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# Periodicity revealed by statistics of the absorption-line redshifts of quasars

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**Abstract.** We study the properties of the heavy-element absorption systems and their evolution with redshift based on the distribution of the free paths (FPs) of the light rays which come from QSOs and are intercepted by absorbers. We find that the mean free path (MFP) regularly varies with the cosmic time and has a definite periodic component, which shows a marked evolution of the absorbers. For the MFP calculated by the catalog of the absorption-line redshifts of Junkkarinen et al. (1991), an useful fitting function is

$$\overline{\lambda_0(t)} \approx 375\,(t_0\,/\,t)[1\,+\,0.125\,\cos(2\,\pi\,t\,/\,\tau)]^{-2}\ \mathrm{h}^{-1}\,\mathrm{Mpc},$$

where period $\tau = 1.55\,10^8\ \mathrm{h}^{-1}$ yr is a result of power-spectrum analysis, $t_0 = 2\,/\,(3H_0)$ and $t = t_0\,(1\,+\,\overline{z})^{-3/2}$ for $q_0 = 0.5$. This period $\tau$ is quite consistent with the dynamic time scale of galaxies, it supports the view that the heavy-element absorption systems are due to intervening protogalaxies. The observational periodicity can be explained as an effect of oscillation of the protogalaxy after the gravitational collapse. That is to say, the heavy-element absorption systems might be due to the protogalaxies which separated from the general expansion of the universe at the cosmic time $t \approx \tau = 1.55\,10^8\ \mathrm{h}^{-1}$ yr, the redshift $z \approx 11$, and the protogalaxies might be pulsating with the period $\tau$ at the QSO epoch.

**Key words:** quasars: absorption lines – galaxies: redshift – cosmology: observations; large scale structure of universe

## 1. Introduction

The study of the QSO absorption-lines is a promising way for obtaining information on the large scale structure, properties of the absorbers and their evolution with redshift. Some results have shown that the absorbers which cause absorption systems having lines of the heavy elements might be young galaxies or their ancestors (Young et al. 1982; Sargent 1988; Bergeron 1986; Bergeron & Ikeuchi 1990; Liu 1995). By means of a statistical test based on the distribution of the free paths (FPs) of the light rays which come from QSOs and are intercepted by absorbers, Liu & Liu (1992) have shown that on smaller scale ($< 10\ \mathrm{h}^{-1}$ Mpc) the absorbers are clustered, but on the scales which are larger than $80(1+z)^{-1}\ \mathrm{h}^{-1}$ Mpc the clusters of absorbers are distributed at random in space.

This statistical method based on the distribution of the FPs can also be used to investigate the evolution of some types such as the evolution of the effective radius and/or number density of the absorbers. Recently, we have studied the distribution of the FPs in different redshift range. We discovered that the mean free path (MFP) regularly varies with the cosmic time and has a periodic component, which shows a marked evolution of the absorbers and confirms the view that the heavy-element absorption systems are due to protogalaxies. In this paper, we first describe the statistical method briefly, and then give our results based on the available data.

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## 2. Statistics based on the free path distribution

Assuming that the absorption-lines of QSOs are due to the intervening absorbers of a kind and the absorbers are distributed at random in space, the MFP of the light rays which come from QSOs and are intercepted by absorbers will be

$$\overline{\lambda_z} = (\sigma_z\,n_z)^{-1}, \tag{1}$$

where $\sigma_z = \pi\,R_z^2$ is an effective cross-section of absorber for interception of a light ray, $n_z$ is number density at the redshift $z$. Since the light rays coming from quasars are intercepted randomly by the absorbers, the probability that the FP has a value $\lambda_z$ in the range $\mathrm{d}\lambda_z$ is

$$\mathrm{dP}(\lambda_z) = (\mathrm{d}\lambda_z\,/\,\overline{\lambda_z})\,\exp\{-\lambda_z\,/\,\overline{\lambda_z}\}, \tag{2}$$

and so probability in the range 0–$\lambda_z$ is

$$\mathrm{P}(\lambda_z) = 1 - \exp\{-\lambda_z\,/\,\overline{\lambda_z}\}. \tag{3}$$

At $z = 0$, the probability that the FP in the range 0–$\lambda_0$ is

$$P(\lambda_0) = 1 - \exp\{-\lambda_0 / \overline{\lambda_0}\}, \quad (4)$$

where $\overline{\lambda_0} = (\sigma_0\, n_0)^{-1}$.

Under the assumption that the size and comoving number density are constant back to epochs corresponding to the largest measured redshifts, i.e.,

$$\sigma_z = \sigma_0 = \pi R^2 \quad \text{and} \quad n_z = n_0\,(1 + z)^3, \quad (5)$$

we have

$$\overline{\lambda_0} = (\sigma_0\, n_0)^{-1} = \overline{\lambda_z}\,(1 + z)^3, \quad (6)$$

and so from Eqs.(3) and (4)

$$\lambda_0 = \lambda_z\,(1 + z)^3. \quad (7)$$

In a Friedmann universe with zero cosmological constant, the light-travel path from $z$ to $z + \mathrm{d}z$ is

$$\mathrm{d}L(z) = -(c/H_0)(1 + z)^{-2}(1 + 2q_0\, z)^{-1/2}\mathrm{d}z.$$

Therefore, corresponding to a light ray from an absorber at $z_1$ to another at $z_2$ , the FP $\lambda_0$ at $z = 0$ will be

$$\begin{aligned}\lambda_0 &= \int_{z_1}^{z_2} (1+z)^3\, \mathrm{d}L(z) \\ &= (c/H_0) \int_{z_2}^{z_1} (1 + z)(1 + 2q_0\, z)^{-1/2}\, \mathrm{d}z \\ &= (c/3H_0 q_0^2)\{(1 + 2q_0\, z_1)^{1/2}(3q_0 - 1 + q_0\, z_1) \\ &\quad - (1 + 2q_0\, z_2)^{1/2}(3q_0 - 1 + q_0\, z_2)\}. \quad (8)\end{aligned}$$

Thus, for a QSO with the observed redshifts: $z_\mathrm{e} > z_\mathrm{a1} > z_\mathrm{a2}\ldots$, we can evaluate FP between two neighboring redshifts $z_i$ and $z_{i+1}$. For example, for $q_0 = 0.5$ and $H_0 = 100$ h km s$^{-1}$ Mpc$^{-1}$, we have

$$\begin{aligned}\lambda_0 &= (2c/3H_0)\{(1 + z_i)^{3/2} - (1 + z_{i+1})^{3/2}\} \\ &= 2000\{(1 + z_i)^{3/2} - (1 + z_{i+1})^{3/2}\}\ \mathrm{h}^{-1}\,\mathrm{Mpc}. \quad (9)\end{aligned}$$

In this way, as long as we evaluate all FPs for each QSO with at least one observed absorption redshift less than emission redshift, we can construct an observational distribution by counting the number $N(< \lambda_0)$ of FPs which are smaller than $\lambda_0$, i.e., the observational probability that the FP has a value in the range 0–$\lambda_0$ ,

$$P_\mathrm{ob}(\lambda_0) = N(< \lambda_0) / N_\mathrm{total}\,, \quad (10)$$

where $N_\mathrm{total}$ is the total number of calculated FPs. By comparing the observational $P_\mathrm{ob}(\lambda_0)$ with expected $P(\lambda_0)$ in Eq.(4), we can judge whether the absorbers are distributed randomly in space or not.

Liu & Liu (1992) have shown that an useful fitting function for the observational distribution (10) can be expressed as

$$P_\mathrm{ob}(\lambda_0) = 1 - A\, \exp\{-\lambda_0 / B\}, \quad (11)$$

where the parameters $A$ and $B$ are estimated by the method of least squares, which depend on $q_0$ and the $A < 1$. For $q_0 = 0.5$, their result is $A = 0.67$ and $B = 1800$ h$^{-1}$ Mpc. The parameter $A < 1$ means that the observational probability in the range of small FPs greatly exceeds that expected by $P(\lambda_0)$ in which $A$ should be one. They have demonstrated that, after removing the shortest $(1 - A)$N FPs, the distribution $P_\mathrm{ob}(\lambda_0)$ of the other $A$N longer FPs would agree with the expected $P(\lambda_0)$, i.e., the parameter $A$ becomes unity and the parameter $B$ in Eq.(11) does not vary and is just the MFP $\overline{\lambda_0}$. They concluded that on smaller scale ($< 10$ h$^{-1}$ Mpc) the absorbers are clustered, but on the scales which are large enough the absorbers are distributed at random in space.

The statistical method based on the FP distribution is also fit to investigate the evolution of some types such as the evolution of the effective radius and/or number density of absorbers, if the redshift data available are enough to work out the MFP in different redshift ranges. In evolving case, it can be expected that the effective radius R and/or number density $n_0$, and so the MFP $\overline{\lambda_0}$ in Eq.(6) will vary with the redshift.

In order to work out the MFP $\overline{\lambda_0}$ in different redshift ranges, we can use the following procedure. (a) Calculate all FPs for each QSO with at least one observed absorption redshift less than emission redshift by Eq.(8). (b) Each FP $\lambda_0$ calculated by two neighboring redshifts, $z_i$ and $z_{i+1}$, is treated as a function of $z_i$, $\lambda_0(z_i)$, so that we can rearrange all FPs according to size of redshifts, i.e., $\lambda_0(z_1), \lambda_0(z_2), \ldots$, where $z_1 >= z_2 \ldots$. (c) Separate them into groups that each contains $\Delta$N FPs with neighboring redshifts in succession, for example, the $j$th group contains $\Delta$N FPs from $\lambda_0(z_j)$ to $\lambda_0(z_{j+\Delta \mathrm{N}})$. (d) For each group, evaluate mean redshift $\overline{z}$, construct the observational distribution $P_\mathrm{ob}(\lambda_0)$ according to Eq.(10) and compare it with Eq.(11) to work out the MFP $\overline{\lambda_0(z)}$, i.e. determine the parameter $B$ in Eq.(11) by the least-squares fit.

## 3. Results

In order to learn about the evolution of the absorbers, as an example of the above-mentioned procedure, we used Table 1 of the catalog of the absorption-line redshifts of Junkkarinen et al. (JHB catalog, 1991). Table 1 of JHB catalog contains 353 QSOs and 862 reliable narrow absorption systems, except for the very large number of Ly$\alpha$ - Ly$\beta$ pairs. Using the redshift data of these QSOs, we calculated 744 FPs from all neighboring redshift pairs of each QSO by Eq.(9) for $q_0 = 0.5$. And then we constructed 694 groups that each contained $\Delta$N = 50 FPs with neighboring redshifts in succession from $\lambda_0(z_j)$ to $\lambda_0(z_{j+50})$, $j = 1, 2, \ldots, 694$. The resulting MFP $\overline{\lambda_0(z)}$ as a function of the mean redshift $\overline{z}$ is shown in Fig. 1.

It can be seen that the MFP $\overline{\lambda_0(z)}$ increases with the mean redshift $\overline{z}$ and has a series of minimums and maximums which appear alternately. This is a very interesting result. It indicates

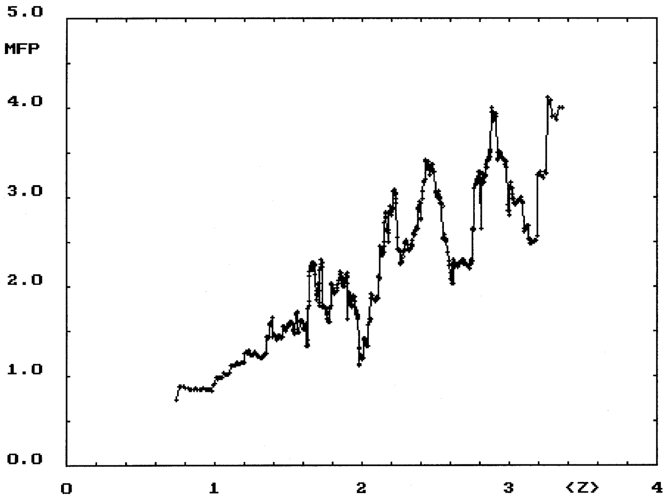


**Fig. 1.** The MFP $\overline{\lambda_0(z)}$ (in $10^3$ $h^{-1}$ Mpc) as a function of the mean redshift $\bar{z}$, from the redshift data in Table 1 of the JHB catalog (Junkkarinen et al. 1991). Each cross is a result calculated by a group of 50 FPs with neighboring redshifts, total number of the groups is 694 as explained in the text

that the effective radius $R$ and/or number density $n_0$ of absorbers depend on the time and may have a periodic or quasi-periodic component.

We found that the general trend of increasing MFP $\overline{\lambda_0(z)}$ with increasing redshift $\bar{z}$ can be fitted by a power law

$$\overline{\lambda_0(z)} = \Lambda\,(1 + \bar{z})^{\beta} \approx 375(1 + \bar{z})^{3/2}\ h^{-1}\,\mathrm{Mpc}. \quad (12)$$

From the regression equations relating $\ln(\overline{\lambda_0(z)})$ and $\ln(1+\bar{z})$, we obtained $\beta = 1.53 \pm 0.09$ and $\Lambda = 375(+74, -62)$ $h^{-1}$ Mpc. For $\bar{z} > 1.29$, the correlation coefficient and the standard deviation of residual are, respectively, $r = 0.822 \pm 0.019$ and $s = 0.181$. The uncertainties in the value of $\beta$ and the correlation coefficient $r$ were estimated by a set of subsamples from resampling of 694 MFPs, for example, the $j$th subsample was constructed by removing $\Delta$N MFPs from 694 MFPs (removing $\overline{\lambda_0(z)}_j$ to $\overline{\lambda_0(z)}_{j+\Delta N}$ for a given number $\Delta N < 50$).

It is noteworthy that the general trend of evolution of the MFP $\overline{\lambda_0(z)}$ can also be estimated approximately from the number of absorption systems per unit redshift range,

$$\mathrm{d}N/\mathrm{d}z = (n_z\,\sigma_z)(c/H_0)(1 + z)^{-2}(1 + 2q_0\,z)^{-1/2}$$
$$= \overline{\lambda_0(z)}^{\,-1}(c/H_0)(1 + z)(1 + 2q_0\,z)^{-1/2}, \quad (13)$$

where $\overline{\lambda_0(z)} = \overline{\lambda_z}(1+z)^3 = (n_z\,\sigma_z)^{-1}(1+z)^3$, in non-evolving case $\overline{\lambda_0(z)} = \overline{\lambda_0} = (n_0\,\sigma_0)^{-1}$ is a constant. According to our result given in Eq.(12), $\overline{\lambda_0(z)} \propto (1 + \bar{z})^{\beta}, \beta = 1.53 \pm 0.09$, it can be expected that the number density of absorption systems per unit redshift for $q_0 = 0.5$ will be

$$\mathrm{d}N/\mathrm{d}z \propto (1+z)^{-\beta}\,(1+z)^{1/2} \approx (1+z)^{-1}. \quad (14)$$

This is comparable to that estimated by Sargent et al. (1988) with their samples of C iv redshifts, for $1.3 < z_a < 3.4$,

$$\mathrm{d}N/\mathrm{d}z \propto (1 + z)^{\gamma}, \gamma = -1.2 \pm 0.7\,.$$

A question of great importance is whether the wavy change appearing in Fig. 1 is an actual periodic variation. If yes, it would be possible to find a periodic component with a definite period $\tau$, and so we would know a time scale of the evolution of absorbers and can judge whether the absorbers are galaxies or not.

A very effective method to search periodic components is power-spectrum analysis. To judge whether the observational MFP $\overline{\lambda_0}\,(z)$ in Fig. 1 possesses a significant periodic component, considering Eq.(12), we can make use of a simple power-spectrum analysis for a new variable

$$X(\bar{z}_i) = \overline{\lambda_0(z)}_i \,/\, \Lambda(1 + \bar{z}_i)^{\beta} - 1$$
$$= \overline{\lambda_0(z)}_i \,/\, (375(1 + \bar{z}_i)^{3/2}) - 1, \quad (15)$$

where $\bar{z}_i$ and $\overline{\lambda_0(z)}_i$ are the mean redshift and the MFP worked out from the $i$th group, $i = 1, ...$N. With $t_i = t_0(1 + \bar{z}_i)^{-3/2}$ and $t_0 = 2 \,/\, (3\,H_0)$ for $q_0 = 0.5$, we can write the variable as a function of time t,

$$X(t_i) = \overline{\lambda_0(t)}_i\,(t_i \,/\, t_0) \,/\, 375 - 1.$$

The power spectrum P($k$) for N $X(t_i)$ or $X(\bar{z}_i)$ with respect to a trial frequency $k$ ($/\,t_0$, corresponding to period $t_0/k$) is given by

$$\mathrm{P}(k) = (1/2)\{[(2/\mathrm{N})\sum_{i=1}^{\mathrm{N}} X(t_i)\,\cos(2\,\pi\,k\,t_i \,/\, t_0)]^2$$
$$+ [(2/\mathrm{N})\sum_{i=1}^{\mathrm{N}} X(t_i)\,\sin(2\,\pi\,k\,t_i/\,t_0)]^2\}$$
$$= (1/2)\{[(2/\mathrm{N})\sum_{i=1}^{\mathrm{N}} X(\bar{z}_i)\,\cos(2\,\pi\,k\,(1 + \bar{z}_i)^{-3/2})]^2$$
$$+[(2/\mathrm{N})\sum_{i=1}^{\mathrm{N}} X(\bar{z}_i)\,\sin(2\,\pi\,k\,(1 + \bar{z}_i)^{-3/2})]^2\}. \quad (16)$$

A periodicity can be observed as a peak in a plot of P($k$) at the relevant frequency.

Figure 2 shows the power spectrum for the variable $X(\bar{z}_i)$, $i$ from 1 to N = 694, calculated by the above-mentioned 694 MFPs. Horizontal line denotes 95% confidence level. It can be seen in Fig. 2 that there is a rather prominent peak at $k \approx 42$. Secondary peak appears in $k \approx$ 10–25. This means that the change of the MFP $\overline{\lambda_0(z)}$ has a significant periodic component of period $\tau$ which can be expressed as

$$\cos[2\,\pi\,a(1 + \bar{z})^{-3/2} + \phi_0] = \cos(2\,\pi\,t/\,\tau + \phi_0), \quad (17)$$

where $a = t_0 \,/\, \tau = 42$ is the result of the power-spectrum analysis, $\phi_0$ is an initial phase, $t = t_0(1 + \bar{z})^{-3/2}$ and $t_0 = 2 \,/\, (3\,H_0)$ for $q_0 = 0.5$. As a result, the period of the principal periodic component is

$$\tau = t_0 \,/\, a = 1.55\,10^8\ h^{-1}\,\mathrm{yr}. \quad (18)$$

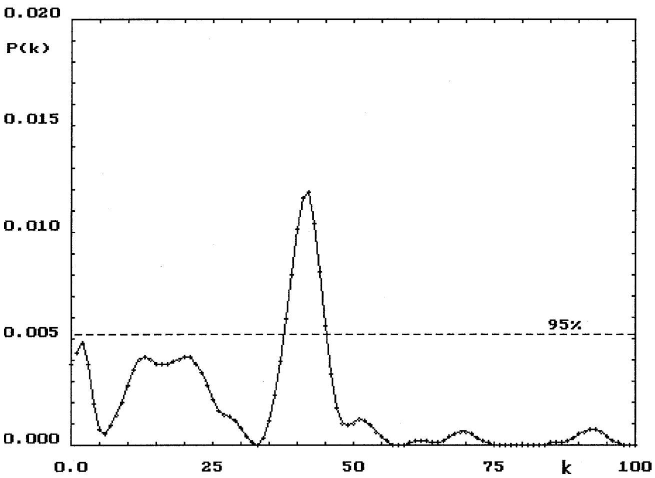


**Fig. 2.** Power spectrum of the variable $X(\overline{z}_i)$ defined by Eq.(15) for the MFPs calculated by Table 1 of the JHB catalog (Junkkarinen et al. 1991). There is a prominent peak at frequency $k \approx 42$. Horizontal line denotes 95% confidence level

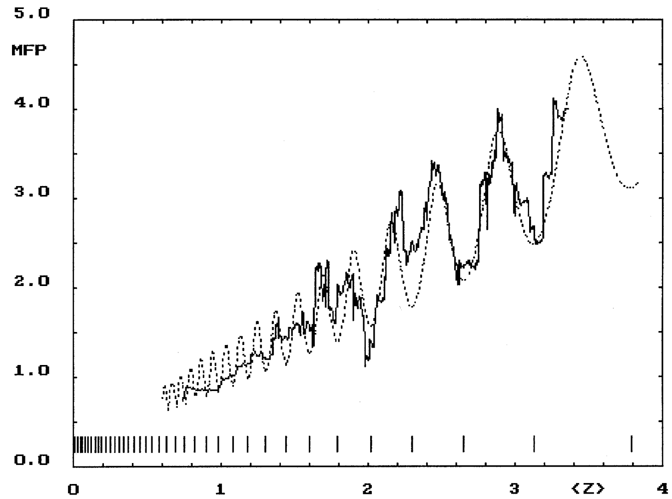


**Fig. 3.** A fitting curve (Eq.(23)) for the observational MFP (Fig. 1), which can be derived from a simple model in which the protogalaxies were pulsating at the epochs of the QSO redshifts. The vertical lines represent the periodicity (Eq.(24) for $42 > \nu > 4$) obtained by the power spectrum analysis in Fig. 2

This period $\tau = 1.55\ 10^8\ \mathrm{h}^{-1}$ yr is quite consistent with the dynamic time scale of galaxies such as the rotation time of a spiral galaxy, which shows that the periodicity is significant not only in statistics but also in physics. It indicates that the periodic variation of the MFP might be due to a dynamic process in distant galaxies.

It is conceivable that the dynamic process which can result in the period change of the MFP may be a small amplitude vibration of the protogalaxy. We have considered a tentative model to explain the evolution of the observational MFP $\overline{\lambda_0(z)}$ in Fig. 1. To determine the physical parameters which dominate the evolution, we assume that the heavy-element absorption systems are due to intervening protogalaxies and the protogalaxies were pulsating at the epochs of the QSO redshifts. Thus, the effective radius and cross-section are

$$R(t) = R[1 + \alpha \cos(2\pi t / \tau + \phi_0)] \tag{19}$$

and

$$\sigma_0(t) = \sigma_0 [1 + \alpha \cos(2\pi t / \tau + \phi_0)]^2. \tag{20}$$

And so the MFP $\overline{\lambda_0(t)}$ as a function of time is expected to be

$$\overline{\lambda_0(t)} = (\sigma_0(t)\, n_0(t))^{-1}$$
$$= (\sigma_0\, n_0(t))^{-1}[1 + \alpha \cos(2\pi t / \tau + \phi_0)]^{-2}. \tag{21}$$

The parameters in Eq. (21) which characterize the pulsating protogalaxies can be determined by comparing with the observational MFP. From Eqs.(12)–(18), for $q_0 = 0.5$, we have known the period $\tau \approx t_0 / 42$ and

$$(\sigma_0\, n_0(t))^{-1} = \Lambda(1 + \overline{z})^{\beta} \approx 375(1 + \overline{z})^{3/2}\ \mathrm{h}^{-1}\,\mathrm{Mpc}$$
$$\approx 375(t_0 / t)\ \mathrm{h}^{-1}\,\mathrm{Mpc},$$

i.e., the number density $n_0(t) \propto t \propto (1 + \overline{z})^{-3/2}$, and so Eq.(21) becomes

$$\overline{\lambda_0(z)} \approx 375(1 + \overline{z})^{3/2}$$
$$\times \{1 + \alpha \cos[2\pi 42(1 + \overline{z})^{-3/2} + \phi_0]\}^{-2}\ \mathrm{h}^{-1}\,\mathrm{Mpc}. \tag{22}$$

In Fig. 3, we give a fitting curve for the observational MFP $\overline{\lambda_0(z)}$,

$$\overline{\lambda_0(z)} \approx 375(1 + \overline{z})^{3/2}$$
$$\times \{1 + 0.125 \cos[2\pi 42(1 + \overline{z})^{-3/2}]\}^{-2}\ \mathrm{h}^{-1}\,\mathrm{Mpc}, \tag{23}$$

i.e.,

$$\overline{\lambda_0(t)} \approx 375(t_0 / t)[1 + 0.125 \cos(2\pi t / \tau)]^{-2}\ \mathrm{h}^{-1}\,\mathrm{Mpc},$$

where we have taken the initial phase $\phi_0 = 0$ and the amplitude $\alpha = 0.125$ in Eq.(21). The initial phase $\phi_0 = 0$ means that the period condition fit for the serial minimums of the observational MFP $\lambda_0(z)$ is just

$$42(1 + \overline{z}_\nu)^{-3/2} = \nu, \tag{24}$$

where $\nu$ is an integer, for observed range, $42 > \nu > 4$, $0 < \overline{z} < 3.8$. At time $t_\nu = \nu\tau$ corresponding to redshift $\overline{z}_\nu = (42/\nu)^{2/3} - 1$, the effective radius of protogalaxy reaches maximum, the MFP $\overline{\lambda_0(t)}$ becomes minimum. This period condition (24) for $\nu >= 4$ is also shown in Fig. 3 by vertical lines. These results show that the periodicity in the observed range can be explained by small amplitude pulsation of the protogalaxies.

Here, it is interesting to note that the period condition (24) is quite consistent with at least five recognizable minimums in Fig. 3 ($1.6 <= \overline{z} <= 3.1, 10 >= \nu >= 5$), that is, the observational periodicity can be described by one principal periodic component with period $\tau$ and phase $\phi_0$. In our model, this means that the majority of protogalaxies at the QSO epoch should pulse with almost the same period and remain in phase. This is a severe condition, but it is not impossible in the standard cosmological model. A possible case is that the density perturbations forming protogalaxies of a kind has been separated from other scale perturbations by a special process in early universe at an earlier time $t_g < \Delta\tau$, where $\Delta\tau$ is the uncertainty of the period $\tau$ permissible to cause the observed periodicity, and evolution of protogalaxies has been determined by their initial state at that time $t_g$. A reasonable estimate for this uncertainty is $\Delta\tau << 0.1\tau$, and so the initial time should be at $t_g << 0.1\tau \approx 1.6\,10^7$ h$^{-1}$ yr, at redshift $z_g >> 56$.

It is also noteworthy that the small amplitude pulsation of protogalaxy can be regarded as the after-effect of the gravitational collapse if the protogalaxy is a self-bound gravitational system developed from an early density perturbation after the initial time $t_g$. According to the simplest spherical collapse model (Peebles 1967, 1993), at some time $t_{ta}$, the density in the perturbed sphere of radius $R(t_{ta})$ (so called the turn-around radius) reaches a minimum, the expansion ceases and contraction begins. That is, after reaching the maximum size $R(t_{ta})$, the perturbed sphere will separate from the general expansion of the universe and become a self-bound gravitational system. Before the perturbed sphere becomes an actual equilibrium configuration, oscillations about an equilibrium situation are a most probable event. Since the periodicity appears in the observed range: $\overline{z} < \overline{z}_{\nu=4} \approx 3.8$ corresponding to the time $t > t_{\nu=4} = 4\tau$, the time $t_{ta}$ when the protogalaxy had its most extended radius $R(t_{ta})$ must be even earlier than $t_{\nu=4}$. If we extrapolate the period condition (24) from $\nu = 4$ to the case of $\nu = 1$, the radius of the protogalaxy reaches the first maximal value at the time $t_{\nu=1} = \tau$. Therefore, it is reasonable to take the time $t_{ta} \approx t_{\nu=1} = \tau = 1.55\,10^8$ h$^{-1}$ yr. According to the spherical collapse model the density $\rho'(t_{ta})$ in the perturbed sphere at $t_{ta} \approx t_{\nu=1}$ is

$$\rho'(t_{ta}) = (3\,\pi\,/\,4)^2\,\rho(t_{ta}) \approx 1.84\,10^{-25}\ \mathrm{h}^2\,\mathrm{g\,cm}^{-3}, \tag{25}$$

where $\rho(t_{ta})$ is the average density of the universe at that time. After virialization, $\rho_{vir} \approx 8\rho'(t_{ta})$, we then get a mass

$$M = (4\pi\,/\,3)\,r^3\,\rho_{vir} \approx 9.11\,10^{10}(r/10kpc)^3\ \mathrm{h}^2\,\mathrm{M}_\odot. \tag{26}$$

which is compatible with mass of a typical galaxy. Although this is only an order-of-magnitude estimate, it indicates that the heavy-element absorption systems are due to the intervening protogalaxies that separated from the general expansion of the universe at the cosmic time $t_{ta} \approx t_{\nu=1} = \tau = 1.6\,10^8$ h$^{-1}$ yr, at the redshift $1 + z_{\nu=1} \approx 12$, and the protogalaxies were pulsating with a definite period $\tau$ at the QSO epoch. Evolution of these protogalaxies have been determined by the initial state of the density perturbations at time $t_g << 0.1\tau \approx 1.6\,10^7$ h$^{-1}$ yr, at redshift $z_g >> 56$. These estimates are not in obvious conflict with some estimates in the commonly discussed models for galaxy formation (Peebles 1993).

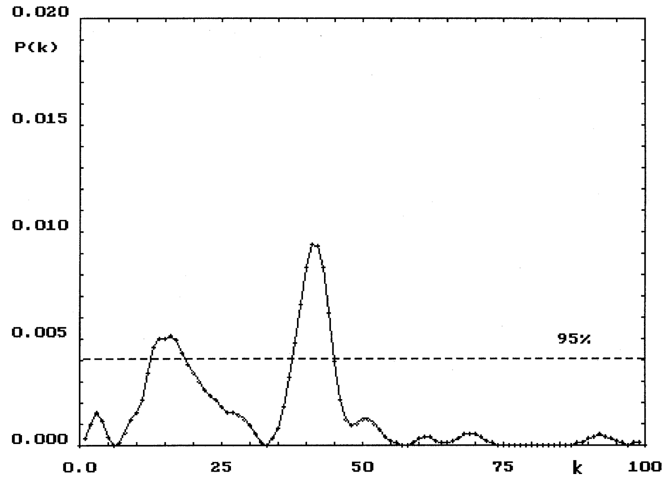


**Fig. 4.** Power spectrum of the variable $X(\overline{z}_i)$ defined by Eq.(15) for the MFPs calculated by a composite absorption-line sample of 425 QSOs (Tanner et al. 1996). A prominent peak at $k \approx 42$ still exists like the case in Fig. 2. Horizontal line denotes 95% confidence level

The above results are based on the FP sample calculated by the redshift data of 353 QSOs in Table 1 of JHB catalog, this is a large sample available but it is not complete in some respects. In order to investigate evolution of the absorbers by means of our statistics, we have to make use of a sample of the FPs which is large enough so that we can work out the MFPs $\overline{\lambda_0(z)}_i$ in sufficiently small redshift region $\Delta z_i$. With the help of statistical tests, we have found that the periodicity persists in some cases, for example, the FP sample is enlarged with additional absorption-line redshifts not in the JHB catalog, or is reduced by removing some FPs but not many (say, less than one tenth of total number of FPs) from the FP sample at random. It implies that the periodicity can not be attributed to a bias in the JHB catalog. In Fig. 4 we show a result of the power-spectrum analysis for a composite absorption-line sample of 425 QSOs given by Tanner et al. (1996), which comprises the QSOs in the JHB catalog and additional objects with absorption-line systems or damped Ly$\alpha$ systems not in the JHB catalog (Tanner et al. 1996, see their Tables 1 and 2). It may be seen in Fig. 4 that the most significant peak at $k \approx 42$ still exists, the difference is only the secondary peak in $k \approx$ 10–25 more significant than that in Fig. 2.

## 4. Conclusion and discussion

We have studied properties of the heavy-element absorption systems and their evolution with redshift by means of the distribution of the FPs of the light rays which come from QSOs and are intercepted by absorbers. We have discovered that the MFP regularly varies with the cosmic time and has a significant periodic component, which shows a marked evolution of the absorbers. For the MFP calculated by the JHB catalog, an useful fitting function is $\overline{\lambda_0(t)} \approx 375\,(t_0\,/\,t)[1 + 0.125\,\cos(2\,\pi\,t\,/\,\tau)]^{-2}$ h$^{-1}$ Mpc, where period $\tau = 1.55\,10^8$ h$^{-1}$ yr is a result of power-spectrum analysis.

Disregarding the small periodic variation, the general trend of increasing MFP $\overline{\lambda_0(z)}$ with increasing redshift $\overline{z}$, $\overline{\lambda_0(z)} \propto (t_0 / t) \propto (1 + \overline{z})^{3/2}$, gives the number density of absorption systems per unit redshift for $q_0 = 0.5$, $\mathrm{dN} / \mathrm{d}z \propto (1 + z)^{-1}$. This is comparable to that estimated by Sargent et al. (1988). We have ascribed this effect to the evolution of the number density of the protogalaxies (see Eq.(22)).

The period $\tau = 1.55\,10^8\ \mathrm{h}^{-1}$ yr is consistent with the dynamic time scale of galaxies, it supports the view that the heavy-element absorption systems are due to protogalaxies. We have shown that the period change of the observational MFP can be attributed to a small amplitude oscillation of the protogalaxy after the gravitational collapse. It implies that the protogalaxies were pulsating with the period $\tau$ at the QSO epoch and the time when the propogalaxies separated from the general expansion of the universe might be at $t \approx 1.55\,10^8\ \mathrm{h}^{-1}$ yr, the redshift $z \approx 11$. From our result, it can be inferred that there should be a periodic component (a series of peaks) in the absorption-line redshift distribution of QSOs, which should satisfy the same period condition concerning the argument $Z = (1 + z)^{-3/2}$ as (24) except a phase constant $\phi_0$. It is possible to find this expectant periodic component on condition that we have a way to get rid of the selection effects and the clustering effect of the absorbers. Note that the selection effects might play a significant role in the formation of certain peaks in the redshift distribution, however, it is very difficult to use them to explain the periodicity.

Problem whether a periodicity exists in the QSO redshift distribution has been discussed for many years (Burbidge 1968; Karlsson 1971, 1977; Barnothy & Barnothy 1977; Liu 1982; Fang et al. 1982; Chu et al. 1984). The statistical result obtained by Karlsson (1971, 1977) is $\log(1 + z_\nu) \propto \nu$, i.e., the periodicity is not with respect to argument $z$ but to $\log(1 + z)$. A similar result has been obtained by Barnothy & Barnothy (1977). Liu (1982) has shown that the periodicity (a series of peaks) which appears in the redshift distribution of distant objects can be explained as vestige of a cosmic density wave. In the case of the deceleration parameter $q_0 \approx 0$, Liu's periodic condition becomes $\ln(1 + z_\nu) \propto \nu$, which is consistent with that obtained by Karlsson. By using the power spectrum analysis, it has been demonstrated that the periodicity concerning $\ln(1 + z)$ is statistically significant not only in the distribution of QSO emission-line redshifts (Fang et al. 1982) but also in the distribution of QSO absorption-line redshifts (Chu et al. 1984). Our results in this paper confirm that there is a periodic component in the absorption redshift distribution, but the periodicity is with respect to $(1 + z)^{-3/2}$ not to $\ln(1 + z)$. This important difference has to be clarified by further statistical test, because it concerns different origin of the periodicity. In another paper (in preparation) we shall give some interesting results relative to this problem.

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