THE ASTROPHYSICAL JOURNAL, 335:542–551, 1988 December 15

A $40h^{-1}$ Mpc DIAMETER VOID IN PISCES-CETUS[1]

JACK O. BURNS AND J. WARD MOODY
Institute for Astrophysics, Department of Physics and Astronomy, The University of New Mexico
JEAN P. BRODIE
Lick Observatory, University of California at Santa Cruz
AND
DAVID J. BATUSKI
Space Telescope Science Institute
Received 1988 January 8; accepted 1988 May 27

ABSTRACT

Evidence is presented for the existence of a large region of space in Pisces-Cetus that is empty of galaxies and clusters of galaxies. The data base consists of rich clusters from the Abell catalog, galaxies from the CfA survey, and new galaxy redshift data collected at Lick Observatory. The volume of this roughly spherical, $40h^{-1}$ Mpc diameter void is comparable to the largest empty region (free of emission-line galaxies) in the recently completed study of the Bootes void. We argue that the observed distributions of galaxies and clusters within the Pisces-Cetus void region are unlike that expected for a uniform distribution taking into consideration observational sampling. We also compare the properties of the Pisces-Cetus void with the results of recent numerical simulations of large-scale structures within hot and cold dark matter scenarios and explosion models.

Subject headings: cosmology— galaxies: clustering

I. INTRODUCTION

Recent redshift surveys have uncovered vast volumes that are seemingly devoid of galaxies (see, e.g., Oort 1983; Gregory *et al.* 1989 for reviews). A supercluster filament or shell often appears to define a boundary of a void in regions such as Coma-A1367 (see, e.g., Gregory and Thompson 1978), Perseus (Gregory, Thompson, and Tifft 1981), and Hercules (Tarenghi *et al.* 1979). The geometry of voids is uncertain, however. In some cases it has been claimed that voids are spherical in shape (i.e., soap bubbles) with dense shells of galaxies defining the boundaries (e.g., de Lapparant, Geller, and Huchra 1986). In other cases, it has been suggested that voids are not isolated, closed structures but, instead, interconnect in a complex network (Gregory, Tifft, and Moody 1988).

There are now known to be more than half a dozen voids with diameters exceeding $15h^{-1}$ Mpc (where $h = H_0/100$ km s^{-1} Mpc^{-1}). Of these volumes, four have been studied in relative detail. The largest known galaxy void is in Bootes with an apparent volume of 10^6 Mpc^3 (Kirshner *et al.* 1981, 1987). However, the entire volume is not empty of galaxies. Recent observations have revealed the presence of at least eight emission-line galaxies of relatively high surface brightness distributed throughout the volume (Moody *et al.* 1987). A smaller, but by far the most thoroughly studied void to date, is in the foreground of the Coma-A1367 supercluster (Gregory *et al.* 1988). This $15h^{-1}$ Mpc diameter void appears to be completely empty of all galaxies with luminosities down to 4 mag below M^* (i.e., M^* is the break luminosity in the Schechter [1976] luminosity function). In the general region centered on Coma, de Lapparent *et al.* have reported the presence of several 30–40 Mpc diameter voids that they describe as "bubbles" (i.e., surrounded by a spherical shell distribution of galaxies). These voids, although significantly underdense in comparison to the average in the nearby regions, contain a few normal (i.e., non-emission line) galaxies within their boundaries. Finally, H I observations of spiral-type galaxies in Pisces-Perseus have uncovered a small, $\approx 15h^{-1}$ Mpc void that is remarkably free of galaxies down to a magnitude well below M^* (Haynes *et al.* 1988; Haynes 1987).

Cosmic voids, more so than supercluster structures, may hold the key to differentiating between models of the formation of large-scale structures (e.g., Melott 1987). However, observations of voids are still lacking in depth and degree and, therefore, do not yet provide adequate tests of theoretical models. Fundamental observational questions remain. These include:

1. What is the size distribution of voids? Is there an upper limit?
2. Why do some voids contain (peculiar?) galaxies and others do not? Is there a relationship between void size and the presence of galaxies?
3. Are voids really bubbles surrounded by galaxies or do voids interconnect in a spongelike topology?

At present, there are too few well-studied galaxy voids to address these questions.

In this paper, we present evidence for the existence of another relatively nearby, large void in Pisces-Cetus. This void was discovered using a technique quite different from the magnitude-limited redshift survey method which (accidentally) uncovered the voids discussed above. This technique employs rich clusters of galaxies as tracers of large-scale structure (Batuski and Burns 1985*a*; Burns and Batuski 1987; Burns, Moody, and Batuski 1987). We have found that Abell (1958) clusters can be quite accurate markers of supercluster structures. For example, a collection of 23 rich clusters surround the heart of the Bootes void, nicely defining the centroid (Bahcall and Soneira 1982; Burns, Moody, and Batuski 1987). The absence of rich clusters was also used by Batuski and Burns (1985*a*) to mark the locations of 29 candidate voids with $z < 0.1$ and radii $> 40h^{-1}$ Mpc.

[1] Based in part on observations made at Lick Observatory.

Near the center of one of the densest superclusters composed of Abell clusters in Pisces-Cetus, we find a ring of eight clusters surrounding an apparent $40h^{-1}$ Mpc diameter void. We use galaxy redshift observations from a recent edition of the CfA catalog and new observations made at the Lick Observatory to verify that a strip across the void center is empty of bright galaxies as well as clusters. The success of our method for locating a void in Pisces-Cetus leads us to conclude that it can be expanded to find more voids in a systematic fashion. Eventually, we may be able to answer the questions posed above.

In § II of this paper, we present the cluster and galaxy observational data. We report on new redshift observations of 45 Zwicky *et al.* (1961–1968) galaxies in the direction of the void made with the 40 (1 m) and 120 inch (3 m) telescopes at the Lick Observatory. In § III, the observational significance of the void is described by comparing the observed distribution of galaxies and clusters with that expected by constrained Poisson statistics. In § IV, the size and density of the void are compared with the results of recent numerical simulations of large-scale structure. A summary and conclusions are presented in § V.

II. DEFINITION OF A VOID IN PISCES-CETUS

From percolation studies of the Abell cluster catalog, Batuski and Burns (1985*b*) reported on the presence of a significantly overdense collection of rich clusters in Pisces-Cetus. This supercluster is composed of 36 clusters with richness classes $R \geq 0$. It spans a redshift range from 0.03 to 0.08. The density of clusters in this volume is 5 times greater than the average density of Abell clusters, making the Pisces-Cetus supercluster one of the densest and most interesting superclusters in the Batuski-Burns catalog. Within this general region, Batuski and Burns also found a remarkable filament of rich and poor clusters that extends from the nearby Perseus supercluster to A2675 in Pegasus. This filament is $230h^{-1}$ Mpc in length surrounded on several sides by voids with diameters of about $75h^{-1}$ Mpc.

We have examined the dense heart of the Pisces-Cetus supercluster in detail using both the distributions of rich clusters (from the compilation of redshifts by Struble and Rood 1987) and galaxies. Interesting, potential large-scale structure in this region was first noted by Einasto, Joeveer, and Saar (1980) and more recently by Tully (1987). The northern-most extent of the supercluster is shown in Figure 1.

The galaxies in Figure 1 are drawn from the Zwicky *et al.* catalog. The measured redshifts of the galaxies are from 6950 km s^{-1} to 14,025 km s^{-1}. Most of the redshifts are taken from a recent edition of the CfA catalog (epoch 1986.5 kindly provided by J. Huchra). In addition, we have also included a first installment of new redshifts for 45 galaxies gathered from observations with 40 and 120-inch telescopes at the Lick Observatory during the summer/fall of 1986 (see also Brodie *et al.* 1987). This installment of the Lick survey covers a relatively narrow region of the sky between $6\overset{\circ}{.}5 < \delta < 15\overset{\circ}{.}5$ and $1^h28^m < \alpha < 2^h40^m$, positioned near the center of the ring of Abell clusters in Figure 1. The northern two-thirds of this region is 95% complete to Zwicky magnitude 15.7, whereas the southern one-third is 65% complete to this limiting magnitude. Observations of this and the surrounding area are continuing. In the case of absorption-line spectra, redshifts were obtained by cross-correlation with high signal-to-noise template spectra (primarily M31 and M32). In the case of galaxies with emission-line spectra, we measured the positions of the Hα + [N II] lines by fitting them to a blend of Gaussian line profiles. Velocities were determined to an accuracy of 50 km s^{-1}. The positions and redshifts of the 45 galaxies observed at Lick are listed in Table 1. These velocities, as well as those from the CfA catalog, were corrected for motion about the galaxy center according to $\Delta v = 300 \sin(l) \cos(b)$ km s^{-1}.

Ten Abell clusters with richness classes $R \geq 0$ form a pro-

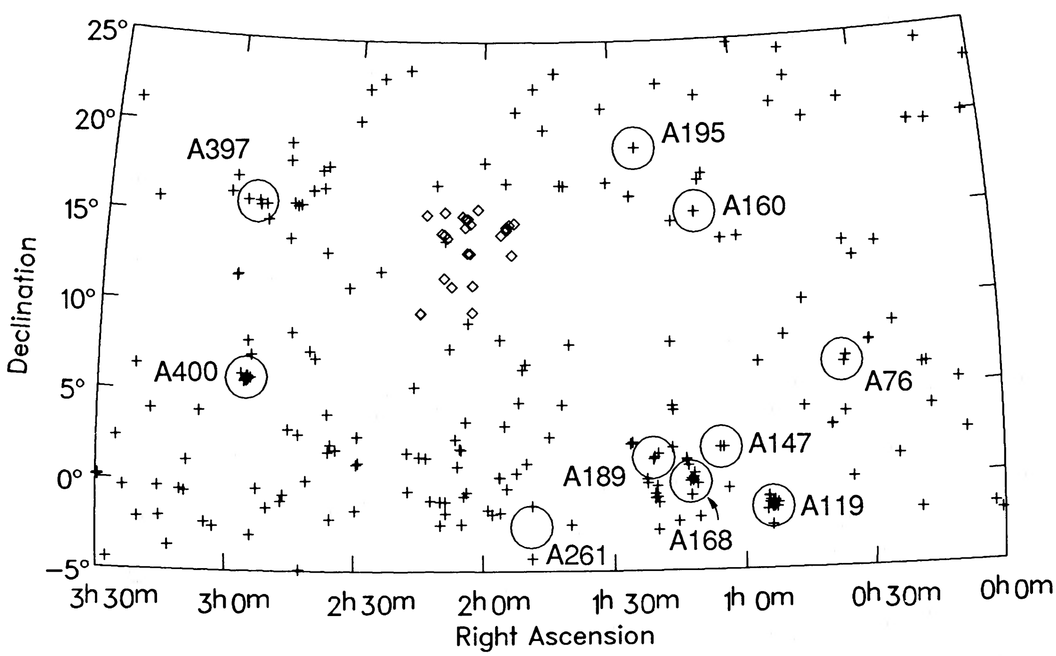

FIG. 1.—Equal-area sky projection of Abell clusters (*circles*), CfA catalog galaxies (*crosses*), and Lick survey galaxies (*rotated squares*) in the Pisces-Cetus region. Only clusters and galaxies with 6950 km s^{-1} < *cz* < 14025 km s^{-1} are displayed. Note the "hole" in the center of the plot.

TABLE 1

NEW REDSHIFTS OF ZWICKY GALAXIES IN THE DIRECTION OF THE PISCES-CETUS VOID

α^a	δ^a	cz^b
1.86	13.28	6185.
1.87	13.23	6419.
1.88	14.70	13373.
1.89	10.55	6185.
1.89	12.92	7824.
1.90	14.77	4818.
1.90	14.63	13310.
1.91	14.50	7878.
1.91	11.28	3608.
1.91	14.32	8029.
1.93	14.05	7994.
1.97	14.93	4721.
1.99	9.72	4883.
1.99	9.73	4664.
2.02	15.50	8123.
2.02	15.07	3730.
2.04	11.18	7922.
2.04	9.68	7845.
2.05	13.00	7860.
2.05	14.68	12672.
2.06	13.03	7406.
2.06	14.97	12859.
2.07	14.98	13064.
2.07	14.98	12421.
2.07	14.48	10444.
2.08	15.12	12945.
2.12	10.73	4731.
2.12	11.12	11095.
2.12	10.53	6877.
2.14	13.88	7770.
2.15	14.07	8170.
2.15	11.60	13531.
2.15	14.07	7807.
2.15	15.35	7924.
2.16	14.13	7991.
2.21	13.63	6608.
2.22	15.17	7005.
2.24	9.58	8245.
2.24	10.03	18771.
2.24	9.63	8456.
2.25	12.28	3745.
2.25	12.25	3742.
2.26	12.97	3718.
2.27	14.93	3862.
2.27	15.03	3924.

[a] Right ascension and declination in decimal hours and degrees, respectively, for epoch 1950.

[b] Redshift in units of km s^{-1} corrected for galactocentric motion.

jected ring on the sky. Two of the southern clusters, A189 and A400, are closest to us and the remaining clusters have a gradient in distances with A168 and A261 being farthest away. The galaxies within this redshift interval generally follow the pattern formed by the rich clusters. The galaxies and clusters encircle a region of space that is underdense with respect to the borders. It is this central, underdense volume that we refer to as the Pisces-Cetus void. For completeness sake, we also note that the Perseus supercluster lies to the north of the region shown in Figure 1 and is considerably closer.

In Figure 2, a velocity wedge diagram illustrates the distribution of galaxies and clusters in the region of the Pisces-Cetus void. A strip that is 22° wide in declination is plotted in cz versus right ascension. Once again, a void of both rich clusters and galaxies is prominently seen in this plot. A ring of eight clusters partially encircles a void that is about $40h^{-1}$ Mpc ($\Delta cz \approx 4000$ km s^{-1}) in diameter. A band of galaxies completes the ring on the eastern edge. The void is centered at R.A. = $1^h.5$, decl. = 12°, and cz = 11,500 km s^{-1}.

A more complete view of the void is presented in Figure 3 where three wedge diagrams in 10° declination strips span the entire region shown in Figure 1. The void is most visible in the wedge diagrams centered at Decl. = 0° and 10°. The void begins to close between 10° < decl. < 20° (i.e., a more uniform sheet of galaxies and clusters appears to form the northern border of the void in Fig. 3*a*). Since the current galaxy data base does not extend below decl. < −5° (limit of Zwicky *et al.*, 1961–1968, is −3°), it is impossible for us to determine how far south the void really extends and whether or not it actually closes on the southern end. Our best estimate with the present data is that the void is at least $40h^{-1}$ Mpc long in the north-south direction, comparable to the dimensions in the east-west direction and along the line of sight. Present limits on this galaxy void suggest that its volume is comparable to that of Bootes and the other largest known totally empty regions within the nearby portions of the universe (see recent paper by Moody *et al.* [1987] that discusses the distribution of emission-line galaxies within the Bootes "void").

In addition to the large void, there is also substantial structure in the distribution of galaxies in the foreground. In all three figures, a very prominent bridge of galaxies appears to connect A400 to A194. A similar bridge between A194 and A189 is seen to lie nearly along the line of sight in Figures 2 and 3. The line of galaxies between A194 and A189 is about $40h^{-1}$ Mpc in length. In addition, the small void centered at R.A. = $0^h.5$ and cz = 3500 km s^{-1} is part of the void noted recently by Haynes *et al.* (1988) in their H I study of the Pisces-Perseus region. There is also a large underdense region to the west of the A194/A189 line centered at cz = 8500 km s^{-1}. The visual impression from this wedge diagram is one of a highly structured, nonrandom distribution of galaxies and clusters. We will attempt to quantify this impression in the next section.

III. GALAXY AND CLUSTER STATISTICS IN THE VOID REGION

Because of the still small and incomplete statistics, we must categorize the Pisces-Cetus region as only a "candidate" void in a fashion analogous to Kirshner *et al.*'s (1981) first suggestion of a galaxy void in Bootes. However, we will argue in this section from analyses of the distributions of both clusters and galaxies that the Pisces-Cetus void is a good candidate. We suggest that the region differs from that expected for a uniform distribution. Each piece of evidence described in the previous section and in what follows is not individually proof-positive, but taken together makes a strong circumstantial case that the volume contains nonrandom structure.

First, we consider the clusters. Otto *et al.* (1986) and Politzer and Preskill (1986) concluded from their analyses of $R \geq 1$, $D \leq 4$ Abell cluster sample that there are no statistically significant voids of rich clusters. This is in spite of the firm observational evidence demonstrating that at least one prominent void of both galaxies and clusters exists in Bootes (Kirshner *et al.* 1987; Burns, Moody, and Batuski 1987).

The statistics of voids in the distribution of rich clusters are of limited usefulness because of the small numbers (≈ 100 clusters in the complete samples used by Otto *et al.* and Politzer and Preskill). In addition, the statistical techniques used to examine underdense regions are not as robust as those that

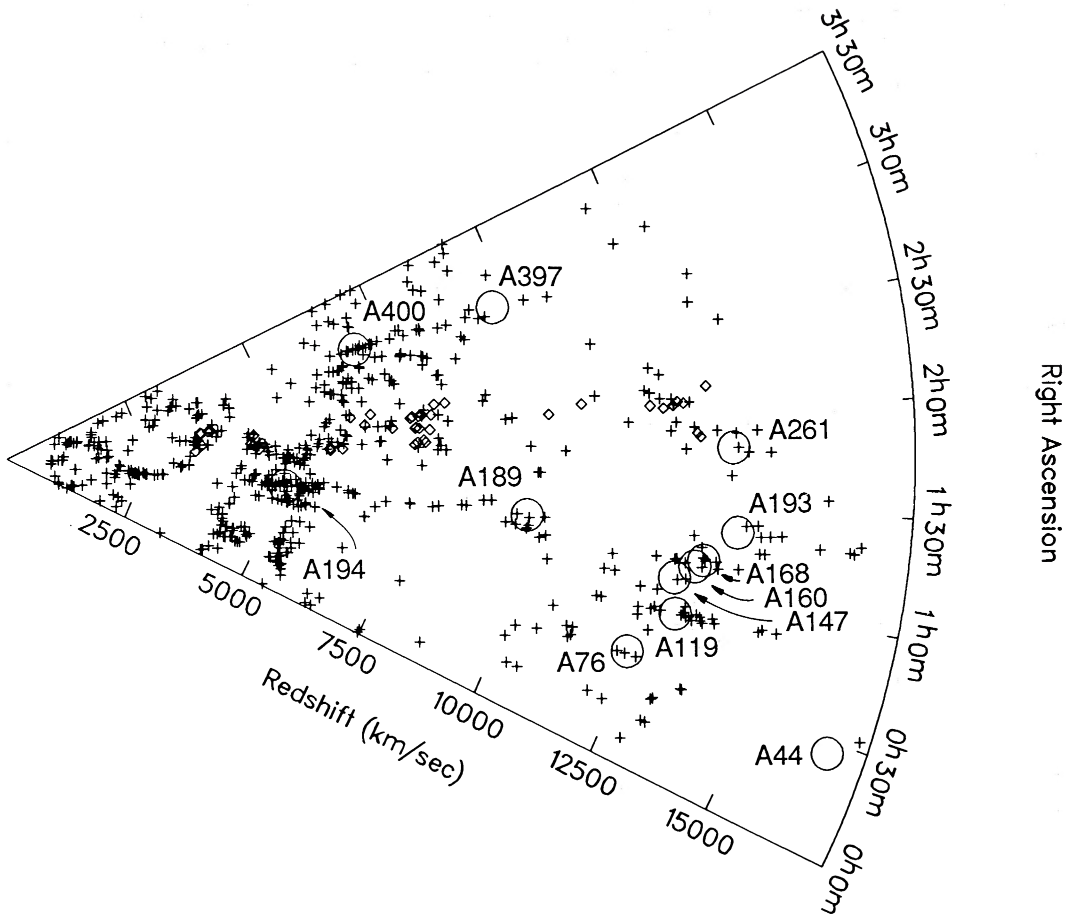

FIG. 2.—Wedge-plot of redshift (cz) right-ascension. Symbols are the same as in Fig. 1. The wedge is a 22° wide strip projected in declination onto a plane centered on $\delta = 5°$. The Pisces-Cetus void is centered at $\alpha = 1^{h}.5$ and $cz = 11{,}500$ km s^{-1}.

describe overdense regions. However, voids are generally surrounded by an enhancement of clusters and galaxies, thus giving the voids definition. For Pisces-Cetus, there is a concentration of rich clusters on the most distant periphery of the void (Fig. 2). In what follows, we examine the probability that this concentration is not a chance coincidence. Although this calculation cannot be directly used to comment on the statistical significance of this void, it is clearly related since it describes how nonrandom the distribution of clusters really is in this region.

There is an arc of seven clusters stretching from A261 to A76 with a linear dimension of $\approx 50h^{-1}$ Mpc. For simplicity's sake, let us consider a spherical volume of this diameter centered on A160. Recently, Batuski *et al.* (1988) have constructed a sample of 225 Abell clusters with $R \geq 0$ and $z < 0.075$. They judge this sample to be complete at high galactic latitudes ($|b| > 30°$), where the density of clusters remains constant out to $z = 0.075$ with an average value of $n \approx 2 \times 10^{-5}h^3$ clusters Mpc^{-3}. Using this density, one would expect to find about 1.2 Abell clusters within this volume if they are distributed uniformly, whereas there are actually seven. The probability of finding k clusters in a region of volume V in a homogeneous universe with average density n is given by the Poisson formula

$$P_k[V] = (nV)^k/k!\, e^{-nv} . \qquad (1)$$

For Pisces-Cetus, $k = 7$, $nV = 1.2$, and $P_7 = 2.7 \times 10^{-4}$. Since there are 23 such volumes within the initial region of our search (within an $\approx 150h^{-1}$ Mpc diameter sphere), the probability of finding such a cluster concentration within this volume is roughly $23 \times P_7$ or 0.6%.

The above calculation assumes that the clusters are uncorrelated. If this were true, then the seven clusters would be statistically independent of one another. However, the observed two-point spatial correlation for rich clusters (e.g., Bahcall and Soneira 1983) indicates that there is some finite probability that clusters will appear in pairs and thus may not be independent samples. We have attempted to determine the magnitude of the effect using the observed cluster-cluster correlation function, $\xi_{cc}(r)$. The number of clusters that one would expect to find in a sphere of radius $R_s = 25h^{-1}$ Mpc if one centers the sphere on a known cluster is roughly

$$N_{cc} = \int_0^{R_s} n[1 + \xi_{cc}(r)]4\pi r^2\, dr . \qquad (2)$$

The first term in equation (2) is the number expected for a uniform distribution (1.2) and the second term is the enhancement caused by the cluster-cluster correlations. For the cluster sample defined by Batuski *et al.* (1988), $\xi_{cc}(r) = 200r^{-1.8}$ and $N_{cc} = 2.8$. Therefore, the probability of finding seven clusters in this volume when 2.8 are expected is found by substituting $nV = 2.8$ in equation (1) and correcting for the volume effect,

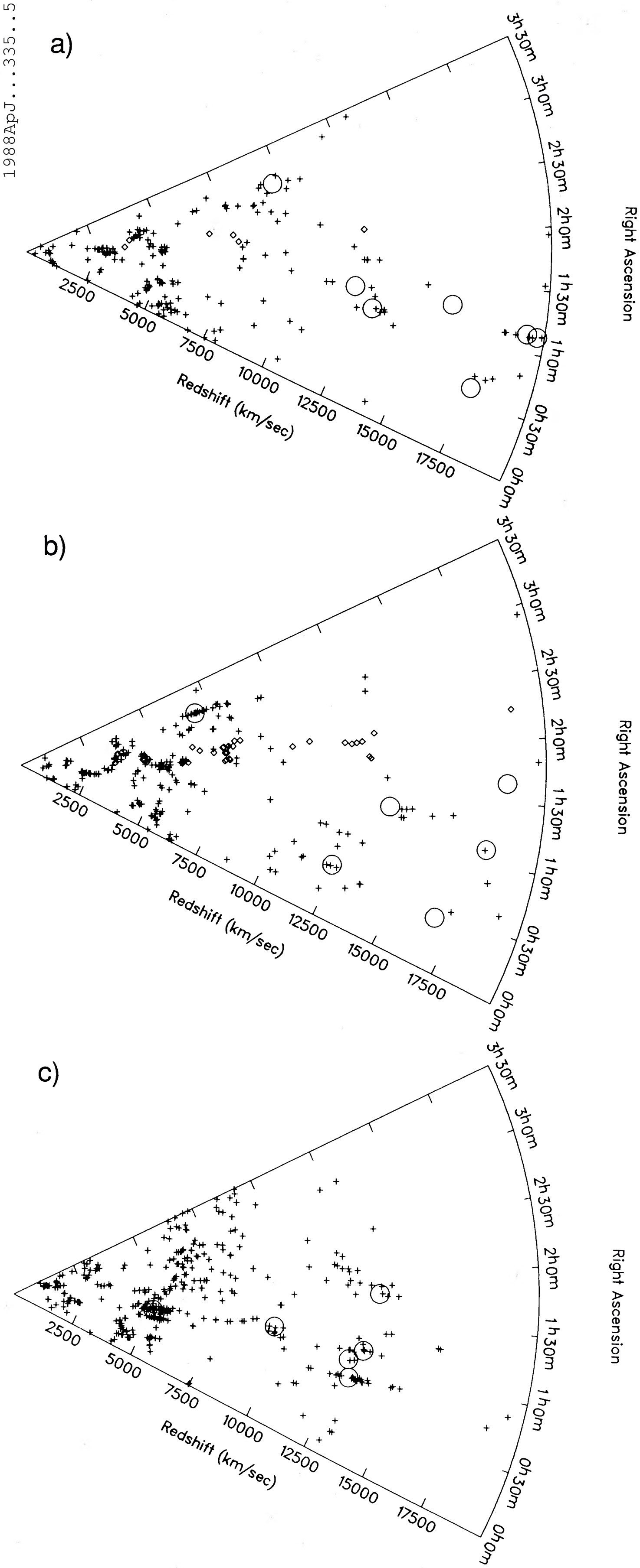

FIG. 3.—Wedge-plots as in Fig. 2. Each wedge is a 10° wide strip in declination. (*a*) is centered on $\delta = 20°$, (*b*) is centered on $\delta = 10°$, and (*c*) is centered on $\delta = 0°$. Note the sheet of galaxies and clusters that forms the northern boundary of the void in (*a*).

i.e., 1.6%. We emphasize that this calculation is not definitive, but it serves to illustrate that the distribution of clusters in this region is probably nonuniform.

Next, we consider the distribution of galaxies seen in Figure 2. Since the Lick galaxies cover only a narrow strip of sky, but to a relatively deeper limiting magnitude, we have excluded them in the following analysis of the CfA galaxy distribution. The CfA catalog is complete to $m_B = 14.5$ but also includes galaxies as faint as 17.1 in this area. Figure 4 shows the integrated count of galaxies in this region $N(>m)$, the cumulative number of galaxies with apparent magnitudes less then m. These data can easily be compared to the distribution expected for a complete, uniform sample—the straight line in Figure 4 (see, e.g., Mihalas and Binney 1981). The slope of the galaxy distribution is clearly steeper than a uniform distribution, a result of the density enhancement at $cz = 5500$ km s^{-1} seen in Figure 2.

The sampling of fainter galaxies is relatively uniform across the volume. We divided the sample into sections and examined the surface density of galaxies in each section. The surface density of fainter galaxies is relatively constant from 0^h to $2^h.5$ across the heart of the void with no evidence of strong concentrations of observed galaxies toward Abell clusters. There is, however, a decrease in sampled galaxy density beyond $2^h.5$. About 80% of the galaxies in this volume (0^h–$2^h.5$) are from general redshift surveys, the vast majority of which are from various extensions of the CfA catalog (J. Huchra, private communication). Therefore, although the sample of galaxies in this volume is not complete down to 17.1 mag, we do believe that it is representative of the general galaxy distribution.

Turning now to the void itself, we ask what is the likelihood of finding a $40h^{-1}$ Mpc empty spherical volume appearing by chance within a distribution of galaxies surveyed as described above? To address this question, we have generated 100 comparison samples with distributions of randomly placed galaxies in a homogeneous universe. These samples follow a Schechter (1976) luminosity function of the form

$$\Delta N(L) = (N_0/L^*)(L/L^*)^{\alpha} e^{-L/L^*} \quad (3)$$

with $\alpha = 1.34$ and $M^* = -19.2$, the parameters found from the CfA survey (Burg 1987). Each sample has the same number of galaxies following the same magnitude distribution as Figure 4. This analysis is a two-dimensional analog of the standard histogram comparison of number versus redshift for observed samples and that predicted by the Schechter luminosity function (see, e.g., de Lapparent, Geller, and Huchra 1986; Kirshner *et al.*, 1987). In this case, we also attempt to correct for observational selection effects using the integrated galaxy counts. Three of the typical comparison samples are shown in Figure 5. Comparing Figures 2 and 5, we see that there is far less coherent structure in the comparison samples and very few large voids. These comparison samples show that the densities on the back side and edges of the Pisces-Cetus void are at least a factor of 4 above that expected for a random distribution. Also, in no cases do we find a void of $40h^{-1}$ Mpc diameter as shown in the size distribution histogram of comparison sample voids in Figure 6.

On average, the comparison samples suggest that there should be $N \approx 20$ galaxies within a void of $40h^{-1}$ Mpc diameter at the distance of Pisces-Cetus. Following the technique described by Politzer and Preskill (1986), the probability of such a void being found in a homogeneous volume is

$$P_0 = e^{-N}(V/v)N^3 = 3.8 \times 10^{-4} , \quad (4)$$

where $V/v = 23$ is the ratio of search-to-void volumes. Once again, the 20 galaxies are not independent samples since there are galaxy-galaxy correlations. The fraction of our sample that

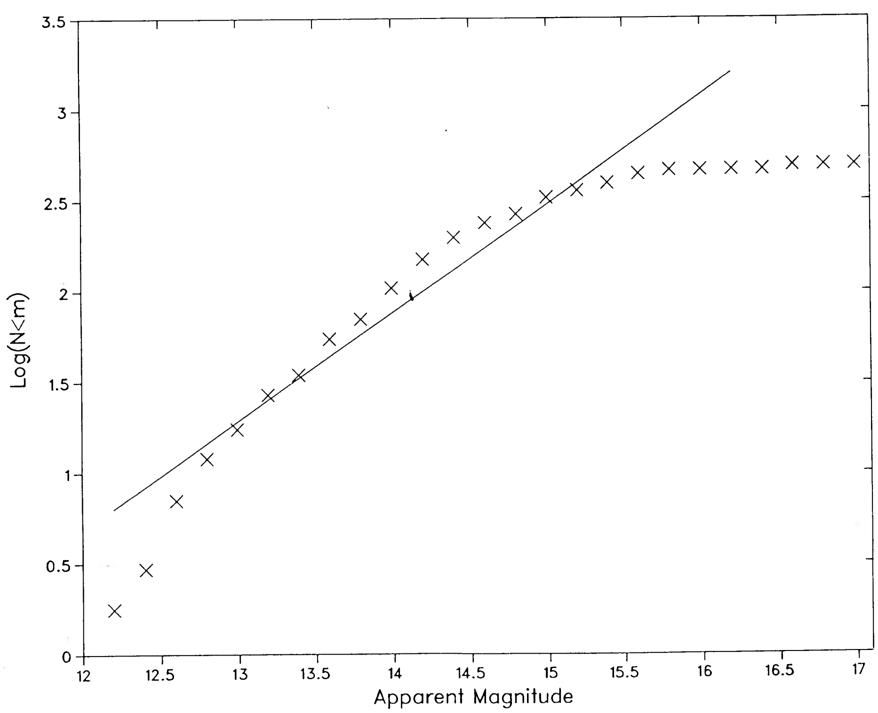

FIG. 4.—Integrated galaxy count as a function of apparent (B) magnitude for the region shown in Fig. 2. X's are the data and the line is that expected for a uniform distribution of galaxies.

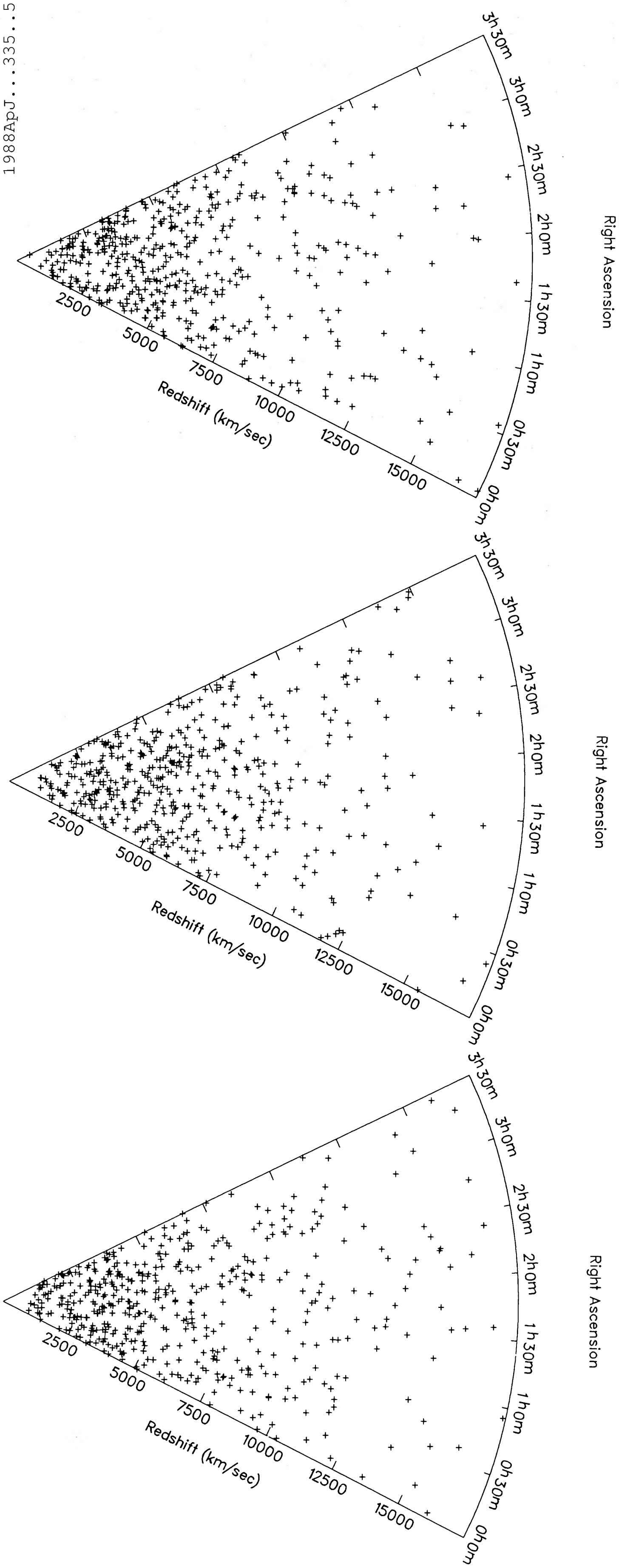

FIG. 5.—Wedge-plots, with the same dimensions as in Fig. 2, for three of 100 models with a uniform distribution of galaxies constrained by the integrated galaxy count in Fig. 4 and the Schechter (1976) luminosity function in (4). There is considerably less structure in these redshift slices than that seen in Fig. 2.

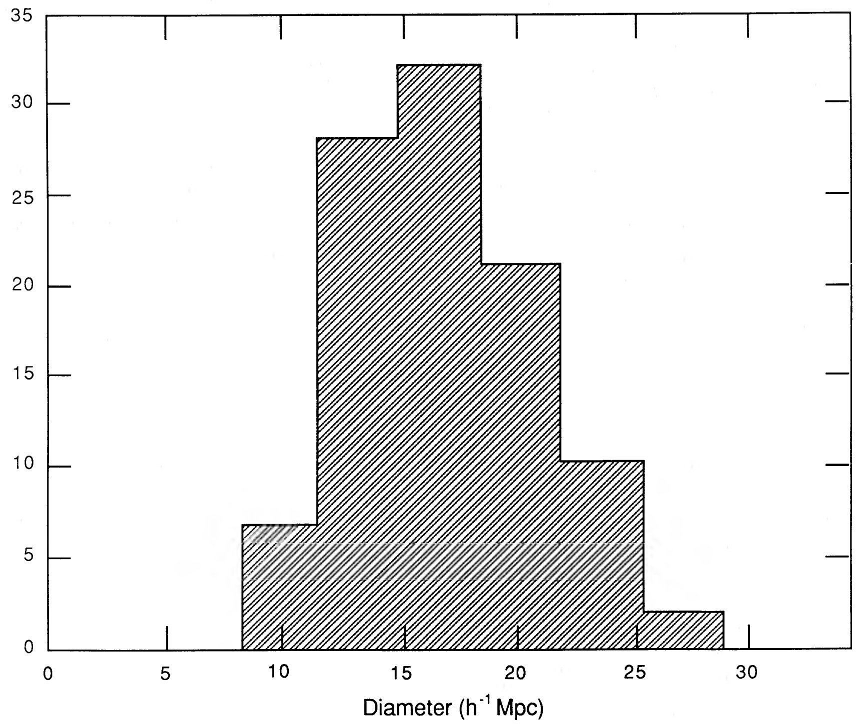

FIG. 6.—The distribution of void sizes seen in the 100 uniform galaxy simulations discussed in the text and in Fig. 5

is not independent is given approximately by

$$f = \frac{\int_0^{R_0} \xi_{gg}(r) r^2\, dr}{\int_0^{R_0} [1 + \xi_{gg}(r)] r^2\, dr} . \tag{5}$$

For $\xi_{gg}(r) = 25r^{-1.8}$ (Peebles 1980) and $R_0 = 20h^{-1}$ Mpc, $f \approx 25\%$. Therefore, the number of independent samples is $N = 15$. Substituting this value into equation (4), the probability of finding no galaxies in a sphere of diameter $40h^{-1}$ Mpc when 15 are expected is about 2.4%.

The above statistical arguments are ultimately limited by the small number statistics of the Abell catalog, the incomplete sampling of galaxies in the current data base, and the *a posteriori* nature of the analysis. These calculations would seem to suggest that the observed distributions of galaxies and clusters of galaxies in Figure 2 depart from that expected for a homogeneous universe. The foreground region is overdense in galaxies, whereas the void is deficient in galaxies in comparison to a uniform sample. However, a more rigorous test of the reality of this void must await the completion of a significantly deeper, statistically complete galaxy redshift survey of this region.

IV. COMPARISONS WITH THEORETICAL MODELS

The size and emptiness of the Pisces-Cetus void can be used to constrain current theoretical models of the formation of large-scale structures. Recently, White *et al.* (1987), Melott (1987), and Saarinen, Dekel, and Carr (1987) have used numerical N-body simulations to examine the distribution of voids and clusters in large volumes. We use the results of these simulations to further analyze the Pisces-Cetus void.

Gaussian adiabatic density fluctuation models generally use dark matter composed of either neutrinos (hot dark matter, HDM) or cold particles (cold dark matter, CDM). In Melott's (1987) 64^3 particle simulations with biased selection of "galaxies" above a density threshold (e.g., Kaiser 1984), the maximum diameter of voids is $1100h^{-1}$ km s^{-1} in CDM models and $2300h^{-1}$ km s^{-1} in HDM models. These are 3 σ limits meaning that there is a 99.7% probability that voids are smaller than these diameters. White *et al.* (1986) find voids that are $\approx 45\%$ larger in their biased CDM models (Melott suggests that the discrepancy in the CDM models arises from the smaller number of particles used by White *et al.*, which results in an overestimate of void sizes). Thus, HDM models with a Hubble parameter somewhat greater than 50 km s^{-1} Mpc^{-1} can reproduce a very low density void having a size comparable to Pisces-Cetus (4000 km s^{-1}). However, Melott's biased CDM models cannot produce very large voids unless H_0 is < 50 km s^{-1} Mpc^{-1}.

It is also important to note that the density contrast between void and void boundaries/filaments is different in the CDM and HDM models. Melott's simulations indicate that CDM voids do possess a low-density threshold of matter which still appears even when galaxy biasing is introduced (albeit at a reduced level). As a result, the size of the voids in CDM models varies with the biasing threshold. From an observational point of view, these models predict that CDM voids should get smaller as one observes to fainter limiting magnitudes. HDM models, on the other hand, have voids that are virtually empty of particles. Melott finds that HDM void size is not a function of bias level. Thus, it is important to observe the Pisces-Cetus void down to lower magnitudes in an effort to differentiate between the two dark matter models.

Finally, it has been suggested that large-scale structure could have been produced by explosive energy released from a first generation of very massive stars as an alternative to primordial density fluctuations (e.g., Ostriker and Cowie 1981; Vishniac, Ostriker, and Bertschinger 1985). Shocks produced by such early very energetic supernovae are believed to form dense expanding shells as they sweep up background matter. The shells are presumed to intersect and fragment, eventually producing filaments of luminous matter and voids with a bubble-like topology. Recently, Saarinen *et al.* performed N-body simulations of the shell-shell interactions to determine the scale sizes of structure that could emerge from such an explosion model. They find that the largest voids that can be produced are less than $30h^{-1}$ Mpc in diameter. Although this model may be consistent with the data on the smaller voids described in § I, it has difficulty producing the large voids like those in Pisces-Cetus and Bootes. A similar conclusion with regard to very large structures was drawn by Peebles (1986). Saarinen *et al.* do suggest that their results should be viewed with some caution, however, because their void statistic may be a strong function of galaxy number density and subject to other edge effects.

V. SUMMARY AND CONCLUSIONS

In this paper, we have presented evidence for the existence of a void in the Pisces-Cetus region. The void is nearly surrounded by a shell of galaxies and eight rich clusters with a diameter of about 4000 km s^{-1} (roughly $40h^{-1}$ Mpc). It is comparable in size to the largest known true void volume within Bootes. The void is enclosed on at least three sides, but current data do not allow us to determine if the region has a bubble-like topology or spongelike (i.e., interconnected voids) topology.

The distribution of clusters and voids in the Pisces-Cetus region appears to differ from that expected from a homogeneous universe. Our illustrative calculation suggests that the probability of finding the seven observed clusters concentrated in a ridge at the edge of the void arising from a randomly distributed parent population is 1.6%. Similarly, from comparison samples of randomly distributed galaxies, we estimate that about 20 galaxies should appear in the void. The two-point galaxy correlation function suggests that 15 of these galaxies are independent samples. The probability that a homogeneous universe will produce such an empty volume is about 2.4%. However, because of the incomplete sampling of galaxies in this region, these statistics should be treated with caution.

Recent numerical simulations of the evolution of adiabatic density fluctuations modulated by hot or cold dark matter were compared with the characteristics of the Pisces-Cetus void. Melott's (1987) calculations suggest that hot particle models can reproduce a truly empty void with a diameter comparable to Pisces-Cetus. However, his cold particle models produce generally smaller voids with sizes that are a function of the galaxy bias threshold. Primordial explosion models also seem unable to produce large voids like that in Pisces-Cetus and in Bootes.

The data displayed in this paper are taken as preliminary evidence for a new large void that is relatively nearby. Since this void is closer than Bootes, it is, therefore, easier to survey for dimmer, possibly low surface brightness galaxies. New observations are underway to address some of the outstanding observational problems noted in § I and to constrain the predictions made by theoretical models. These observations include a complete redshift survey of the volume down to the limits of the Zwicky *et al.* (1961–1968) catalog (Brodie *et al.* 1987). Preliminary results suggest that the void remains significantly underdense down to 15.7 mag. Deeper observations are also planned down to 17 mag in selected regions to set stronger limits on the density of luminous matter in the void. We have also undertaken a Schmidt objective prism survey of Pisces-Cetus, similar to that recently completed on Bootes, to determine if emission-line galaxies populate the void. Finally, in an effort to determine the void topology, observations south of $-3°$ are planned. Taken together with the recent work on Bootes, these new observations of Pisces-Cetus will set important limits on the size and density of large cosmic voids.

The authors wish to thank J. A. Willick for his assistance with the Lick observations. We are also indebted to S. A. Gregory, A. L. Melott, M. Sulkanen, and L. Thompson for comments on the paper, and J. Huchra for providing us with a recent edition of the CfA catalog. This work at UNM was supported by NSF grant AST-8520115. J. O. B. would also like to thank the National Center for Supercomputing Applications at the University of Illinois, for their hospitality, where some of this work was completed.

REFERENCES

Abell, G. O. 1958, *Ap. J. Suppl.*, **3**, 211.
Bahcall, N. A., and Soneira, R. M. 1982, *Ap. J.* (*Letters*), **258**, L17.
———. 1983, *Ap. J.*, **270**, 20.
Batuski, D. J., and Burns, J. O. 1985*a*, *A. J.*, **90**, 1413.
———. 1985*b*, *Ap. J.*, **299**, 5.
Batuski, D. J., Burns, J. O., Laubscher, B., and Elston, R. 1988, *A.J.*, submitted.
Brodie, J., Willick, J., Bowyer, S., and Burns, J. O. 1987, preprint.
Burg, R. I. 1987, Ph.D. thesis, M.I.T., p. 123.
Burns, J. O., and Batuski, D. J. 1987 in *IAU Symposium 124, Observational Cosmology*, ed. A. Hewitt, G. Burbidge, and L. Fang (Dordrecht: Reidel), p. 319.
Burns, J. O., Moody, J. W., and Batuski, D. J. 1987, in *Proc. 13th Texas Symposium on Relativistic Astrophysics*, ed. M. Ulmer (Singapore: World Scientific), p. 286.
de Lapparent, V., Geller, M. J., and Huchra, J. 1986, *Ap. J.* (*Letters*), **302**, L1.
Einasto, J., Joeveer, M., and Saar, E. 1980, *M.N.R.A.S.*, 193, 12.
Gregory, S. A., Moody, J. W., Burns, J. O., and Tifft, W. 1989, *Pub. A.S.P.*, in preparation.
Gregory, S. A., and Thompson, L. A. 1978, *Ap. J.*, **222**, 784.
Gregory, S. A., Thompson, L. A., and Tifft, W. G. 1981, *Ap. J.*, **243**, 441.
Gregory, S. A., Tifft, W. G., and Moody, J. W. 1988, *A.J.*, **95**, 662.
Haynes, M. P. 1987, in *Proc. 13th Texas Symposium on Relativistic Astrophysics*, ed. M. Ulmer (Singapore: World Scientific), p. 278.
Haynes, M. P., Giovanelli, R., Starosta, B. M., and Magri, C. 1988, *A.J.*, **95**, 607.
Kaiser, N. 1984, *Ap. J.* (*Letters*), **284**, L9.
Kirshner, R. P., Oemler, A., Schechter, P. L., and Schectman, S. A. 1981, *Ap. J.* (*Letters*), **248**, L57.
———. 1987, *Ap. J.*, **314**, 493.
Melott, A. L. 1987, *M.N.R.A.S.*, **228**, 1001.
Mihalas, D., and Binney, J. 1981, *Galactic Astronomy* (2d ed; San Francisco: Freeman), p. 206.
Moody, J. W., Kirshner, R. P., MacAlpine, G. M., and Gregory, S. A. 1987, *Ap. J.* (*Letters*), **314**, L33.
Oort, J. H. 1983, *Ann. Rev. Astr. Ap.*, **21**, 373.
Ostriker, J. P., and Cowie, L. L. 1981, *Ap. J.* (*Letters*), **243**, L127.
Otto, S., Politzer, H. D., Preskill, J., and Wise, M. B. 1986, *Ap. J.*, **304**, 62.
Peebles, P. J. E. 1980, *The Large-Scale Structure of the Universe* (Princeton: Princeton University Press).
———. 1986, *Nature*, **321**, 27.
Politzer, H. D., and Preskill, J. P. 1986, *Phy. Rev. Letters*, **56**, 99.
Saarinen, S., Dekel, A., and Carr, B. J. 1987, *Nature*, **325**, 598.

Schechter, P. 1976, *Ap. J.*, **203**, 297.
Struble, M. F., and Rood, H. J. 1987, *Ap. J. Suppl.*, **63**, 543.
Tarenghi, M., Tifft, W. G., Chincarini, G., and Rood, H. J. 1979, *Ap. J.*, **234**, 793.
Tully, B. 1987, *Ap. J.*, **323**, 1.
Vishniac, E. T., Ostriker, J. P., and Bertschinger, E. 1985, *Ap. J.*, **291**, 399.
White, S. D. M., Frenk, C., Davis, M., and Efstathiou, G. 1987, *Ap. J.*, **313**, 505.
Zwicky, F., Herzog, E., Karpowitz, M., Kowal, C. T., and Wild, P. 1961–1968, *Catalogue of Galaxies and Clusters of Galaxies* (Pasadena: Californin Institute of Technology).

D. J. Batuski: Space Telescope Science Institute, Homewood Campus, Baltimore, MD 21218

J. P. Brodie: Lick Observatory, University of California, Santa Cruz, CA 95064

J. O. Burns: Institute for Astrophysics, Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131

J. W. Moody: Department of Physics, Weber State College, Ogden, UT 84408