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A MILLION CUBIC MEGAPARSEC VOID IN BOÖTES?

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ABSTRACT

In the course of a redshift survey of galaxies brighter than $R \approx 16.3$, 133 redshifts were measured in three fields, each separated by roughly 35° from the other two. If the galaxies in these fields were distributed uniformly, the combination of a galaxian luminosity function and our magnitude limits predicts that the distribution of redshifts should peak near 15,000 km s^{-1}. In fact, only one galaxy of the 133 was observed with a redshift in the 6000 km s^{-1} interval centered on 15,000 km s^{-1}. One plausible interpretation is that a large volume in this region of order 10^6 Mpc^3 is nearly devoid of galaxies.

Subject headings: galaxies: clusters of — galaxies: redshifts

I. INTRODUCTION

It is widely observed that the universe is inhomogeneous on the scales of galaxies and clusters of galaxies, and it is widely believed that the universe is homogeneous on the largest scales (see, for example, Peebles 1980). The origin of the observed inhomogeneities is a topic of lively discussion. They may have grown from small scales to large scales through gravitational instability or descended from large scales to small through gas dynamical processes (Zeldovich 1978). In either case, our physical understanding of the origin of inhomogeneities in the universe may be advanced by empirical work on inhomogeneities at the largest observable scales.

One approach to describing the scale of galaxy clustering makes use of the spatial two-point correlation function. Peebles and collaborators (Groth and Peebles 1977; Soneira and Peebles 1978) have determined a spatial correlation function $\xi(r)$ based on the angular distribution of the galaxy counts of Shane and Wirtanen (1954). They find $\xi(r)$ has an amplitude much smaller than unity and exhibits a steepening at a separation of $\sim 10\ h^{-1}$ Mpc.[4] A similar effect has been reported for a deeper two-dimensional sample by Ellis (1980) and by Shanks *et al.* (1980) at a separation of $3\ h^{-1}$ Mpc. In contrast, a study based on redshifts, positions, and magnitudes for 166 galaxies brighter than $R \approx 14$ in eight widely separated fields (Kirshner, Oemler, and Schechter 1978, 1979) yielded a correlation function with an amplitude of order unity at a spatial separation of $25\ h^{-1}$ Mpc.

To help resolve this discrepancy, we carried out a deeper redshift survey, measuring galaxies brighter than $R \approx 16.3$ in six fields, three in the south galactic hemisphere and three in the north. The deeper sample has many more pairs of galaxies separated by $10\ h^{-1}$ Mpc or more and should provide improved statistics on the correlation function at large separations. However, the distribution of galaxy redshifts in the three northern fields is so striking that a more direct discussion seems appropriate. In this *Letter* we show that the data suggest a giant void in the northern sky with a volume of order 10^6 Mpc^3. A more detailed analysis of the entire sample will be presented elsewhere.

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[4] Here h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}.

II. DATA

The coordinates of our three northern fields, each of them 1°.4 square, are given in Table 1, along with limiting F magnitudes in Oemler's (1974) system and the number of galaxies observed. Red plates of each field taken with the Palomar 48 inch (1.3 m) Schmidt telescope were scanned on the Yale PDS microdensitometer, and total instrumental magnitudes, computed as in Kirshner, Oemler, and Schechter (1978), were obtained for all galaxies above some threshold. Later these were calibrated photoelectrically using the Kitt

TABLE 1

SURVEY FIELDS

Designation	$\alpha_{(1950)}$	$\delta_{(1950)}$	b^{II} (°)	F_{lim}	N_g	Completeness
NP 5...........	$13^h37^m.2$	+26°55′	79	16.10	58	0.87
NP 7...........	16 03.5	+41 11	48	16.65	30	0.95
NP 8...........	14 00.9	+69 45	46	16.05	45	0.88

Peak National Observatory (KPNO) 1.3 m telescope. Redshifts for galaxies brighter than the magnitude limits given in Table 1 were obtained from spectra taken at KPNO with the Intensified Image Dissector Scanner on the 2.1 m telescope, at Palomar with the Gunn-Oke SIT and the Shectman photon-counting Reticon on the 5 m Hale telescope, and at Mount Hopkins with the CFA photon-counting Reticon on the MMT spectrograph. Redshifts have been obtained for all but a small fraction of the galaxies in each field, as indicated in Table 1. A histogram of the observed redshifts, coded by field, is presented in Figure 1.

III. INTERPRETATION

In addition to the observations, Figure 1 shows the distribution of redshifts predicted using the luminosity function derived by Kirshner, Oemler, and Schechter (1979) ($\alpha = -1.10$; $M_F{}^* = -22.25$), assuming a spatially homogeneous galaxy distribution with a number density φ^* of 0.00235 Mpc^{-3}, and the apparent magnitude limits given in Table 1. The total number of galaxies observed with redshifts less than 50,000 km s^{-1} was 133; the predicted total was 99. One striking feature of Figure 1 is the paucity of galaxies with redshifts $12{,}000 < cz < 18{,}000$ km s^{-1}. This 6000 km s^{-1} gap is surprising, first, because it occurs near the maximum in the predicted redshift distribution, where our survey is most sensitive; and second, because the fields are separated from each other by roughly 35°, corresponding to a distance of 8000 km s^{-1} $H_0{}^{-1}$ or 80 h^{-1} Mpc at redshifts of 15,000 km s^{-1}. The data suggest a region nearly devoid of galaxies of comparable spatial extent both along and perpendicular to the line of sight. The volume of this region could be of order 10^6 Mpc^3.

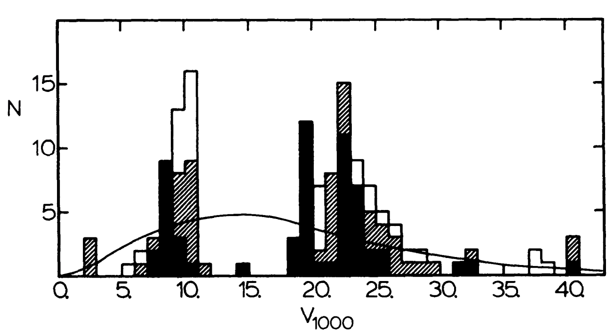

FIG. 1.—Histogram of observed redshifts in 1000 km s^{-1} intervals. The dark, light, and hatched areas show, respectively, fields NP 5, 7, and 8. The solid line shows the expected distribution of redshifts.

Almost as remarkable as the minimum in the galaxy distribution are the two large maxima located in front of it at about 9000 km s^{-1} and behind it at 21,000 km s^{-1}. The nearer of the two maxima was seen in the survey by Kirshner, Oemler, and Schechter (1979). Using galaxy counts and counts of clusters, it was demonstrated that the feature was real and extends over a significant fraction of the north galactic cap. The more distant maximum is also impressive in its extent, since it appears in fields separated by 35°, which at a redshift of 21,000 km s^{-1} corresponds to roughly 11,000 km s^{-1} or 110 h^{-1} Mpc.

a) Statistical Significance

We would like to know whether the histogram in Figure 1 is the result of a profound fact about the universe or a statistical accident. An estimate of the likelihood of observing such a gap by chance in a similar sample requires detailed knowledge of the clustering properties of galaxies. From Figure 1, we see that roughly 25 galaxies (with absolute magnitudes $M^* + 1$ and brighter) were expected in the observed gap. Were galaxies independently and randomly distributed, the probability of observing only one galaxy in the gap would have been 25 exp (-25). But since galaxies come in aggregates, the number of independent points missing from the gap is substantially smaller than 25, perhaps as small as 6. The significance of the gap is further reduced, since we have identified the redshift range of the gap after the fact. The probability of finding a gap in a distribution is surely higher if the gap is identified after the points are distributed.

b) Other Tracers

It is of considerable interest to ask whether other surveys in the same part of the sky show a dearth of objects in the same redshift range. Hoessel, Gunn, and Thuan (1980) have obtained redshifts for all Abell clusters with distance class $D \leq 4$ and richness class $R \geq 1$. None of these lies within the boundaries of our region in the redshift interval 12,000–18,000 km s^{-1}.

Shectman (unpublished) has measured approximately 50 redshifts in a region of sky surrounding the Corona Borealis Cluster (A2065) which is just south of the triangular region defined by our three fields. From the depth and completeness of his redshift sample, approximately six galaxies were expected in the velocity interval $12{,}000 \text{ km s}^{-1} < v < 18{,}000 \text{ km s}^{-1}$. None was found.

The available supporting evidence for our density minimum is slim. Because of this, we are undertaking a new redshift survey covering the entire region to confirm the reality of the feature and to survey its extent and galaxy content.

c) Comparison with Previous Observations

Several different groups of observers have identified regions that are relatively devoid of galaxies (Gregory, Thompson, and Tifft 1978; Gregory and Thompson 1978; Chincarini 1978 and references therein). Data for three of these regions, drawn from Chincarini (1978) and Tarenghi *et al.* (1980), and for the present region are given in Table 2. Also given in Table 2 are data for a region in Pisces that Einasto, Jôeveer, and Saar (1980) have found to be devoid of nearby Zwicky clusters. As is evident from the entries, the empty region suggested by the present study spans a larger volume that those previously discovered.

The volumes given in Table 2 were computed assuming a Hubble constant of 50 km s^{-1} Mpc^{-1} applies both to the universe as a whole and within the minima as well. It should be noted, however, that if the minima grew from small density perturbations (see § IV), the local values of the Hubble constant and, consequently, the true spatial depths along lines of sight through the minima might be smaller by factors as large as 3/2, if $\Omega = 1$.

IV. DISCUSSION

It is not plausible that the large vacant region we observe can be the result of peculiar velocities relative to the Hubble flow over a region where the Hubble flow itself spans 6000 km s^{-1}. As Jôeveer, Einasto, and Tago (1977) have argued, it seems much more likely that large empty regions have their origins in primordial density fluctuations.

But just as density enhancements grow as the universe evolves, density diminutions also grow. While we see just one galaxy in our gap, our data seem consistent with the hypothesis that the galaxy density in our region is no more than one-tenth of the background density of the universe. Following Gunn and Gott (1972), we can compute the amplitude required for a spherical density perturbation at recombination (taken to occur at $1 + Z = 1000$) to give a present density contrast of one-tenth. The results, presented as a function of the cosmological density parameter Ω, are shown in Table 3. Also given are the collapse times (in units of the Hubble time) of a *positive* density perturbation of the same amplitude. The rather deep density minima observed today evidently imply only modest density perturbations at recombination.

While the needed perturbations have amplitudes much less than unity, they are nonetheless large when compared with the amplitudes required to give clusters of galaxies and comparable with those that give rise to galaxies. This may be seen from the fact that a positive perturbation of the same amplitude as our postulated negative one would have a collapse time as short as the typical observed dynamical time for a *galaxy*.

If a positive density perturbation encompassing the mass of a galaxy were superposed on a more extensive negative perturbation of comparable amplitude, the collapse of the galaxy-sized perturbation would be delayed, if not completely inhibited. This suggests that such galaxies as might be found in a density minimum of the depth and extent suggested by our observations might be different from their counterparts in regions of average density.

Our method for establishing the presence of the density minimum is not entirely consistent with this argument. We have assumed that the luminosity function and mass-to-light ratio are the same everywhere and have used that assertion to infer a deep density minimum from the redshift histogram. Yet the depth of the density minimum implies that the luminosity function could be different in our region. Therefore, the fact that the number density of "typical" galaxies (with luminosities roughly equal to that of M31) is low does not compel us to believe that the mass density in the region must be equally low. It is conceivable that some mass might be present in the form of low luminosity galaxies. It should be noted that any galaxies present

TABLE 2

Summary of Data on Nearly Empty Regions

Name	$\Delta\Omega$ (sr)	Redshift Range (km s^{-1})	$B_{\rm lim}$	N_g	Approximate Vol.[a] ($\div 10^3$ Mpc^3)
Coma/A1367	0.05	5000–6200	15.0	0	15
Perseus/Pisces	0.15	1200–4000	14.0	2	25
Hercules	0.007	5500–8500	15.7	0	8.3
Pisces	~0.4	6500–10,000	...	...[b]	~770
Boötes	0.172	12,000–18,000	~17.3	1[c]	2000

[a] $H_0 = 50$ km s^{-1} Mpc^{-1}.

[b] Pisces region shows an absence of Zwicky clusters but has not been systematically searched for galaxies.

[c] N_g is the number of galaxies in the 0.0018 sr actually sampled.

TABLE 3

AMPLITUDES OF PERTURBATIONS REQUIRED TO GIVE A PRESENT DENSITY CONTRAST OF 1/10 AND ASSOCIATED COLLAPSE TIMES

Ω	$-\delta\rho/\rho$	t_c
0.999	0.0086	0.022
0.316	0.0182	0.015
0.100	0.0444	0.0083
0.032	0.116	0.0039

in the region must be several magnitudes fainter than typical galaxies, since the large void is not near the limit of our sample.

Our calculation of the density perturbation required to give a present density of one-tenth the background assumes that the mass interior to any spherical shell remains constant through time. However, for density perturbations as deep as those indicated in Table 3, the different decelerations felt by successive shells outside the perturbation may be so large that inner shells overtake outer shells. For step-function density profiles at recombination of the depths indicated in Table 3, this does in fact happen, with the edge of the perturbation overtaking shells which start as much as a factor of 1.4 further from the center of the perturbation. Including the effects of shell crossing should not change our conclusion that perturbations large enough to produce the observed minimum are large enough to alter galaxy formation.

It is instructive to consider the effect that large-scale density inhomogeneities could have on the Hubble flow. Even if the minimum in galaxy density that we see corresponds to a minimum in the mass density, the large intervening region moderates the influence of the empty region. A spherical shell centered on the minimum and passing through our position would have a mean interior density of roughly $(1 - x^3)$ times the mean density, where x is the ratio of the radius of the density minimum to the radius of the shell. The Hubble constant associated with that shell would likewise be close to the average value; in general, we expect little peculiar velocity away from the void. Taking x to be 0.2 for the present case, we expect deviations in the Hubble flow at the Milky Way of, at most, 1 part in 100, or 150 km s^{-1}.

While we have concentrated on the apparent density minimum in Figure 1, the apparent maxima also deserve comment. Although their present spatial extent is roughly equal to that of the minimum, the larger mass indicates fluctuations on a larger scale than the progenitor of the minimum. Its amplitude, however, need not have been as large.

In conclusion, we believe this redshift survey suggests that the distribution of galaxies may contain features at the scale of 50–100 h^{-1} Mpc. We note that this is a few percent of the horizon size at the present epoch —large enough to be interesting but not so large as to undermine confidence in the cosmological principle. Of course a deeper survey would be needed to establish the presence of still larger structures. Our present intention is to conduct a more extensive investigation of galaxy redshifts and galaxy properties in the vicinity of the 10^6 Mpc^3 void in Boötes.

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