Title
Deviation from periodicity in the large-scale distribution of galaxies

Journal
The Astrophysical Journal, 356(1)

ISSN
0004-637X

Authors
Kurki-Suonio, H
Mathews, GJ
Fuller, GM

Publication Date
1990-06-01

DOI
10.1086/185738

Peer reviewed

THE ASTROPHYSICAL JOURNAL, 356: L5–L7, 1990 June 10

DEVIATION FROM PERIODICITY IN THE LARGE-SCALE DISTRIBUTION OF GALAXIES

H. KURKI-SUONIO AND G. J. MATHEWS
University of California, Lawrence Livermore National Laboratory
AND
G. M. FULLER
Physics Department, University of California, San Diego
Received 1990 January 23; accepted 1990 March 22

ABSTRACT

We investigate the recently observed periodicity of the distribution of galaxies at high redshift by comparing the data with models in which galaxies reside on the surfaces of bubbles or sheets. A statistical analysis of the deviation from periodicity along various lines of sight seems to suggest that the data more closely resemble a regular cellular pattern in which the bubble centers are strongly anticorrelated than a distribution produced by random voids or sheets. We discuss how such a regular structure might arise and suggest some observational tests of this interpretation.

Subject headings: cosmology — galaxies: redshifts — galaxies: structure

Recent observations (Broadhurst *et al.* 1990) of the redshift distribution in 40′ pencil beams near the Galactic poles out to high redshift ($z \leq 0.5$) have revealed a remarkable periodicity in the distribution of galaxies. When corrected for selection effects, the galaxy number counts indicate narrow concentrations of galaxies separated by voids of $\sim 130h^{-1}$ Mpc comoving size in which there are significantly fewer galaxies. Such structure is consistent with the scale of the nearby void or bubble seen in galaxy distribution studies such as de Lapparent, Geller, and Huchra (1986) which examined a larger patch on the sky but which had a much smaller limiting redshift. Such structure is also consistent with the reported periodicity in the distribution of QSOs (cf. Foltz *et al.* 1989) and the Lyman-α forest (Chu and Zhu 1989) and the locally observed galaxy cluster correlation function (Bahcall, Henriksen, and Smith 1989).

Although the observed pattern is striking, it is not precisely regular. We estimate that the standard deviation of the observed distances from perfect regular spacing is about 17% of the mean comoving separation. The question then arises as to whether this pattern represents a random occurrence of voids produced by intersecting walls of different sized bubbles or reflects a more regular cellular structure. Indeed, even for a perfectly regular lattice structure, a random line of sight would not produce an exactly periodic behavior except along a few special directions. Our intention therefore is simply to study several different geometries for galaxies and voids and deduce the probability that a random trajectory in such a structure would appear like the data. The geometries we consider are (1) randomly placed voids which presumably would be the most natural structure in a universe in which such voids were produced by a completely stochastic process, (2) a pattern of randomly intersecting sheets such that along a line of sight there is a random probability to encounter a wall at any distance, and (3) the regular cellular structure of a simple cubic or close-packed face-centered cubic lattice. Although such completely regular structures might seem a bit unrealistic, they could represent the extreme limit of a mechanism for producing voids in which the presence of one void precludes the possibility of another nearby void, i.e., the void centers could be strongly anticorrelated and tend to reside at an optimum regular separation distance.

We construct the random-void and cellular structures by assigning void points either randomly or at regularly spaced positions, $x = c\{k\hat{x} + l\hat{y} + m\hat{z}\}$, where c gives the scale; $\hat{x}$, $\hat{y}$, $\hat{z}$ are orthogonal unit vectors; and k, l, m are integers for the simple cubic structure. For the face-centered cubic structure, k, l, m are either all integers or two of them are half-integers for alternating planes. The voids are defined by the volume enclosed by boundaries constructed halfway between neighboring points. In the random sheet structure, the boundaries of voids are described by randomly oriented infinite planes.

The face-centered cubic structure is common in metal lattices, with nuclei in the place of void centers. We chose this structure because it is the most regular of the close-packed structures. The significance of close packing in the present work is that the voids are as close to spherical as possible.

The distribution of galaxies from Broadhurst *et al.* (1990) exhibit an obviously peaked structure corrected for sampling effects in the emission-line data. For the purpose of the present analysis we use the redshift distribution shown in Figure 1 of Broadhurst *et al.* (1990) and only redshift bins with more than two galaxies are counted. This distribution is then converted to comoving proper distance. When there is more than one close lying peak, they are assigned to the same group such that the deviation from periodicity is minimized. We define the deviation from periodicity as

$$\delta \equiv \min_{\{j(i)\}} \left[(1/b) \min_{\{a,\, b\}} \left\{ \sum_{i=1}^{N} w_i [y_i - a - j(i)b]^2 \Big/ \sum_{i=1}^{N} w_i \right\}^{1/2} \right], \quad (1)$$

where b is the interval of the periodicity, a is a starting point, and $j(i)$ is the index for the group corresponding to point i. The minimization is done first with respect to a and b and then with respect to $j(i)$. For the observed data, y_i are the comoving distances to the bin centers and w_i are the weights (number of galaxies). The points are assigned to groups, $j = 1, \ldots, 13$, by first choosing $N = 13$ peaks closest to the origin and using $j(i) = i$. Then we repeatedly add the next nearest point ($N \rightarrow N + 1$) and combine the closest pair of points into a single group. This method reproduces the 13 groups with $z < 0.35$ indicated in Figure 1 of Broadhurst *et al.* (1990). From that figure we obtain $\delta = 0.17$, i.e., the deviation from periodicity is 17% of the average period. If we replace the original bins by the averaged position of each group, we obtain $\delta = 0.07$. However, this latter number is not a good measure of the regularity because some groups (especially at $z \sim 0.08$ or 0.3 [north] and $z \sim 0.05$ [south]) look much more like several sheets than one sheet at the centroid so that the periodicity is not well defined by these points. The number obtained from equation (1) better reflects this uncertainty.

For the model universes the peaks in the data are presumed to arise at the location of bubble walls. We apply the same analysis to the model structures as is applied to the observations. The pencil beam is represented by a randomly oriented line of sight through the structure. The points, y_i, are at the intersection of the line of sight with a wall of the structure. For simplicity each wall is assigned an equal weight.

Figure 1 shows the distribution of deviations from regular periodicity based upon a sampling of 10,000 or 100,000 random lines of sight from random locations in structures containing random voids, random sheets, a simple cubic cellular structure (SC), and a face-centered close-packed cubic lattice (FCC). Our determination of the standard deviation of the observed periodicity is indicated by the arrow on Figure 1. It is striking that the standard deviation of the observed distribution is close to the most likely deviation from periodicity expected from a regular cellular structure. There is a 40% probability that any random line of sight through such a structure would give a deviation from periodicity of the observed value or less.

On the other hand, that much regularity in the periodicity is quite unlikely for a random distribution of sheets or voids. For a random distribution of voids, we estimate only a 2% probability for a deviation equal to or less than the observed value. For a random distribution of sheets, the probability drops down to 5×10^{-4}. Thus, a simple test of these basic structures should be possible simply by obtaining other periodicity distributions along a line of sight at a sufficiently large angle with respect to the previous determination to avoid passing through the same walls. We estimate that an angle of $\geq \pi/4$ is sufficient for any of the structures studied. Unless the void centers are arranged in a regular structure, one should observe a significantly diminished periodicity along other directions.

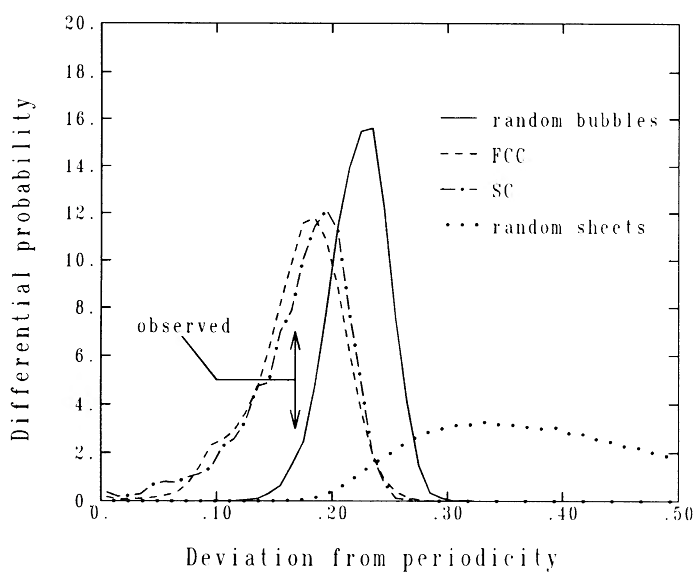

FIG. 1.—Distribution of the deviation from regular periodicity for random lines of sight from random locations within: a structure of random voids; a simple cubic lattice structure (SC); a close-packed face-centered cubic lattice (FCC); and a structure containing random sheets. The arrow indicates our value for the deviation from periodicity from the observed redshift distribution along the Galactic poles.

In the above direct comparison of computer-generated structures with the observed distribution of galaxies, we have assumed that galaxy clustering occurs along the edges of voids. Even if the galaxy distribution had an underlying regular cellular structure, there should be some dispersion in the observed galaxy distribution around the edge of the voids. In this sense, the obtained deviation of 17% should be considered an upper limit since we have neither allowed for a dispersion of galaxies around the edges of voids nor corrected for observational error. Therefore, the underlying structure is probably even more periodic than that indicated by the observed deviation of 17%. These considerations make it even less likely that a random structure could explain the observed distribution and even for a perfectly regular structure a somewhat favored direction and/or location within the structure may be required.

We note that the distributions of deviation from periodicity are narrow when analyzed in this way. This narrowness is at least partly due to using an optimum grouping of points. The different model structures always produce a certain uniformity in the distribution of points along a line of sight. By optimally grouping the points some amount of periodicity can always be found. Without this grouping the distributions would be shifted to the right and become much broader.

Given that the observations are most consistent with a regular cellular structure, it is amusing to consider Figure 2 which shows the distribution of deviations from periodicity in $\theta - \phi$ coordinates for 10^4 random lines of sight through a face-centered close-packed cubic lattice. Various values for the deviation from periodicity tend to form a regular pattern which reflects the inherent symmetries in such a close-packed structure. Although this much regularity might be unrealistic as a representation of the large-scale structure of the universe, similar patterns emerge for other cellular structures such as the simple-cubic lattice, and it is tempting to speculate that the patterns observed on Figure 2 might emerge for the true distribution of galaxies if the separation between voids is sufficiently anticorrelated to approximate such regular cellular structures.

If further surveys continue to indicate such regular periodicity, then on the basis of Figure 2 one can speculate upon an observing program to test this existence of regular cellular structure. The observed deviation of $\sim$15%–20% from regular periodicity should occur with almost equal probability along any direction of the sky. However, one might search for intervals of $\sim \pi/4$ in which the periodicity would vary from much more regular (<15% deviation from periodicity) to much worse (>20% deviation). Although the existence of such regularity seems unlikely and observation of such a variation depends to some extent upon the location of the observer within the structure, nevertheless the search for such regularity would seem to be worthwhile given the present indications from the data.

We conclude this *Letter* with several speculations as to how such regular cellular structure might arise. For one, a late time phase transition (postrecombination) could lead to the development of domain-wall structures (Hill, Fry, and Schramm

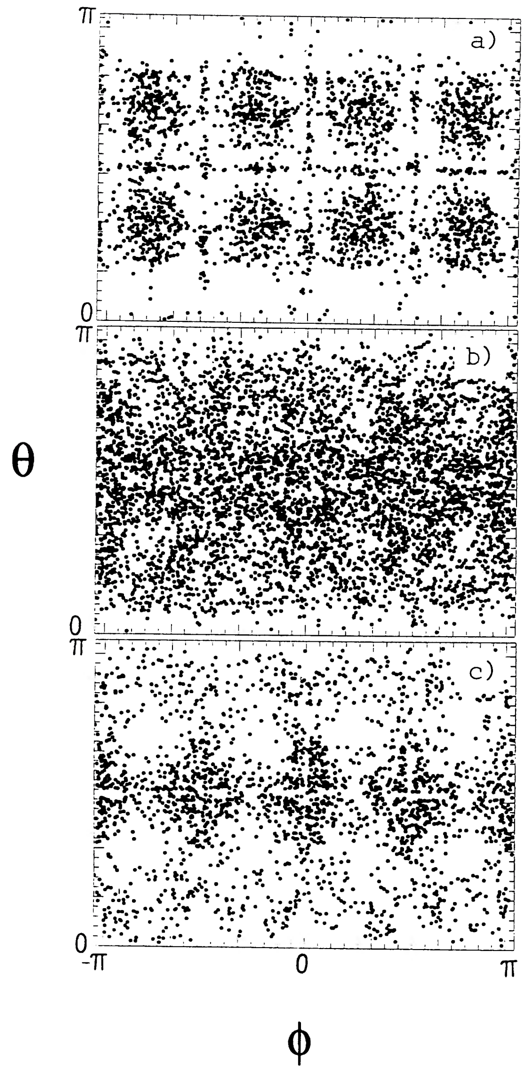

FIG. 2.—Coordinates for lines of sight which produced different deviations from periodicity from random locations in a close-packed face-centered cellular structure: (*a*) is for a deviation less than 15% of the mean separation; (*b*) is for a deviation from 15% to 20% (similar to that observed); and (*c*) is for a deviation ≥20%.

1989; Stebbins and Turner 1989; Fuller and Schramm 1990; Ozernoy 1990) with a size on the order of or less than the horizon at the time of the transition. If the developing domains exerted a pressure upon neighboring domains, they might tend to grow to an optimum cellular size. Another possibility is that of explosive events possibly associated with galaxy formation (Ostriker and Cowie 1980; Ostriker, Thompson, and Witten 1986). If the shock from one explosion induces subsequent explosions (Ostriker and McKee 1988) at an optimum separation distance, then a regular cellular structure might emerge, or even the simple merging of expanding blast waves can lead to a regular structure of larger spherical shells with blast energies equal to the sum of the collided shells (Ostriker and Strassler 1989). Yet a third possibility might be that of primordial fluctuations produced during inflation which reentered the horizon at late times. A comoving size today of $130h^{-1}$ Mpc corresponds to the horizon at a redshift of $z \sim 10^4$ and a mass of $\sim 10^{18}\ M_\odot$. This mass enters the horizon during the interesting epoch between the time at which an $\Omega = 1$ universe first becomes matter-dominated ($z \sim 3 \times 10^5$) and the epoch of recombination ($z \sim 10^3$). Although the Jeans mass and the horizon mass are equal during this epoch, at recombination the Jeans mass suddenly becomes less than the horizon and fluctuations $\sim 10^{18}\ M_\odot$ can begin to grow. We speculate that nonlinear dissipative effects (Peebles 1970; Liang 1977) may have damped fluctuations on smaller scales leaving $10^{18}\ M_\odot$ the optimum scale for the development of large-scale structure. Self-gravity might then optimize the arrangement of this structure into a regular cellular pattern (Liang 1979). However, any model to produce structure before recombination might have difficulty in explaining the observed isotropy of the cosmic background radiation.

Clearly there is a need for even a few more line-of-sight studies of the galaxy distribution at high redshift. Such studies could confirm or refute the apparent regularity in the large-scale structure of the universe and provide important clues to the early evolution of matter after the big bang.

The authors are grateful for useful discussions with E. Liang and D. N. Schramm. Work performed under the auspices of the US Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and in part under NSF grant Phy-8914379 at U.C.S.D.

REFERENCES

Bahcall, N. A., Henriksen, M. J., and Smith, T. E. 1989, *Ap. J.* (*Letters*), **346**, L45.
Broadhurst, T. J., Ellis, R. S., Koo, D. C., and Szalay, A. S. 1990, *Nature*, **343**.
Chu, Y., and Zhu, X. 1989, *Astr. Ap.*, **222**, 1.
de Lapparent, V., Geller, M., and Huchra, J. 1986, *Ap. J.* (*Letters*), **302**, L1.
Foltz, C. B., *et al.* 1989, *A.J.*, **98**, 1959.
Fuller, G. M. and Schramm, D. N. 1990, *Ap. J.*, submitted.
Hill, C., Fry, J., and Schramm, D. N. 1989, *Comm. Nucl. Part. Phys.*, **19**, 25.
Liang, E. P. T. 1977, *Ap. J.*, **216**, 206.
Liang, E. P. T. 1979, *Ap. J.*, **230**, 325.
Ostriker, J., and Cowie, L. 1980, *Ap. J.* (*Letters*), **243**, L127.
Ostriker, J. P., and McKee, C. F. 1988, *Rev. Mod. Phys.*, **60**, 1.
Ostriker, J. P., and Strassler, M. J. 1989, *Ap. J.*, **338**, 579.
Ostriker, J. P., Thompson, C., and Witten, E. 1986, *Phys. Letters*, **B180**, 231.
Ozernoy, L. 1990, *Ap. J.*, submitted.
Peebles, P. E. J. 1970, *Phys. Rev.*, **D1**, 397.
Stebbins, A., and Turner, M. S. 1989, *Ap. J.* (*Letters*), **339**, L13.

G. M. Fuller: University of California San Diego, Physics Department, La Jolla, CA 92093

H. Kurki-Suonio: L-413, University of California, Lawrence Livermore National Laboratory, Livermore, CA 94550

G. J. Mathews: L-297, University of California, Lawrence Livermore National Laboratory, Livermore, CA 94550