observationally possible to \textit{clearly distinguish} between the Ly\( \alpha \) absorption in the diffuse intergalactic medium leading to a true GP-effect and that in the individual clouds leading to the Ly\( \alpha \) forest lines. As will be shown below, this conclusion is misleading and is a consequence of the simplifying assumptions underlying the common approach. As a result the diffuse neutral hydrogen opacity mentioned above may have been considerably underestimated.

With respect to the saturated Ly\( \alpha \) forest lines, corresponding to clouds with \( 10^{14} \lesssim N_{\text{HI}} \lesssim 10^{16} \text{ cm}^{-2} \) it has been pointed out recently (Levshakov & Kegel 1996), that the quantitative interpretation may be changed substantially when one accounts for a stochastic
velocity field with finite correlation length within the individual clouds. In particular it has been shown by means of Monte-Carlo [MC] simulations (Levshakov, Kegel & Mazets 1997) that such a velocity field can lead to a rather structured line profile with several subcomponents, which in the traditional analysis would be attributed to individual clouds while in the underlying model a homogeneous density was assumed.

This latter result led us to investigate in which way the GP-effect is modified when a stochastic velocity field with a finite correlation length is superposed on the general Hubble flow with a homogeneous comoving density. In fact our results show (Fig. 1) that such fields can give rise to a ‘line-like’ structure of absorption features similar to the observed unsaturated Lyα forest lines ($10^{11} \lesssim N_{\text{HI}} \lesssim 5 \times 10^{13} \text{cm}^{-2}$).

To describe our mesoturbulent model ($l_0 > 0$) the following set of the parameters has to be specified: the neutral hydrogen number density $n(\text{HI})$ at cosmic time $t$, the kinetic temperature $T_{\text{kin}}$, the ratio of the rms value of the line-of-sight stochastic velocity dispersion $\sigma_t$ to the thermal velocity $v_{\text{th}}$, the correlation length $l_0$, and the parameter $q_0$. We take the Hubble constant in units of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and the cosmological constant $\Lambda = 0$. The stochastic velocity field is assumed to be governed by a stationary Markov process (see Levshakov & Kegel 1994, 1997 for details).

The value of $\sigma_t$ may be estimated from the observed distribution function of peculiar velocities of galaxies. Recent observations indicate, for example, large-scale motions with $\sigma_{\text{gal}} \sim 700 \text{ km s}^{-1}$ on scales up to 70 Mpc (Raychaudhury & Saslaw 1996). However, if the peculiar bulk motions are produced by gravity they should be smaller at high redshifts. An order of magnitude of $\sigma_t$ at $z = 3$ may be estimated from the linear theory of the gravitational instability which leads to $\sigma_t \propto (1 + z)^{-1/2}$ when the density parameter $\Omega = 2q_0$ is equal to 1 (see e.g. Zel’dovich & Sunyaev 1980). For our MC simulations we therefore adopt $\sigma_t = 300 \text{ km s}^{-1}$, as well as $q_0 = 0.5$ and $z_e = 3$. The choice of the kinetic temperature of $T_{\text{kin}} = 10^4 \text{ K}$ is based on the arguments given by Levshakov & Kegel (1996). For the correlation length $l_0$ we chose a value of 24 Mpc. Assuming the velocity fluctuations to be ‘frozen’ into the IGM and just expanding along with the general expansion, we then have $l_z = l_0/(1 + z) = 6 \text{ Mpc}$.

An order of magnitude of $n(\text{HI})$ may be estimated from the average value of $D_A$ – the continuum depression between HI Lyα and Lyβ emission lines in low dispersion spectra with FWHM $\sim 80 - 100 \text{ Å}$ $|D_A \equiv [1 - F_{\text{obs}}/F_{\text{int}}]|$, where $F_{\text{obs}}$ and $F_{\text{int}}$ are the observed and
Figure 1. MC simulations of QSO absorption spectra for three random realizations of the stochastic velocity field along a given line-of-sight. Panels a, b, and c show a portion of the spectrum blueward of Lyα emission for $z_e = 3$ computed with the parameters $q_0 = 0.5$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $n$(HI) = $4 \times 10^{-11}$ cm$^{-3}$. In addition to the mesoturbulent spectra, results obtained under the condition that the bulk motions have zero correlation coefficient and $\sigma_t/\sigma_{th} > 1$ (panel a), or have a finite correlation coefficient but $\sigma_t/\sigma_{th} \ll 1$ (panel b) are shown in order to demonstrate the microturbulent solution and the case of purely thermal broadening, respectively. Panel c shows both a high-resolution and a low-resolution spectrum with FWHM = 0.12 Å and 80 Å, respectively. The number density of the absorption features in this portion of the simulated QSO spectrum is $N(z) \simeq 500$ which is in a good agreement with observations (cf. Kirkman & Tytler 1997).
Figure 2. An example of MC simulations. (a) – One realization of the stochastic velocity field (in units of the rms velocity $\sigma_t$) versus the cosmological redshift $z_{\text{cosm}}$. (b) and (c) – The corresponding local absorption coefficients for fixed $\lambda_a = 4743$ Å and $\lambda_b = 4753.5$ Å, respectively (thin curves, correlation length $l \neq 0$), and for comparison $k_{\lambda}$ for a purely thermal gas (thick curves, $l = 0$). (d) – A portion of the resulting absorption spectrum. The simulated intensities at the fixed wavelengths $\lambda_a$ and $\lambda_b$ are marked by dots and the corresponding cosmological redshifts $z_a$ and $z_b$ are shown on panel (a). Panel (e) illustrates the effect of the contribution from different volume elements to the absorption at a given value of $\lambda$ when the peculiar velocity field (panel a) is superposed on the general Hubble flow.
intrinsic fluxes per unit wavelength in the QSO rest frame]. At \( z = 3 \) one finds \( D_A \approx 0.25 \) according to the data compiled by Kennefick et al. (1995).

We will consider in some detail a narrow spectral range of \( \Delta \lambda_{\text{obs}} = 30 \) Å between the Ly\( \alpha \) and \( \beta \) emission lines. For this range we assume that the contribution to \( D_A = 0.25 \) comes in general from the cumulative effect of weak absorption features, and we will show that in this case the Doppler effect caused by the peculiar velocities superposed on the Hubble flow leads to the observed picture – instead of a characteristic smooth GP-trough one observes a 'line-like' structure. We emphasize that this does not rule out the possibility of a clumpy IGM, but our results indicate that the interpretation of the current high resolution observations of QSOs is not unique and therefore the classical analysis may yield misleading parameters of the IGM.

Having specified the free parameters we can simulate a QSO absorption spectrum for a random realization of the velocity field. All our synthetic spectra were calculated with a signal-to-noise ratio of 100, an instrumental resolution of 8 km s\(^{-1}\), and a pixel size of 2 km s\(^{-1}\) to match the data obtainable with the HIRES spectrograph of the Keck I telescope.

We calculate \( \tau_\lambda \), the total optical depth at wavelength \( \lambda \), following GP, the essential difference being that in our model the local absorption coefficient \( k_\lambda(z) \) is a stochastic variable (see Fig. 2b,c) which we estimate by means of our MC technique (Levshakov, Kegel & Mazets 1997).

Fig.1 shows three mesoturbulent spectra calculated for three different realizations of
the velocity field. For comparison and in order to validate our procedure, we calculated in addition $\tau_\lambda$ for zero correlation coefficient $f = 0$ and $\sigma_t/v_{th} > 1$, and for a finite correlation coefficient but $\sigma_t/v_{th} \ll 1$. For both cases one expects to obtain a classical GP-trough. The first case corresponds to the microturbulent limit, while in the second case thermal broadening dominates. The results of these tests are shown in Fig. 1a and 1b, respectively, and marked by ‘GP\textsubscript{micro}’.

With $n(\text{HI}) = 4 \times 10^{-11} \text{ cm}^{-3}$ at $z = 3$ our microturbulent results are found to fit the continuum depression $D_A \sim 0.25$. The corresponding GP-optical depth $\tau_{GP}$ is about 0.3.

– Fig. 1c shows a high resolution mesoturbulent spectrum and for comparison the same spectrum degraded to a resolution of 80 Å. The latter resembles the microturbulent spectra in panels a and b. – Commonly one attempts to estimate $n(\text{HI})$ in the diffuse IGM, i.e. inbetween Ly\textsubscript{a} clouds, by measuring the intensity distribution near the apparent continuum level in high resolution spectra of QSOs (see e.g. Fang & Crotts 1995). The corresponding regions in our mesoturbulent spectra are labeled by ‘GP\textsubscript{meso}’ in Fig. 1. It is clearly seen that instead of $\tau_{GP} \simeq 0.3$ one may obtain only an upper limit or a very small value for $\tau_{GP}$ in this case.

In order to illustrate these calculations, Fig. 2a shows one random realization of the stochastic velocity field along a given line of sight. – The peculiar velocities have the effect that different volume elements may contribute to the absorption at the same value of $\lambda$. This is shown in Fig. 2b,c by the thin curves. For example, the contribution to $k_\lambda$ comes from individual volume elements spread over 1 Mpc. For comparison also the absorption by a purely thermal gas (no peculiar correlated velocity field) is shown by the thick curves. Finally Fig. 2d shows the resulting absorption spectrum and Fig. 2e the effect of compensating the general Hubble expansion by hydrodynamic perturbations.

In order to stress the difference in the interpretation of weak Ly\textsubscript{a} forest lines we fitted a part of the simulated spectrum ($4743 < \lambda < 4756$ Å) shown in Fig. 1a in the usual way by considering 18 individual Voigt profiles. The result is shown in Fig. 3 and the corresponding parameters are listed in Table 1. As can be seen from the figure the fit is satisfactory, the derived ‘physical parameters’ are in the ranges $6.6 \times 10^{11} \leq N(\text{HI}) \leq 4.0 \times 10^{13} \text{ cm}^{-2}$, and $12.95 \leq b \leq 37.12 \text{ km s}^{-1}$ (note the thermal width in our model corresponds to $12.89 \text{ km s}^{-1}$). So, one can obtain a typical spread of ‘physical parameters’ for the Ly\textsubscript{a} forest lines (cf. e.g. Kirkman & Tytler 1997), while a homogeneous model was assumed.
Table 1. ‘Lyα cloud parameters’ derived from the spectrum shown in Fig. 3 by fitting Voigt profiles

<table>
<thead>
<tr>
<th>No.</th>
<th>λ_{obs}, Å</th>
<th>N(HI), cm^{-2}</th>
<th>b, km s^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4743.76</td>
<td>6.93(11)</td>
<td>16.10</td>
</tr>
<tr>
<td>2</td>
<td>4744.26</td>
<td>6.65(11)</td>
<td>12.95</td>
</tr>
<tr>
<td>3</td>
<td>4744.78</td>
<td>1.84(12)</td>
<td>16.56</td>
</tr>
<tr>
<td>4</td>
<td>4745.34</td>
<td>2.16(12)</td>
<td>18.50</td>
</tr>
<tr>
<td>5</td>
<td>4745.82</td>
<td>2.03(12)</td>
<td>13.13</td>
</tr>
<tr>
<td>6</td>
<td>4746.33</td>
<td>7.21(12)</td>
<td>18.99</td>
</tr>
<tr>
<td>7</td>
<td>4746.82</td>
<td>7.89(12)</td>
<td>17.32</td>
</tr>
<tr>
<td>8</td>
<td>4747.43</td>
<td>1.28(13)</td>
<td>17.88</td>
</tr>
<tr>
<td>9</td>
<td>4747.92</td>
<td>6.60(12)</td>
<td>22.78</td>
</tr>
<tr>
<td>10</td>
<td>4749.18</td>
<td>6.78(12)</td>
<td>37.12</td>
</tr>
<tr>
<td>11</td>
<td>4749.78</td>
<td>1.53(13)</td>
<td>30.43</td>
</tr>
<tr>
<td>12</td>
<td>4750.84</td>
<td>4.02(13)</td>
<td>24.54</td>
</tr>
<tr>
<td>13</td>
<td>4751.91</td>
<td>1.15(13)</td>
<td>23.01</td>
</tr>
<tr>
<td>14</td>
<td>4752.50</td>
<td>1.10(12)</td>
<td>21.12</td>
</tr>
<tr>
<td>15</td>
<td>4753.18</td>
<td>6.33(12)</td>
<td>19.30</td>
</tr>
<tr>
<td>16</td>
<td>4753.72</td>
<td>3.00(12)</td>
<td>23.51</td>
</tr>
<tr>
<td>17</td>
<td>4754.50</td>
<td>2.32(13)</td>
<td>26.43</td>
</tr>
<tr>
<td>18</td>
<td>4755.60</td>
<td>3.63(12)</td>
<td>17.05</td>
</tr>
</tbody>
</table>

Thus, our calculations offer a new interpretation of the observed Lyα forest lines and explain why high resolution spectra show only a very small GP-effect. Our results show that at least some of the Lyα forest lines may be caused by absorption in the diffuse medium between the intervening clouds giving rise to saturated lines. This implies that in the diffuse IGM n(HI) may be substantially higher than estimated from the upper limits for τ_{GP} in previous studies. For example Giallongo et al. (1995) give a value τ_{GP} = 0.01 ± 0.03 for PKS 2126–158 (z_e = 3.3) which implies n(HI) \lesssim 2 \times 10^{-12} \, \text{cm}^{-3}. This is an order of magnitude below the value we assumed in our model. – If one wants to derive from n(HI) the total baryon density, one has to know the degree of ionization of the IGM. With the assumptions that (i) the ionization of the IGM is in equilibrium, (ii) the ionizing continuum can be described by a power law with spectral index = −1.5 and a flux at the hydrogen Lyman
limit $\simeq 3 \times 10^{-21} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}$ (see e.g. Bechtold 1994), (iii) $n(\text{HI}) = 4 \times 10^{-11} \text{ cm}^{-3}$, (iv) $T_{\text{kin}} = 10^4 \text{ K}$, and (v) all the IGM density is in the form of hydrogen, an order of magnitude estimate leads to a current baryon density of $\Omega_{\text{IGM}} \simeq 0.08$, i.e. it is about 8 percent of the mass needed to close the Universe.

Taking this at face value, we conclude that $\Omega_{\text{IGM}} \simeq 0.08$ is consistent with the most conservative upper limit on baryonic mass $\Omega_b \lesssim 0.06$ from Big Bang Nucleosynthesis (e.g. Fields & Olive 1996). It follows that the density of the IGM may be considerably larger than the observed density of luminous matter $0.003 \lesssim \Omega_{\text{lum}} \lesssim 0.007$ (e.g. Jedamzik et al. 1995), and the baryon density in the Ly$\alpha$ clouds, $\Omega_{\text{Ly}} \simeq 0.002 - 0.003$ (Lanzetta et al. 1991).

While our model is highly idealized (smooth density), the results clearly show that the formation of the GP-depression is intimately related to the formation of narrow absorption lines. Thus, there is no simple way to distinguish observationally between the diffuse IGM and intervening clouds as was suggested by the classical interpretation of the GP-effect and the Ly$\alpha$ forest lines.

**Acknowledgements**

We thank K. Tomita and F. Takahara for discussions and an anonymous referee for constructive criticism. This work was supported in part by the RFFR grant No. 96-02-16905-a and by the Deutsche Forschungsgemeinschaft. Numerical computations in this work was supported by the Yukawa Institute for Theoretical Physics.
REFERENCES