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The Spatial and Temporal Distribution of Matter in the Redshift Interval z = 1.2–3.2

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Abstract—A statistical analysis of the distribution of C IV absorption systems observed in the spectra of quasars with cosmological redshift z is presented. Absorption systems in the redshift interval $z_{abs} = 1.2$–3.2 are considered. The isotropy (or anisotropy) of the distribution of matter is determined by comparing independent distributions of C IV absorption systems in opposite hemispheres with various orientations. The results indicate that the overall distribution is isotropic, but is non-uniform in the spatial–temporal interval considered. There are maxima in the concentration of absorption systems at $z_{abs} = 1.46$, 1.60, 1.78, 1.98, 2.14, 2.45, 2.64, and 2.86 (±0.04), independent of the direction of observation. The resulting distribution of matter resembles embedded spheres corresponding to these z_{abs} values. The most probable origin for this distribution is the appearance of distinct epochs with durations from 200–600 million years (depending on the choice of cosmological model) during the process of cosmological evolution.

1. INTRODUCTION

Most modern cosmological models are based on the assumption that all points in space are equivalent, so that, on average, the Universe is uniform and isotropic. This so-called cosmological principle has been widely discussed in the literature (see, for example, Peebles 1993).

The aim of our study is to investigate the degree of uniformity and isotropy of the distribution of matter in the redshift interval $z = 1.2$–3.2. We used the absorption lines of the resonance C IV doublet ($\lambda_0 = 1548$ and 1550 Å) as an indicator of the presence of matter. These lines are often observed in the spectra of quasars with large emission-line redshifts z_{em}. We assumed that the redshift of the absorption lines z is cosmological, i.e., $\lambda = \lambda_0(1 + z)$, and that the observed C IV doublet absorption systems are associated with ionized gas in galaxies or clusters of galaxies at large cosmological distances along the line of sight between the quasar and the observer.

2. DISTRIBUTION OF THE C IV ABSORPTION SYSTEMS IN THE REDSHIFT INTERVAL $z = 1.2$–3.2

2.1 Uniformity of the Distribution

We considered 307 C IV absorption systems observed in quasar spectra (Bergeron *et al.* 1987; Boisse and Bergeron 1985; Caulet 1989; Lanzetta *et al.* 1987; Lanzetta and Bowen 1992; Petitjean and Bergeron 1990; Robertson *et al.* 1986, 1988; Sargent *et al.* 1982, 1988a, 1988b, 1989, 1990; Sargent and Steidel 1987; Steidel 1990; Steidel and Sargent 1992; Turnshek *et al.* 1989; Foltz *et al.* 1986; Khare *et al.* 1989; Young *et al.* 1982). Figure 1 shows the redshift values z and the right ascensions α for each of these systems (the equatorial coordinates α and δ have been projected onto the $\delta = 0$ plane, where δ is the declination).

Our null hypothesis was that the C IV absorption systems for our sample were distributed uniformly in the redshift interval $z = 1.2$–3.2. We divided this interval into n equal independent bins, so that, according to our null hypothesis, the probabilities of an absorption system falling into various bins were the same and were equal to $1/n$. We determined the empirical distribution of the absorption systems by finding the n probability values ω_i, where $i = 1, 2, \ldots, n$ is the bin number. To test the correctness of our null hypothesis, we calculated the quantity

$$X^2 = \sum_{i=1}^{n} (\omega_i)^2 - \frac{\left(\sum_{i=1}^{n} \omega_i\right)^2}{n},$$

which is distributed as χ^2 with $(n-1)$ degrees of freedom. When $X^2 > \chi^2_{1-p}$, where χ^2_{1-p} are tabulated values of χ^2 corresponding to a given significance level p, the hypothesis that the absorption systems are uniformly distributed can be rejected with confidence $\beta = 1 - p$.

Figure 2 presents the calculated values of X^2 as a function of the number of bins n into which the interval $z = 1.2$–3.2 is divided. Comparison of the calculated X^2 and tabulated χ^2_{1-p} values allows us to reject the hypothesis that the distribution is uniform for $n > 6$ with confidence $\beta = 0.998$ (at the 3σ level). Thus, the absorp-

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tion-system distribution is not monotonic for $n > 6$, and has local maxima (peaks) and minima (valleys) relative to the median distribution. The excess of the calculated X^2 over the tabulated χ^2_{1-p} values is most appreciable when the number of bins is $n = 9$, 28, 36, and 57. This indicates that the deviation from a uniform distribution in z is most pronounced when the total redshift interval is divided into these numbers of bins. The z distribution for $n = 9$ has two broad peaks, which separate into eight narrower peaks as n is increased. Figure 3 shows the z distribution of the absorption systems for $n = 28$, which corresponds to a bin width of 0.071. We determined the positions of the maxima as the coordinates of the centers of gravity of the peaks along the $z$axis. The corresponding values of z are 1.46, 1.60, 1.78, 1.98, 2.14, 2.45, 2.64, and 2.86, with accuracy ±0.04 (half the bin width). The significance levels for the peaks corresponding to these z values are approximately 3σ, 3σ, σ, 2σ, σ, 3σ, 2σ, and 2σ. For $n > 28$, the distribution becomes more jagged due to statistical fluctuations; additional peaks that appear in this case are not statistically significant (< σ), and we will not consider them further.

Thus, our results provide evidence for a nonuniform distribution of matter in the redshift interval $z = 1.2$–3.2, with confidence level more than 0.998.

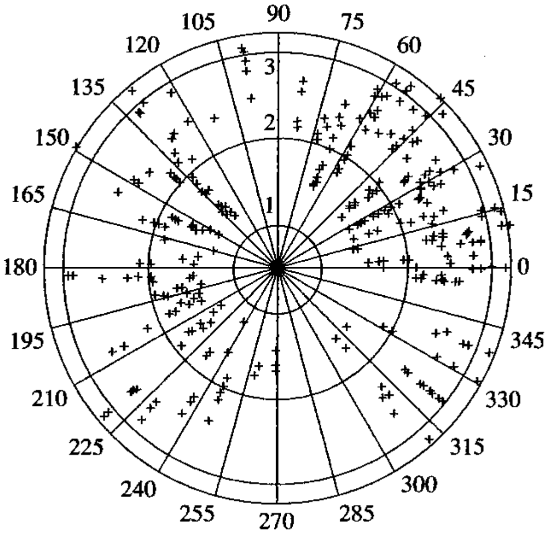

Fig. 1. Distribution of 307 C IV absorption systems in a (z, α) coordinate system, where the redshift $z$is the radial coordinate and the right ascension α is the angular coordinate. The values of z are indicated by the numbers near the concentric circles (the center corresponds to $z = 0$), and α is given in degrees near the radial lines.

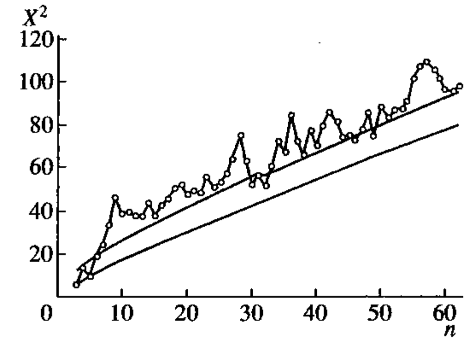

Fig. 2. Comparison of the X^2 values calculated using (1) and the tabulated values of χ^2_{1-p} for the two confidence levels $\beta = 1 - p = 0.998$ (upper line) and $\beta = 0.950$ (lower line) for division of the redshift interval $z = 1.2$–3.2 into n bins. The vertical axis plots the values of X^2 and χ^2_{1-p} and the horizontal axis the number of bins n.

2.2 Isotropy of the Distribution

We tested the isotropy of the distribution by comparing the z distributions of the C IV absorption systems in opposite hemispheres. We divided the celestial sphere into two hemispheres separated by the plane passing through the world axis and two meridians whose right ascensions α differ by 180° (12^h). We obtained 12 pairs of independent hemispheres by consecutively rotating the division plane about the world axis in 15° (1^h) steps in α. For each hemisphere, we constructed the z distribution of the absorption systems for $n = 28$. Our null hypothesis in this case was that the z distributions obtained for the two independent hemispheres would be uncorrelated.

We calculated the correlation coefficient r for each pair of hemispheres and compared it with tabulated values r_β of sample correlation coefficients for a given sample size ($n = 28$) and confidence level β. When $r > r_\beta$, the null hypothesis can be rejected with confidence β.

Figure 4a shows the z distributions in the two opposite hemispheres α = 0–180° and α = 180–360°. The calculated correlation coefficient for these distributions is $r = 0.613$, while $r_\beta = 0.578$ for $n = 28$ and $\beta = 0.999$; this provides evidence that the two distributions obtained are correlated at the 3σ level. Figure 4b demonstrates the high levels of correlation for the pairs of distributions for various numbers of bins dividing the total redshift interval considered.

Figure 5 shows the absorption-system distributions in z for the 24 hemispheres. The vertical axis plots the right ascension of the hemisphere centers α_c in degrees. The light areas correspond to enhanced concentrations of absorption systems, and the dark areas to reduced concentrations; black areas are those for which we do not have all the necessary data for the analysis. We can see continuous bands at $z = 1.46$, 1.60, 1.78, 1.98, and 2.86, for which the positions of maxima in the z distributions (with allowance for the errors) do not depend on α_c; i.e., they are the same for all hemispheres. On the

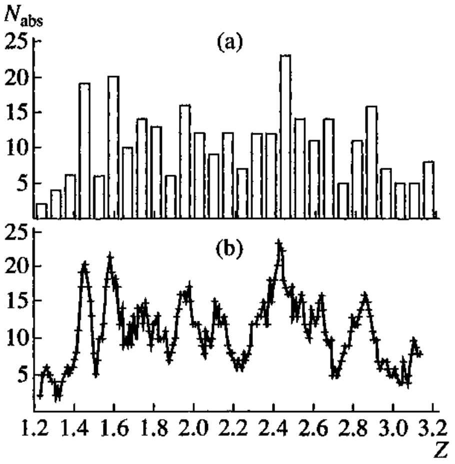

Fig. 3. Distribution of the C IV absorption systems in z for n = 28: (a) histogram of the distribution of the 307 absorption systems; (b) distribution obtained by performing consecutive shifts of all bins in the histogram along the z axis with step 0.01 within the limits of a single bin.

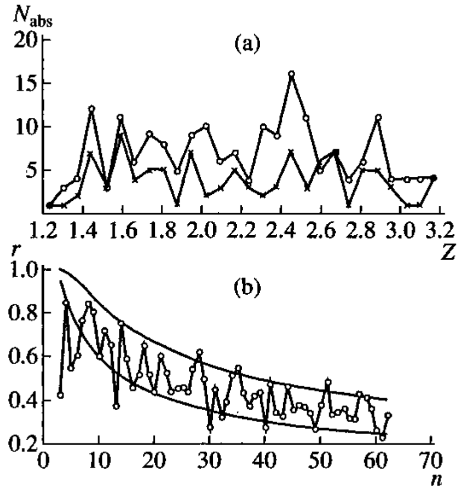

Fig. 4. (a) z distribution of the C IV absorption systems for n = 28 in the two oppositely directed hemispheres α = 0–180° (circles) and α = 180–360° (crosses). The correlation coefficient for the two distributions is 0.613, and the corresponding tabulated value of the sample correlation coefficient is $r_\beta = 0.578$ for a confidence level $\beta = 0.999$. (b) Comparison of the calculated correlation coefficients r and the tabulated values r_β for the two confidence levels $\beta = 0.999$ (upper line) and $\beta = 0.950$ (lower line) when the redshift interval z = 1.2–3.2 is divided into n bins.

contrary, the bands at z = 2.14, 2.45, and 2.64 are fragmented, possibly as a result of insufficient statistics. Figure 6 shows that, for virtually all pairs of opposite hemispheres, the correlation of the z distributions is significant at the 2σ level ($\beta \geq 0.95$).

To verify that the positions of the maxima in the distribution of absorption systems do not depend on the orientation of the axis about which we rotated the plane dividing the celestial sphere in half, we also performed the procedure described above in Galactic coordinates (l, b). In this case, the rotation was done about the axis passing through the north and south Galactic poles. Figure 7 shows the positions of absorption systems in the coordinates l and z in projection onto the Galactic plane, b = 0. Figure 8 depicts the z distribution of the absorption systems in the resulting 24 hemispheres. The vertical axis plots the Galactic longitude of the hemisphere centers l_c. It is clear from a comparison of Figs. 5 and 8 that the positions of the maxima and minima in the z distributions of the C IV systems do not change (within the errors) when we make this transition to a Galactic coordinate system; consequently, they do not depend on the direction in which the observations were made.

Figure 9 presents the correlation coefficients for the z distributions in pairs of opposite hemispheres as a function of the longitude $0 \leq l_c \leq 180°$ of one of the two hemispheres. It is clear that the significance levels for the correlations between pairs of distributions exceed 2σ in most directions. The low confidence levels for the correlations between pairs of hemispheres corresponding to the longitude interval $90° \leq l_c \leq 150°$, and also the break in all the light bands near Galactic longitude l_c = 300°, are associated with the absence of observational data in the interval l_c = 285–330° (see Fig. 7).

Thus, our results indicate that the distribution of absorbing material is isotropic.

3. NORMALIZED DISTRIBUTION OF THE C IV ABSORPTION SYSTEMS

The statistical material considered in Sec. 2 was inhomogeneous, since we used data on quasar spectra obtained in many different studies, which applied a variety of criteria for the detection and identification of absorption systems. In this case, the probabilities for detecting and identifying absorption systems could be different for different bins in the interval z = 1.2–3.2, and this could imitate nonuniformity of the z distribution. In order to exclude this effect, we developed an algorithm to construct normalized distributions that ensure *a priori* equal probabilities for the detection and identification of the absorption systems. This algorithm has been described in detail by Ryabinkov, Varshalovich, and Kaminker (1998).

Briefly, the algorithm consists of the following operations. We consider the wavelength interval in the spectrum of each quasar between the Ly-α and C IV emission. The boundaries of this interval were determined in terms of their redshifts. For each quasar spectrum, we calculated the threshold value of the absorption equivalent width W_{th}, such that a line with an equivalent width in its rest frame $W_\lambda/(1 + Z) \geq W_{th}$, would be

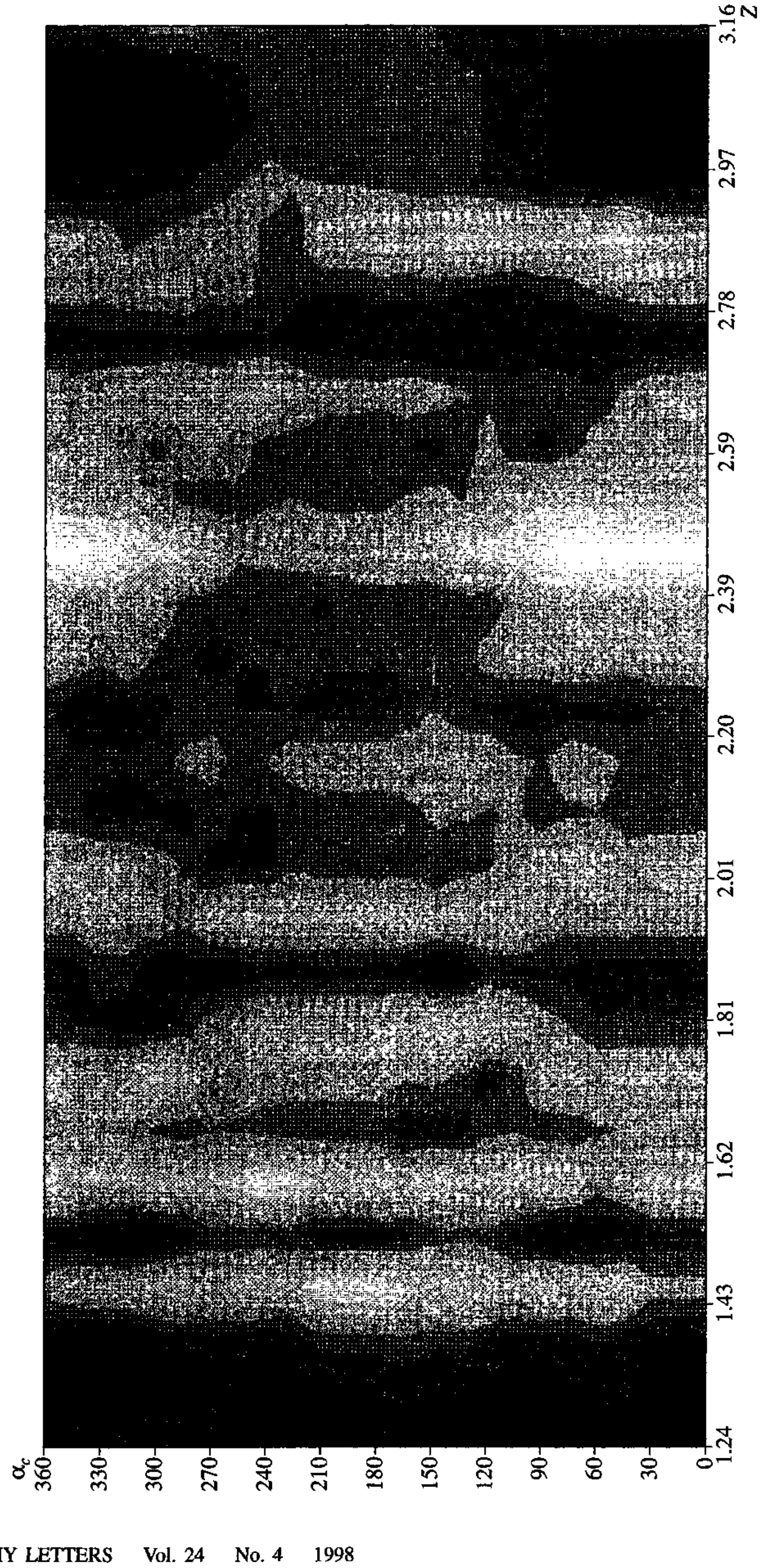

Fig. 5. z distribution of the C IV absorption systems in 24 hemispheres in equatorial coordinates. The horizontal axis plots z and the vertical axis plots α_c—he right ascension of the hemisphere centers in degrees, in steps of 15° (1^h)).

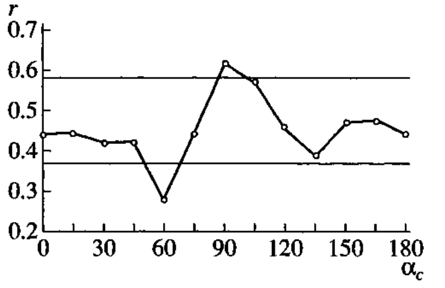

Fig. 6. Correlation coefficients r for the z distributions of the C IV absorption systems in pairs of opposite hemispheres. The horizontal axis plots the right ascensions of the centers of the hemisphere in each pair that is in the range $\alpha_c \in$ (0–180°). The tabulated values $r_\beta = 0.578$ for the confidence level $\beta = 0.999$ (3σ) and $r_\beta = 0.369$ for $\beta = 0.950$ (2σ) are presented.

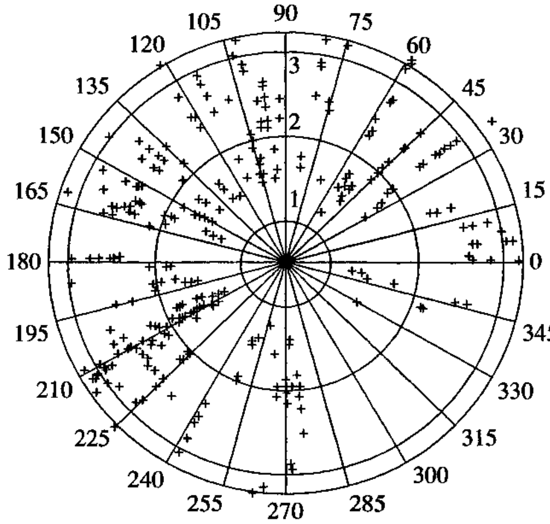

Fig. 7. Same as Fig. 1, but in the (z, l) coordinate system. The redshift z is the radial coordinate and the Galactic longitude l is the angular coordinate. The values of z and l are indicated in the same way as in Fig. 1.

detected reliably in the given interval of z. Criteria for the identification of absorption systems are formulated, and are used to select out from all detected absorption lines only the pairs of lines formed by the absorption systems in which we are interested (in our case, the C IV doublet). We adopt the equivalent width of the weaker line of the C IV doublet in its rest frame (λ_0 = 1550 Å) as the equivalent width of the absorption system W_{abs}.

An interval Δz (bin) and value for the minimum equivalent width W_{min} are chosen. We find the ratio of the number of absorption systems ΔN_{abs} with $W_{abs} \geq W_{min}$ observed in the selected interval Δz to the total number observed in the quasar spectra ΔN_{QSO} (of sufficiently high quality, so that $W_{th} \leq W_{min}$) that include the interval Δz. The quantity ΔN_{QSO} includes both spectra in which absorption systems are detected and those in which they are not. The resulting ratio $\Delta N_{abs}/\Delta N_{QSO}$ characterizes the probability of observing absorption systems in a given interval Δz (for a specified W_{min}). The dependence of $\Delta N_{abs}/\Delta N_{QSO}$ on z is a normalized distribution of absorption systems with redshift.

This strict algorithm for selecting absorption systems and quasar spectra reduces the amount of observational material to be included in the statistical analysis by a factor of 2.5. However, the results obtained using the normalized distributions should not be subject to observational selection effects. Therefore, in addition to the statistical analysis described in Sec. 2, it is useful to perform an analogous analysis using the normalized distributions.

3.1 Uniformity of the Distribution

Figure 10 shows the normalized z distributions of the C IV absorption systems for n = 28 and W_{min} = 0.2 Å. It is clear that these distributions are not monotonic, and that they have local maxima and minima. The calculated X^2 = 44.4 exceeds the tabulated value χ^2_{1-p} = 40.1 for β = 0.95, confirming the conclusion in Sec. 2 that the distribution of material in the redshift interval z = 1.2–3.2 is nonuniform at the 2σ level. The positions of the maxima (centers of gravity of the peaks) z = 1.45, 1.63, 1.78, 1.95, 2.11, 2.38, 2.63, and 2.91 are in agreement with the maxima determined in Sec. 2 to within ±0.04.

3.2 Isotropy of the Distribution

Figure 11 shows the normalized z distributions in 24 hemispheres of the celestial sphere. The vertical axis plots the right ascensions of the hemisphere centers α_c in degrees. We can see an alternation of light and dark bands, similar to those in Fig. 5. There are again continuous bands in which the positions of the maxima of the z distribution are independent of α_c to within the errors (z = 1.45, 1.63, 1.95, and 2.11) and other bands that are more fragmented (z = 1.78, 2.38, 2.63, and 2.91). In Fig. 11, the black areas are those in which the data required to determine ΔN_{abs} and/or ΔN_{QSO} are not available (see, for example, the interval z = 1.45–2.85). The increase of the number of such "black" regions in Fig. 11 as compared to Figs. 5 and 8 is associated with the sharp decrease in the amount of statistical material as a consequence of our strict criteria for selecting the absorption systems for the analysis using the normalized distributions, as described above.

Thus, although our analysis using normalized distributions is less statistically reliable, it confirms the results obtained in Sec. 2: the distribution of material in

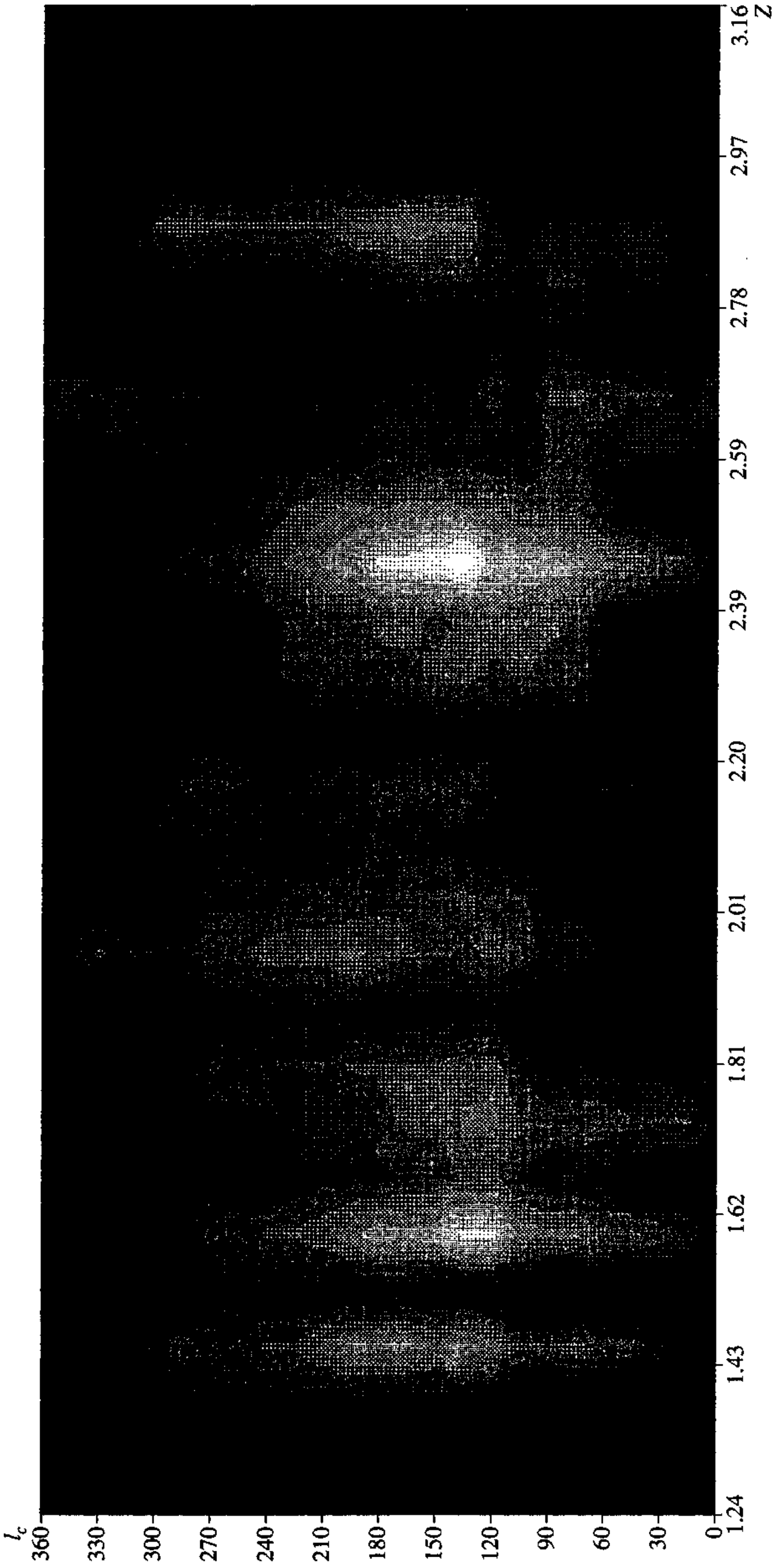

Fig. 8. Same as Fig. 5, but in Galactic coordinates. The horizontal axis plots the Galactic longitudes of the centers of hemispheres l_c in degrees in steps of 15° (1^h).

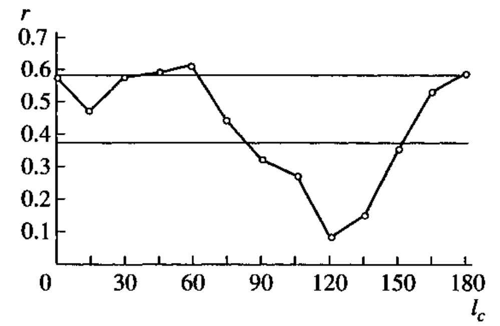

Fig. 9. Same as Fig. 6, but for a Galactic coordinate system. The horizontal axis plots the Galactic longitudes of the centers of the hemisphere in each pair that is in the range l_c = 0–180°.

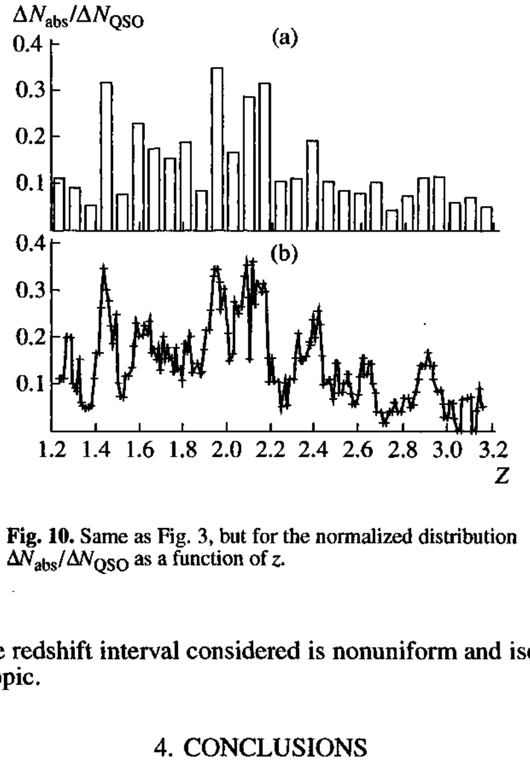

Fig. 10. Same as Fig. 3, but for the normalized distribution $\Delta N_{abs}/\Delta N_{QSO}$ as a function of z.

the redshift interval considered is nonuniform and isotropic.

4. CONCLUSIONS

Our statistical analysis of the distribution of C IV absorption systems with redshifts in the interval z_{abs} = 1.2–3.2 observed in quasar spectra leads to the following conclusions.

(1) The z distribution of the absorption systems is nonuniform, and has alternating maxima and minima. The maxima in the distribution are observed at epochs corresponding to the redshift values z_{abs} = 1.46, 1.60, 1.78, 1.98, 2.14, 2.45, 2.64, and 2.86, with accuracy ±0.04, independent of the direction in which we observe. Some of these maxima in the distribution of absorbing material were reported earlier in the literature (see, for example, Arp *et al.* 1990), but only along specific directions on the celestial sphere.

(2) The most probable spatial picture for the z distributions we have derived is a series of embedded spheres of absorbing material, corresponding to the z_{abs} values indicated above. Note that the bin width we adopted, $\Delta z = 0.071$, is appreciably larger than the values Δz associated with the peculiar motions of galaxies, including flows in the richest clusters of galaxies. Thus, the nonuniformity of the distribution of absorbing material due to local structures should completely average out. Therefore, the large-scale nonuniformity in the distribution of material is most likely associated with the appearance of special epochs with characteristic time intervals of 300 ± 100 million years during the course of cosmological evolution (in a standard cosmological model with $\Omega = 1$, $\Lambda = 0$, and t_0 = 15 billion years). Variations with a characteristic time scale of this order can be understood in the framework of a number of cosmological scenarios that take into account the scalar field or phase transitions in late stages of the evolution of the Universe, which can lead to quasi-periodic oscillations in the gravitational constant G, the Hubble constant H_0, and the cosmological constant λ_0 (see, for example, Morikawa 1991, Damour and Polyakov 1994, and Sisterna and Vucetich 1994).

(3) The corresponding distances between the maxima in the distribution of absorbing material in a comoving coordinate frame in the redshift interval z_{abs} = 1.2–3.2 are equal to $(116 \pm 50)h^{-1}$ Mpc, where $h = H_0/100$ km s^{-1} Mpc^{-1}. This scale coincides, within the errors, with the value 128 h^{-1} Mpc obtained by Broadhurst *et al.* (1991) for $z \le 0.5$ and the value 120 h^{-1} Mpc obtained by Einasto *et al.* (1997) for $z \le 0.12$. Thus, our results show that the spatial scales for inhomogeneities found in these studies are also present at earlier epochs, right to z = 3.2. Note that the inhomogeneities discussed by Einasto *et al.* (1997) are spatial structures in the form of a "three-dimensional chess board", which are quite different from the nonuniformity we have considered here. Our results do not exclude the existance of global spatial structures at the epochs z = 1.2–3.2. Such structures may be detected as more statistical material is accumulated, for example, in the bands in Figs. 5, 8, and 11 that are fragmented. On the other hand, at small values of z, the velocities of the peculiar motions of galaxies are comparable to the velocity due to the cosmological expansion. Therefore, we expect that, if sufficient stastical material is collected, large-scale inhomogeneities associated with global cosmological processes should be more pronounced at $z > 1$ than at $z < 1$.

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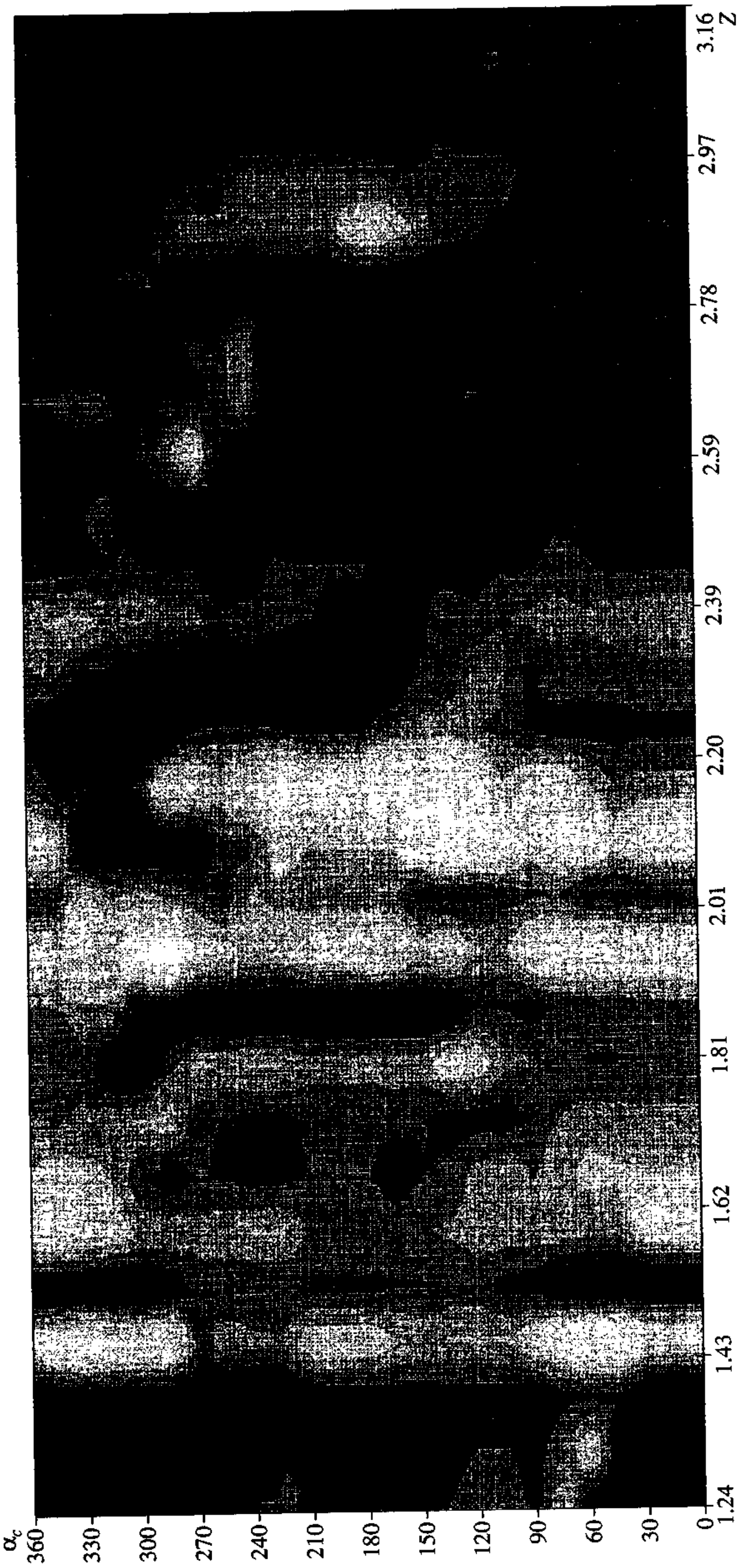

Fig. 11. Same as Fig. 5, but for the normalized distribution $\Delta N_{abs}/\Delta N_{QSO}$ as a function of z.

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