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A POSSIBLE 300 MEGAPARSEC FILAMENT OF CLUSTERS OF GALAXIES IN PERSEUS-PEGASUS

DAVID J. BATUSKI[1] AND JACK O. BURNS[1]
Department of Physics and Astronomy, University of New Mexico
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ABSTRACT

In this paper, we present the results of redshift observations for Abell clusters with $m_{10} < 16.5$ and medium-distant Zwicky clusters in a large region of the South Galactic Cap. The region contains a possible filament of galaxies and galaxy clusters which includes the Perseus-Pisces Supercluster and has a total apparent length of over 300 h^{-1} Mpc. A $|\cos\theta|$ test is used as a measure of filamentation. We compare the observed distribution of three-dimensional cluster alignments with that for a random distribution of clusters constrained to have the same two-point spatial correlation function as the Abell clusters. The Kolmogorov-Smirnov test indicates less than 0.3% probability that the apparent filament could occur in the "constrained random" samples. We also discuss some of the possible implications that the existence of such large structures might have for the more popular theories on the formation of galaxies and clusters.

Subject headings: cosmology — galaxies: clustering — galaxies: redshifts

I. INTRODUCTION

Recent observations of large-scale structure in the universe suggest that filamentary arrangements of galaxies are very common. Gregory and Thompson (1978) found such a filament bridging the $\sim 30h^{-1}$ Mpc ($h = H_0/75$ Mpc km^{-1} s^{-1}) distance between the Coma and A1367 Clusters. The Perseus-Pisces Supercluster region shows evidence of several filaments, the most prominent of which contains three Abell clusters and two smaller groups of galaxies; it has an overall length of $\sim 70h^{-1}$ Mpc (Gregory, Thompson, and Tifft 1981; Chincarini, Giovanelli, and Haynes 1983). Similarly, the Hercules Supercluster appears to be a collection of rich ($R > 0$) Abell clusters spanning a region of $\sim 70h^{-1}$ Mpc extent with an $R = 0$ cluster and numerous galaxies forming a filamentary connecting structure (Chincarini, Rood, and Thompson 1981). Abell clusters are obvious dominant components of these structures. We have begun an observational program based on the premise that the Abell clusters are good tracers of large-scale structure (e.g., Einasto, Joeveer, and Saar 1980, and references therein). Some of these new observations have helped define an apparent filamentary arrangement of Abell clusters that has a length of more than $300h^{-1}$ Mpc.

As a tool for investigating large-scale structure in the universe, a finding list of supercluster candidates (Batuski and Burns 1985) was constructed by applying the percolation technique to a nearby portion ($z < 0.13$) of the Abell (1958) catalog of clusters of galaxies. The term "candidates" here emphasizes the fact that the percolation technique was used only to identify interesting regions for further study. The technique, when applied to clusters, cannot really define superclusters, since the distribution of galaxies between clusters is a key factor in delineating the superclusters thus far observed.

One of the more interesting nearby candidates in the finding list is impressively large, spanning $23^{h}.2 < \alpha < 1^{h}.9$ and $-25° < \delta < 30°$, roughly bounded by the constellations of Pisces and Cetus. This candidate originally consisted of 36 Abell clusters of all richness classes ($R \geq 0$), having a range in redshift of $0.025 < z < 0.090$. Five of these clusters had only estimated redshifts (estimated from the magnitude of the tenth brightest galaxy, m_{10}) at the time the catalog was completed, and 12 had only a single measured galaxy redshift. Thus more redshift data were necessary for reliable determinations of the positions of these Abell clusters.

We also recognized the need for more redshift data to verify the assumption inherent in the finding list that the Abell clusters are good tracers of the general distribution of galaxies. A reasonable initial step in examining this assumption would be to obtain redshifts for some poor clusters from Zwicky, Karpowicz, and Kowal (1965–1968), selected because they appear in projection to be in gaps in the Abell cluster distribution.

In 1983 September we obtained spectroscopic measurements of galaxies in Abell clusters and poor Zwicky clusters in the Pisces-Cetus region at the Kitt Peak National Observatory, using the intensified image dissector scanner on the 2.1 m telescope. This paper reports the results of these observations.

Section II summarizes the general approach and specific methods used in the observations and presents a listing of the redshifts obtained. In § III the region observed is examined for structure in the arrangement of the clusters, with particular emphasis on an apparent long filament of clusters. In § IV a first-order test for filamentation is applied to the clusters in the apparent filament and to the entire sample of Abell clusters in the nearby ($z < 0.085$) portion of the universe. Some interesting theoretical implications of the possible existence of such large structures as the Perseus-Pegasus filament are discussed in § V. Section VI is a summary of our results, with suggestions for further observational work.

II. THE OBSERVATIONS

The Abell clusters selected for measurement were among those listed as members of the Pisces-Cetus Supercluster candidate, candidate 5 in the Batuski and Burns (1985) finding list, or they were "neighbors" of this candidate, having somewhat lower probability of supercluster membership. These clusters

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1985ApJ...299....5B

had no measured redshifts reported in the literature except for A189 and A279, each of which had a single member galaxy with a measured redshift. With the new measurements, only two of the 52 Abell clusters in the region $23^h.2 < \alpha < 1^h.9$, $-25° < \delta < 30°$ with $m_{10} < 16.5$ still have unmeasured redshifts. These are A74 and A2656, which are both apparently near the periphery of the candidate supercluster.

The Zwicky clusters that we observed were chosen according to three criteria: (1) they are all in Zwicky distance class MD (medium distant, $0.05 < z_{\text{estimated}} < 0.10$), which is comparable to the distances of the Abell clusters under consideration; (2) the Zwicky clusters do not have Abell clusters of comparable distance class within their boundaries; and (3) they appear to lie in large gaps between some of the Abell clusters in the supercluster candidate. These observations are then a significant test of whether rich clusters are good tracers of large-scale structure in the general distribution of luminous matter. In fact, as discussed in § III below, four of these five clusters have redshifts that place them within $30h^{-1}$ Mpc of Abell clusters.

The new redshifts were obtained in 1983 September using the 2.1 m telescope at KPNO with the intensified image dissector scanner, a 600 line grating, and the "Gold" spectrograph. The spectra were taken in the blue (3600–5600 Å) and had 79 Å mm^{-1} dispersion. The standard KPNO IIDS reduction programs were then used to measure the galaxy redshifts.

Table 1 lists the results of these observations. The first three columns contain the identifying numbers of the Abell and Zwicky clusters and their richness and distance classes. Columns (4) and (5) list the coordinates of the particular cluster member galaxies that were observed. The measured velocities, including a 300 km s^{-1} cos b sin l correction to galactocentric coordinates, are in column (6). The errors listed in column (7) were estimated by first finding the difference between the velocities measured from the calcium H and K lines for a particular galaxy. The errors from these differences were then added in quadrature with the standard deviation of velocities of several "standard" galaxies that were measured on each night of the observations. Column (8) shows the spectral lines used for these measurements. In all cases the calcium H and K lines were used for the principal redshift determination. Other lines listed were used only for confirmation. These other lines (all G-band, except for one case) were given lower weighting because the H and K lines were strong, sharp, and reasonably consistent in all cases, while the G band was frequently too wide or distorted or both for reliable measurement of the line center.

III. ANALYSIS OF CLUSTER ARRANGEMENT

The new Abell cluster redshifts made only minor alterations in the "percolation membership" of the Pisces-Cetus candidate supercluster listed in Batuski and Burns (1985). A71, A75,

TABLE 1

OBSERVATIONS OF ABELL AND ZWICKY CLUSTERS

Cluster (1)	D (2)	R (3)	α (1950) (4)	δ (1950) (5)	Redshift (km s^{-1}) (6)	Error (km s^{-1}) (7)	Lines Used (8)
A71	3	0	$0^h35^m49^s.7$	+29°14′12″	5460	180	H, K, G
			0 35 18.9	+29 18 13	7710	110	H, K
A75	3	0	0 37 10.6	+20 56 28	9330[a]	160	H, K, G
			0 36 55.5	+20 57 43	18690	120	H, K
			0 37 4.4	+20 57 38	17160	110	H, K, G
A102	3	0	0 46 16.0	+1 6 0	19850	110	H, K
			0 46 3.9	+1 8 1	20250	180	H, K
			0 46 2.8	+1 9 3	20450	140	H, K, G
A116	4	0	0 53 12.2	+0 22 28	20230	250	H, K
			0 53 10.6	+0 22 3	20260	220	H, K, G
A117	4	0	0 53 21.1	−10 20 42	16380	180	H, K
			0 53 48.0	−10 19 25	15900	180	H, K
A134	4	0	1 0 29.1	−2 49 24	26570[b]	140	H, K, G
			1 0 34.4	−2 48 44	20510[b]	130	H, K
A189	4	1	1 20 52.1	+1 26 42	10170	230	H, K, G
			1 20 49.4	+1 23 24	9720	140	H, K
A279	5	1	1 53 46.2	+0 48 0	24990	200	H, K
A2665	4	0	23 48 17.2	+5 52 14	16990	120	H, K, G, OII
2336+20	MD	0	23 36 38.3	+20 46 20	17000	230	H, K, G
0003+32	MD	0	0 2 44.1	+32 41 57	10440	110	H, K, G
			0 2 43.9	+32 41 54	10470	210	H, K, G
2349+32	MD	0	23 49 54.0	+33 8 26	12930	280	H, K
			23 50 12.7	+33 3 3	12770	140	H, K, G
			23 50 0.0	+33 7 30	12980	110	H, K
2339+14	MD	0	23 39 18.3	+14 46 0	21250	270	H, K
			23 39 17.0	+14 47 42	20441	180	H, K
			23 39 11.0	+14 47 22	20620	200	H, K
2349+16	MD	0	23 50 18.2	+17 28 22	23170	180	H, K
			23 50 13.8	+17 33 9	22360	200	H, K

[a] Not averaged into the cluster redshift. This object is surely a foreground galaxy, since its redshift is so much lower than those of the other two measured galaxies, which also closely match the photometrically estimated redshift for that cluster.

[b] The two measurements for A134 differ by too much for both galaxies to be in the same cluster. There is no strong reason to favor one of the measurements, so an accurate cluster redshift must await further observations. At either redshift, this cluster would not be in close association with other Abell clusters in the Pisces-Cetus supercluster candidate.

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1985ApJ...299....5B

A102, and A116 were originally selected as members of the candidate supercluster on the basis of their estimated redshifts; and only A71 retained its membership, after measurement, by being within $40h^{-1}$ Mpc of another member cluster. Clusters A117, A134, and A2665 had estimated redshifts that excluded them from membership in the Pisces-Cetus candidate, but they were assigned to the "neighborhood" of Pisces-Cetus in Batuski and Burns (1985), meaning that they had some reasonable probability that measured redshifts would place them in the supercluster candidate. Of these three clusters, A117 was the only one that was found to be a member of Pisces-Cetus. Finally, our confirming measurements of the previously measured A189 and A279 indicate that these clusters do indeed satisfy the $40h^{-1}$ Mpc criterion for membership in the candidate supercluster.

The average redshift for A71 places it in position to serve as a link between the Pisces-Cetus supercluster candidate and the Perseus-Pisces Supercluster (A262/347/426). With the inclusion of Perseus-Pisces and the other changes indicated above, the candidate now has a percolation membership of 37 Abell clusters, all but one (A74) having at least one measured redshift.

Because of the limited utility of percolation analyses, we also used the calculated three-dimensional positions of the clusters to produce plots like Figure 1, so that various regions near Pisces-Cetus could be visually examined for large-scale structure. This plot is a projection of the three-dimensional distribution of the clusters in a $(200h^{-1}\ \mathrm{Mpc})^3$ volume, as it would be seen by a hypothetical observer located $400h^{-1}$ Mpc from the center of the cube. The symbols are sized linearly with distance of the cluster from the observer. This allows for greater variation of symbol size than the true perspective (inverse of the distance from the observer to the cluster) variation, so that differences are more apparent to the reader. Earth's position would be slightly to the left of and above the top front corner of this cube. All Abell clusters with redshifts (estimated or measured) that would place them within this block of space have been plotted in Figure 1. The positions of the five poor Zwicky clusters for which we obtained redshifts are also shown in this figure. Table 2 summarizes the available position data for all the clusters plotted in this figure.

Most of the 25 clusters that make up the main body of the Pisces-Cetus candidate supercluster can be seen in the lower left portion of Figure 1. This collection of clusters with characteristic length scale $120h^{-1}$ Mpc must be considered a particularly strong candidate supercluster, since the density of clusters is approximately five times the average spatial number of density of Abell clusters for $R \geq 0$ and $z < 0.085$. The average separation between nearest neighbors in this portion of Pisces-Cetus is only $22h^{-1}$ Mpc.

Another most important feature of the region in Figure 1 is the long apparent filamentary arrangement of clusters high lighted by the dashed contour in the figure. There are 16 Abell clusters within this contour. The approximate distances between the clusters that lie most directly along the filament are listed in the last column in Table 2B. All the links between the Abell clusters in this possible chain are less than $40h^{-1}$ Mpc except for the $51h^{-1}$ Mpc gap that separates A2593 and A2626. The Zwicky cluster ZW 2336+20 appears to be in a position to partially reduce this gap, suggesting a bridge between the Abell clusters. Three of the other four Zwicky clusters that we measured were also found to lie along or near (within $30h^{-1}$ Mpc) the arrangement of the Abell clusters in this region. The portion of the filament toward the top of the

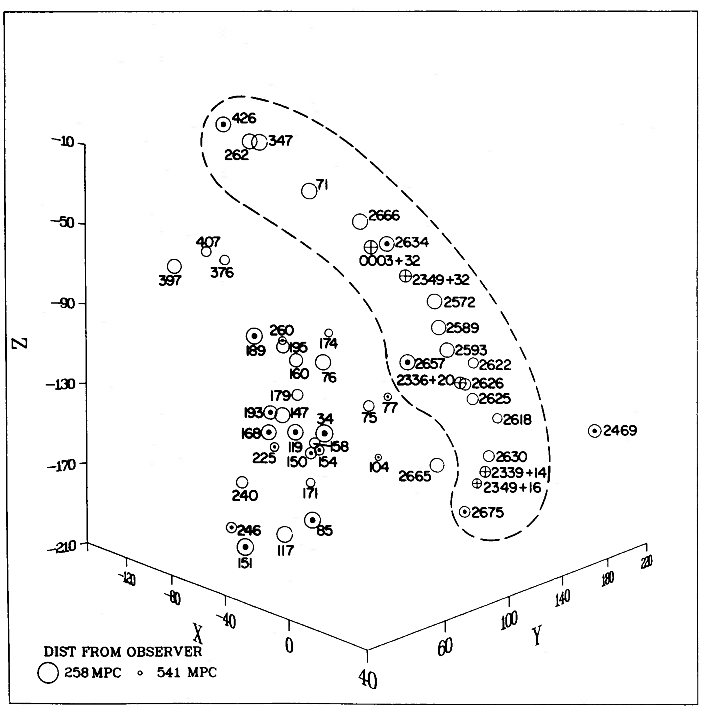

FIG. 1.—Plot of projection of the three-dimensional arrangement of clusters in the Pisces-Cetus supercluster candidate and neighboring clusters. Units for the axes are h^{-1} Mpc. Earth is at $X = Y = Z = 0$, Z-axis is along North Galactic Pole, and X-axis is along $l = b = 0°$. Each symbol represents one cluster and is sized to show distance from the observer's "position" in space, $400h^{-1}$ Mpc from center of cube. Symbols: $\odot$, rich ($R > 0$) Abell cluster, $\bigcirc$, poor ($R = 0$) Abell cluster, $\oplus$, poor Zwicky cluster. The filamentary arrangement within the dashed contour is over $310h^{-1}$ Mpc in length.

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1985ApJ...299....5B

TABLE 2

CLUSTERS IN THE REGION OF THE PERSEUS-PEGASUS FILAMENT

A. NONMEMBERS OF FILAMENT

Cluster	b	l	Z^a	N_Z
A34	−70°8	104°5	0.0410	1
A75	−41.5	119.3	0.0598[b]	2
A77	−33.3	120.1	0.0812	1
A85	−72.1	115.1	0.0518	3
A104	−38.3	122.4	0.0812	1
A117	−72.9	126.8	0.0528[b]	2
A119	−64.1	125.7	0.0440	21
A147	−60.4	131.4	0.0435	3
A150	−49.5	129.6	0.0600	1
A151	−77.6	142.9	0.0526	2
A154	−45.0	129.5	0.0658	11
A158	−45.7	129.9	0.0628	7
A160	−47.0	130.5	0.0430	8
A168	−62.0	135.7	0.0452	13
A171	−46.2	131.7	0.0729	1
A174	−26.7	129.4	0.0632	0
A179	−42.8	132.7	0.0547	3
A189	−60.2	139.3	0.0331[b]	1
A193	−53.3	136.9	0.0478	1
A195	−42.9	134.4	0.0437	1
A225	−42.6	138.3	0.0692	1
A240	−53.2	144.1	0.0618	2
A246	−54.6	146.3	0.0700	2
A376	−20.6	147.1	0.0489	1
A397	−37.2	161.9	0.0325	6
A407	−59.9	205.4	0.0472	1
A2665	−53.7	96.9	0.0566[b]	1
ZW 2349+33	−28.0	108.9	0.0436[b]	3

B. FILAMENT MEMBERS

Cluster	b	l	Z^a	N_Z	Separation (Mpc)
A426	−13.4	150.4	0.0183	108	
A347	−17.6	141.2	0.0187	19	14
A262	−25.1	136.6	0.0161	31	16
A71	−33.2	119.4	0.0219[b]	2	31
A2666	−33.8	106.4	0.0265	15	24
A2634	−33.1	103.5	0.0312	17	18
A2572	−38.9	94.2	0.0383	5	33
A2589	−41.2	94.7	0.0414	13	13
A2593	−43.2	93.5	0.0440	2	11
ZW 2336+20	−38.6	101.1	0.0567[b]	1	49
A2626	−38.4	100.5	0.0573	4	3
A2625	−39.0	100.1	0.0602	3	10
A2618	−36.5	100.6	0.0705	2	35
A2630	−43.5	98.1	0.0675	2	33
ZW 2339+14	−44.9	98.8	0.0692[b]	3	12
A2675	−49.1	101.7	0.0726	1	23
A2622	−32.4	102.8	0.0615	1	
A2657	−50.3	96.7	0.0408	2	
ZW 2349+16	−43.4	103.3	0.0759[b]	2	
ZW 0003+32	−28.8	112.2	0.0348[b]	2	

NOTE.—b, galactic latitude; l, galactic longitude; Z, cluster redshift; N_Z, number of galaxy measurements averaged into Z; separation, distance between sequentially listed clusters.

[a] Redshifts from Struble and Rood 1983, Sarazin *et al.* 1982, or Fanti *et al.* 1983, except as indicated by note b.

[b] Measured by authors.

cube in Figure 1 (A426 to A71) runs largely in the plane of the sky, but the filament's general curvature causes its more distant clusters (e.g., A2593, A2625, A2675) to be distributed very nearly along the line of sight.

In Figure 2 the region of interest is displayed in a pair of plots, so that the reader may have a stereoscopic view of the three-dimensional arrangement of the clusters in this region. Here one can see that the bridge suggested by ZW 2336+20 results in a very impressive string of clusters, extending from A426/262/347 (the much-studied Perseus-Pisces Supercluster—Gregory, Thompson, and Tifft 1981; Chincarini, Rood, and Thompson 1983) to A2675.

The upper corners of Figures 1 and 2 are at low Galactic latitudes, and their apparent emptiness may be at least partially caused by dust obscuration by our Galaxy. *Galactic obscuration should not, however, have major effects on the apparent structure along most of the filament.* The Perseus-Pisces Supercluster portion of the filament (A262, 347, 426; $-25° < b < -13°$), runs deeply into the zone of avoidance, but this region has been very thoroughly studied and its filamentary nature is well established (Gregory, Thompson, and Tifft 1981; Chincarini, Giovanelli, and Haynes 1983). The remaining clusters in Table 2B all lie below Galactic latitude $-32°$, which is roughly the edge of the area excluded by Abell (1958) in defining his statistical sample. The more distant clusters (center and bottom right of the filament as viewed in Figs. 1 and 2) are generally well away from the zone of avoidance and from any Galactic H I spurs (Burstein and Heiles 1978).

Very important to the definition of structure in the portion of space shown in Figures 1 and 2 are several large unobscured regions that are apparently devoid of Abell clusters. Between the A71-to-A2593 portion of the filament and the main body of the Pisces-Cetus supercluster candidate, which begins with A76/A160/A189/A195, there is a roughly ellipsoidal void of clusters with dimensions is $\sim 80h^{-1}$ Mpc by $\sim 120h^{-1}$ Mpc. This void is pinched off by A2657, which is in a position that suggests a bridge between the filament and this other group of clusters. A2665 appears in Figures 1 and 2 to be in front of a more nearly spherical void that is $\sim 90h^{-1}$ Mpc in diameter. Finally, A2469 is an apparently isolated cluster $\sim 70h^{-1}$ Mpc from A2630, in what would otherwise be a 100–150h^{-1} Mpc void. Burstein and Heiles (1978) presented a detailed investigation of Galactic obscuration variation across the sky caused by variations in H I column density (Heiles 1975) and the dust-to-gas ratio. We used their results to examine the regions of these apparent voids and found no indication of large amounts of obscuration. For example, the last mentioned region above had an average of 0.2 mag more obscuration than that predicted by the simple Galactic latitude correction used by Abell (1958). This is roughly the same as Abell's own estimated magnitude errors and could not contribute greatly to the dearth of clusters in the region. These three void regions, so effectively isolating the filament, are the primary reason that the filament appears to be a single, very prominent structure in these plots.

Adding up the separations of the Abell clusters that are direct links in the chain yields a total length of over $310h^{-1}$ Mpc. To our knowledge, this is the largest supercluster structure yet claimed. It is also of interest that Giovanelli and Haynes (1982) have hypothesized that the Lynx–Ursa Major Supercluster may be linked to the Perseus-Pisces complex by a bridge of galaxies that disappears into the Galactic obscuration. If this additional structure were considered, the total filament length could be greater than $400h^{-1}$ Mpc.

In Figure 3, the locations of most of the Abell clusters in the filament have been plotted in right ascension and declination, along with all the galaxies (down to magnitude 15.7) in the region from Zwicky, Karpowicz, and Kowal (1965–1968). The solid contours represent "near" clusters in the Zwicky catalog (generally poorer than the Abell clusters). The dashed contour in the figure outlines the location of the filament. The filament

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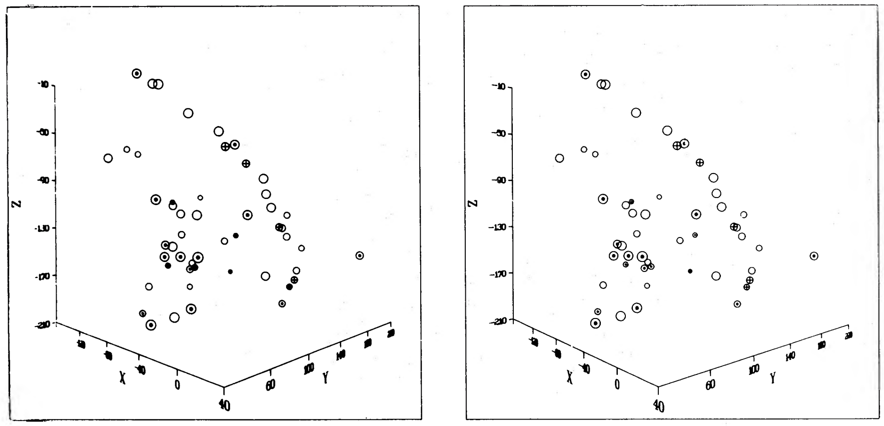

FIG. 2.—Stereoscopic view of same region as in Figure 1. With some practice, the three dimensional effect can be seen by looking directly at the images. A stereoscopic viewing device can also help greatly.

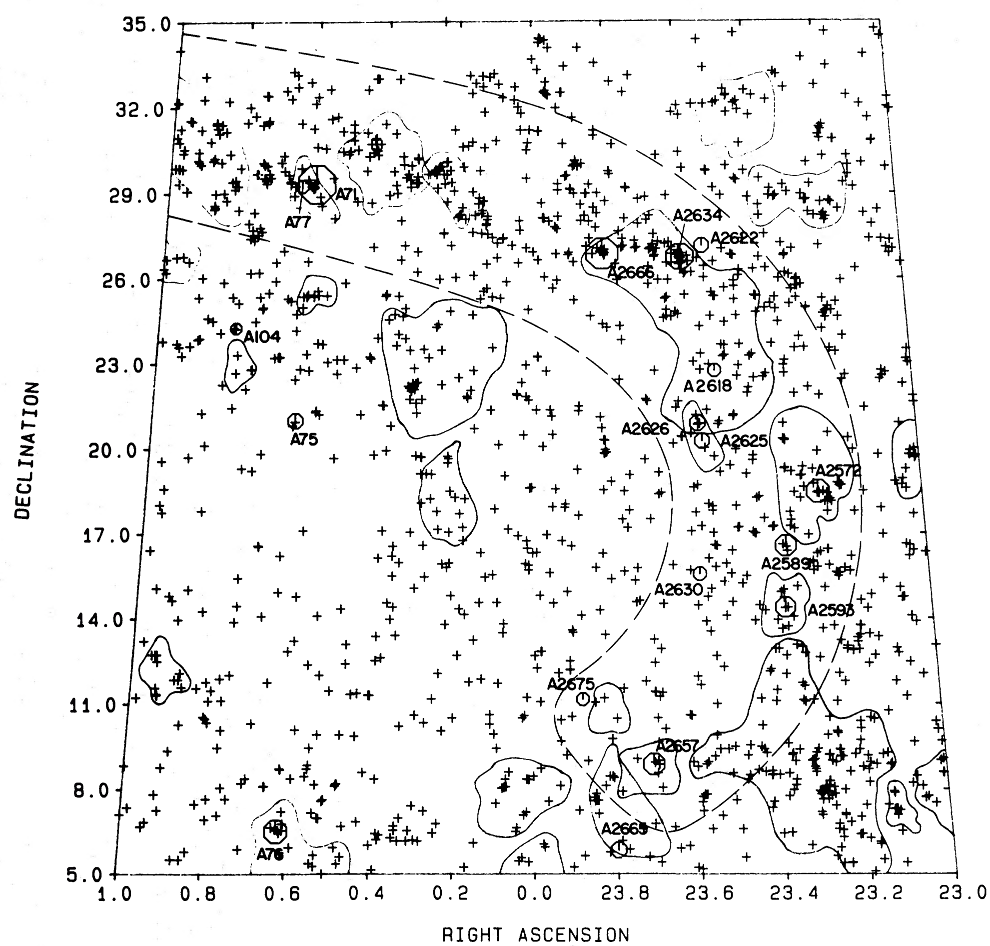

FIG. 3.—Region of sky containing most of the filament of clusters identified in Fig. 1, with locations of Zwicky galaxies down to 15.7 mag plotted. All Abell clusters with $z < 0.09$ in this region are designated by octagons sized inversely with redshift. Zwicky clusters of the "near" category (Zwicky *et al.* 1965–1968) are shown in rough contours.

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1985ApJ...299....5B

runs roughly from Perseus, 2^h to the east of the left edge of Figure 3, to Pegasus, which occupies all of the right half of this figure above $\delta = 8°$. A density enhancement in the Zwicky galaxies can be seen following the arrangement of the Abell clusters to the vicinity of A2593, where the filament turns strongly into the plane of the sky, causing an apparent loop back to the north and east in Figure 3. A part of this galaxy density enhancement was identified by Einasto, Joeveer, and Saar (1980) as a possible extension of the Perseus-Pisces Supercluster. The average density in galaxies per square degree within the dashed contour in Figure 3 varies from 1.5 to more than 3.0 times the average in the large, sparser region in the southeast (i.e., lower left-hand) portion of the figure. The Zwicky clusters also show an obvious density enhancement along the filament in this two-dimensional picture. Thus, it is interesting to note that even in two dimensions (with likely foreground/background contamination), the filament is visible in both the cluster and galaxy distributions.

This tendency of galaxies and poor clusters to follow the arrangement of the Abell clusters is more clearly evident in three dimensions. Fourteen of the 18 poor Zwicky clusters in Figure 3 that have redshifts in the Center for Astrophysics survey (Huchra *et al.* 1983) are within $35h^{-1}$ Mpc of the Abell cluster filament (as are four of the five MD Zwicky clusters that we measured). The individual galaxies with redshifts in the CfA survey also predominantly follow the Abell clusters in the filament, as shown in the wedge diagram in Figure 4. This figure is a redshift versus right ascension plot of all 363 CfA galaxies (including 50 with unpublished redshifts from Huchra *et al.* (1984), used with their kind permission) that lie within $\pm 3°$ of a straight line that runs along the filament. The line passes near A347 in the Perseus-Pisces Supercluster on its eastern end and goes through A2634 near its western end. The clusters can be identified with clumps of galaxies in this figure (usually elongated in the redshift dimension by the dynamics within the clusters themselves) as follows: A347 at $2^h.4$, 5000 km s^{-1}; A262 at $1^h.8$, 4800 km s^{-1}; A2666 at $23^h.8$, 7900 km s^{-1}; and A2634 at $23^h.6$, 9400 km s^{-1}. A71 would lie at $0^h.6$, 6000 km s^{-1}, but it does not have enough measured redshifts to show up as a clump in Figure 4. Here the galaxies that are not obvious cluster members still follow the clusters very strongly out to a redshift of 11,000 km s^{-1}, while in the left-hand portion of the figure there is a pronounced deficiency in the numbers of galaxies from 7000 to 10,000 km s^{-1}—a "near void" of galaxies. The sample of galaxies in the CfA data is complete only to magnitude 14.5, however, and Figure 4 includes 199 galaxies of various fainter magnitudes (represented by plusses). If the fainter galaxies are removed from Figure 4, the filament becomes less prominent but is still obviously present.

In adjacent 6° strips on the sky, the CfA survey galaxies show no similar redshift versus right ascension distribution beyond 6000 km s^{-1} and much reduced galaxy densities in nearer regions, so the structure in Figure 4 indeed appears to be a filamentary arrangement of galaxies. These data and the results of Gregory, Thompson, and Tifft (1981) and Chincarini, Giovanelli, and Haynes (1983) show that the first $90h^{-1}$ Mpc

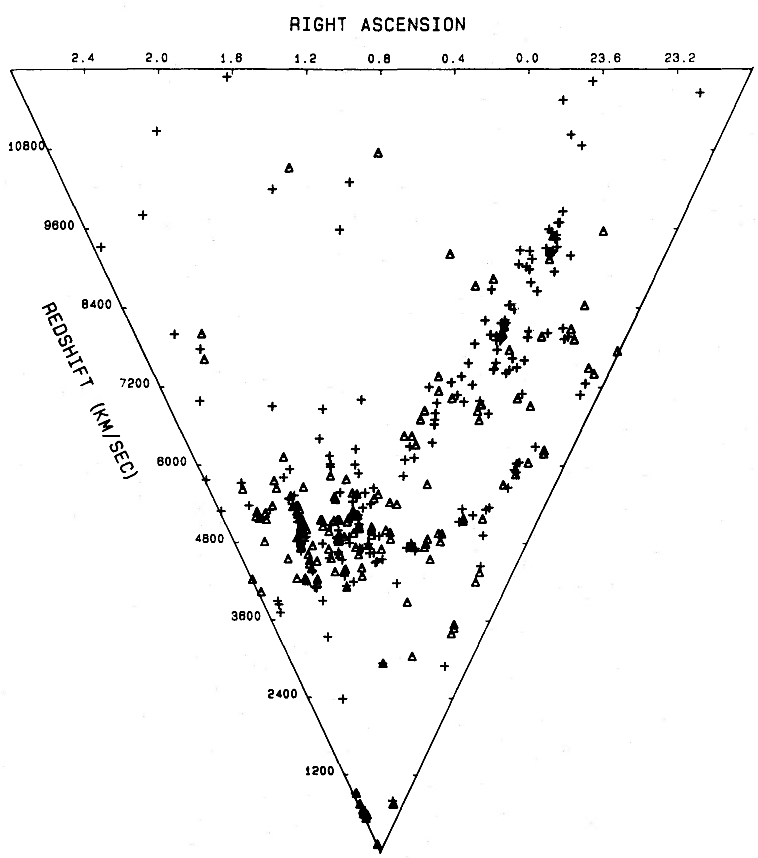

FIG. 4.—Wedge diagram of the galaxies with measured redshifts in the CfA survey that lie in the region within $\pm 3°$ of a line on the sky that runs through the projected low-redshift ($z < 0.040$) portion of the Perseus-Pegasus filament. Triangles indicate galaxies that are in the "complete" portion of the survey (down to 14.5 mag), and plusses are fainter galaxies.

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1985ApJ...299....5B

(i.e., the nearby portion) of the filament of clusters is well connected by galaxy bridges. Thus both the poor cluster and general galaxy distributions support our hypothesis that the Abell clusters are good tracers of large-scale structure in the nearer parts of this particular region. Much deeper redshift surveys will be necessary to see if the same is true along the more distant parts of the filament.

IV. THE STATISTICAL SIGNIFICANCE OF THE OBSERVED FILAMENTATION

Is the filament suggested by Figures 1–3 a real, physically significant entity, or merely another example of star chains (e.g., Peebles 1984)? Unlike the star chains which result from accidental projections of random three-dimensional positions onto a two-dimensional photograph, the alignment of Abell clusters in Perseus-Pegasus is an observed three-dimensional structure, since all coordinates are measured. We argued in the previous section that this alignment is also clearly not a result of dust obscuration from our Galaxy. The low-redshift portion of the filament stretches across more than 45° of sky, from Perseus to A2634, through regions of low to moderate (15°–35°) Galactic latitude, and the evidence of the filament is quite consistent throughout (see Fig. 4 and Gregory, Thompson, and Tifft 1981; Chincarini, Giovanelli, and Haynes 1983). As for the more distant parts of the filament, the surrounding voids that contribute so much to its definition are not significantly obscured and are still free of Abell clusters. The nearest of these voids also appears to have a significantly lower projected galaxy density, evident in the lower left portion of Figure 3.

Given these facts, we conclude that the apparent filamentary structure is real, even beyond the well-measured first $90h^{-1}$ Mpc. However, is this filament merely an accidental alignment which has arisen by chance? This is more difficult to answer with only the single example at hand and a rather limited sample of other clusters with measured redshifts.

To address this question we first used the techniques of Bahcall and Soneira (1983) to calculate the two-point spatial correlation function for the entire sample of Abell clusters that have measured or estimated redshifts $z < 0.085$ and that are outside the Galactic latitude limits of obscuration as defined by Abell (1958). This sample contains 226 clusters, 15% of which have unmeasured redshifts. Of these unmeasured clusters, all but two are in richness class $R = 0$. While the inclusion of the $R = 0$ clusters was essential for this analysis, the unmeasured redshifts should have had some tendency to dilute actual physical correlations that might otherwise show in the data. However, for separations of less than $100h^{-1}$ Mpc, our correlation function $\xi(r) = 100r^{-1.53}$, as shown in Figure 5, is quite similar to the Bahcall and Soneira (1983) result for $R > 0$ clusters, $\xi(r) = 500r^{-1.8}$, which indicates that this effect was not a serious influence on the correlation function.

One hundred "constrained" catalogs of clusters that had the average correlation function indicated by the triangles in Figure 5 (but that were otherwise randomly distributed throughout the same-shaped volume as that occupied by the "unobscured" Abell clusters) were then generated. For this task, a simplified version of the hierarchical "nested pairs" technique of Soneira and Peebles (1978) was used. Thus these "constrained" comparison catalogs had gross clumping and geometrical limit characteristics of the Abell cluster sample.

We then applied a test for filamentation to both samples. For each of the 169 Abell clusters with $z < 0.075$ and each cluster in the comparison catalogs out to an equivalent distance, we calculated the cosine of the angle θ between the vectors from that cluster to its two nearest neighbors. We used the $z < 0.075$ subsets of these $z < 0.085$ catalogs in order to reduce "edge effects" from the distance cutoff. For a filamentary arrangement of clusters with various separations, the frequency of values for $|\cos\theta|$ should be strongly peaked around 1.0 (angles of 0° and 180°) should have a distinct minimum near zero. As expected, however, the comparison catalogs showed only a very flat frequency distribution for $\cos\theta$, except

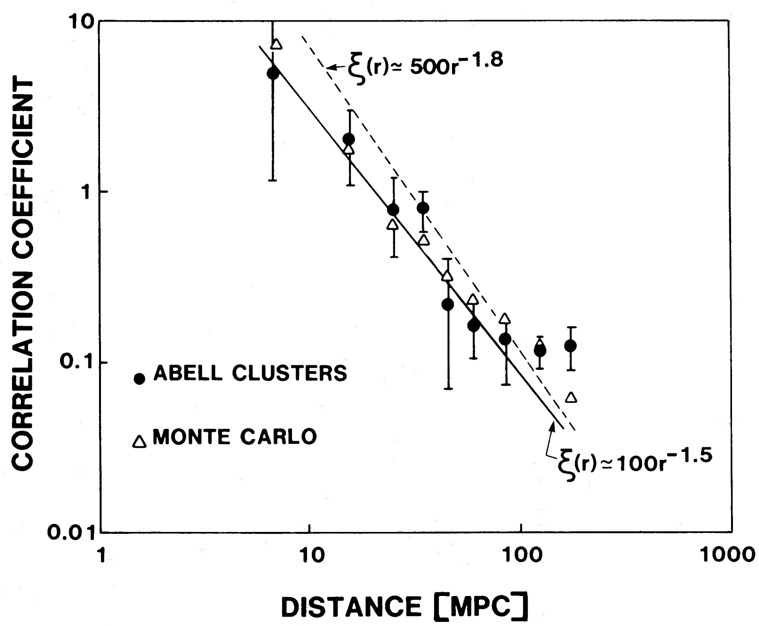

FIG. 5.—The two-point spatial correlation function for the 226 Abell clusters with $R \geq 0$, $z < 0.085$, within Abell's (1958) Galactic latitude limits for completeness. The correlation function for our constrained Monte Carlo simulations is also shown. The solid line is the weighted least-squares fit to the first seven points in the Abell function, and the dashed line is from Bahcall and Soneira (1983) for $R > 0$ clusters.

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1985ApJ...299....5B

for a modest peak near $\theta = 0°$ that resulted from the enforced clumping.

Because the effects of filamentation should be most noticeable in the sample bin near $|\cos\theta| = 1.0$, we used the number of clusters with $0.8 < |\cos\theta| < 1.0$ for a rough visual comparison of the different populations in Figure 6. Nine of the 16 clusters in the Perseus-Pegasus filament fall in the $0.8 < |\cos\theta| < 1.0$ bin, as represented by the last bar in Figure 6. If 16 clusters were chosen at random from the constrained catalogs, one would expect an average of 3.8 in this bin (the second bar in Fig. 6). The bar labeled "Abell" in Figure 6 shows that 4.3 clusters would be expected in the $0.8 < |\cos\theta| < 1.0$ bin if 16 clusters were selected at random from the 169 Abell cluster sample. Thus, there is only a slight indication of filamentation in the entire $z < 0.075$ Abell cluster sample. The expected number of objects in the $0.8 < |\cos\theta| < 1.0$ bin for a strictly random (Poisson) spatial distribution has also been represented in Figure 6 as a point of reference.

We then used the Kolmogorov-Smirnov goodness-of-fit test to compare the frequency distribution of $|\cos\theta|$ for the clusters in the Perseus-Pegasus filament with the distributions for the larger Abell cluster sample and for the 100 comparison catalogs. The test indicates less than 0.3% probability that the $|\cos\theta|$ values of the members of the filament would occur in a sample of 16 clusters from the constrained catalogs. Similarly, the filament has less than 1% likelihood of occurring in the Abell cluster sample.

These results suggest that a structure like Perseus-Pegasus would be very unlikely to be produced by a random cluster distribution constrained by the two-point spatial correlation function of the Abell clusters. Such a structure also appears to be a rarity in the local ($z < 0.085$) distribution of clusters. Data from a much larger volume of space will be necessary to determine just how common such large structures really are.

While this test for filamentation has shown that Perseus-Pegasus is a statistically significant arrangement of clusters, the results would no doubt be much more statistically significant if a more powerful test of filamentation could be devised. The test is not very sensitive to large-scale structures such as Perseus-Pegasus or the "wall" of clusters around the Bootes void (Bahcall and Soneira 1982) that is so evident in the northern hemisphere data, primarily because the test only considers three relatively close clusters at a time. No additional weight is assigned to situations in which the three clusters under consideration are lined up with other groups of clusters. Schemes to develop such weightings which we have thus far considered appear to be too arbitrary, or they seem impractical because of the small number of clusters and very limited volume of space that can be considered. The $|\cos\theta|$ test is an extremely conservative test for filamentation, and the fact that it still identifies the apparent filament of clusters as a substantial deviation from the "constrained" case encourages us to believe that the filament will prove to be a highly significant structure when a more powerful test of filamentation becomes available.

The Perseus-Pegasus-Cetus region is the first large part of the sky in which all $R = 0$ clusters with estimated redshifts below 0.085 ($m_{10} < 16.5$; Abell 1958) now have measured redshifts. $R = 0$ clusters dominate the Perseus-Pegasus filament, which indicates that they may be extremely important in identifying other such structures. It remains to be seen if the apparent large degree of filamentation in this region is duplicated in other, larger volumes of space.

V. THEORETICAL CONSIDERATIONS

If structures of the scale of this filament are common in the universe, then they would have major implications for the three commonly referenced theories on the formation of clusters and galaxies: the isothermal, neutrino, and cold particle models.

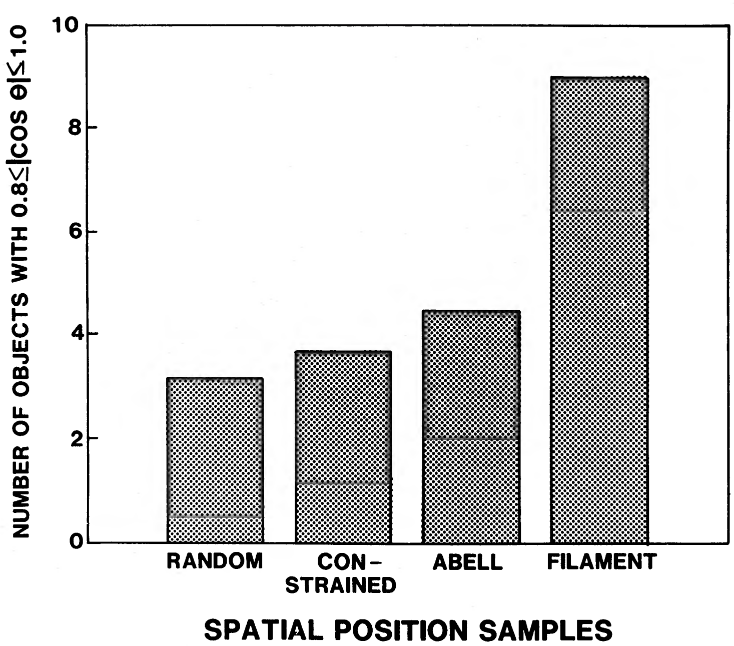

FIG. 6.—Comparison of the number of clusters in the Perseus-Pegasus filament with $0.8 < |\cos\theta| < 1.0$ with the expected results when 16 clusters are chosen at random from three different populations: *random*, clusters randomly distributed throughout the same volume as occupied by the Abell clusters; *constrained*, Monte Carlo simulations constrained to have the two point spatial correlation function shown in Fig. 5; *Abell*, the 226 Abell clusters from the sample used for Fig. 5.

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1985ApJ...299....5B

a) Isothermal Models

In these models, the large amounts of power present on small scales in the matter density fluctuation spectrum would result in objects of Jeans mass 10^5–10^6 $M_\odot$ (like globular clusters) being the first to form (Peebles 1980). Galaxies and larger structures would then form by hierarchical clustering on progressively longer time scales. The existence of the Pegasus-Pisces filament and other such large structures would be clearly incompatible with these models because of the long times required for formation. As indicated by *N*-body simulations for a baryon-dominated universe (e.g., Frenk, White, and Davis 1983), a Hubble time is much too short for gravitational aggregation of galaxies onto $\sim 300h^{-1}$ Mpc filaments.

b) Hot Particle Models

The neutrino (or hot particle) pancake model where small wavelength adiabatic density fluctuations are effectively damped may also have problems producing such large structures (Centrella and Melott 1983; Shapiro, Struck-Marcell, and Melott 1983). In this model, the superclusters result from the free-streaming of a hot, light particle (the nonzero rest mass neutrino is the only known candidate) that would erase all but the very largest scale structures. The remaining large positive density fluctuations would collapse in a non–spherically symmetric fashion in the pressureless environment, resulting in the formation of "pancakes" and filaments (Zel'dovich 1970). Galaxies and clusters would form later from the fragmentation of these large strcutures. The free-streaming of the particles (Landau damping) to form very large structures requires very low mass particles, so that they do not become nonrelativistic too soon after the big bang. It can be shown (Bond, Efstathiou, and Silk 1980) that a neutrino-like particle must have a mass

$$m_\nu = 4 \text{ eV} \frac{310 \text{ Mpc}}{\lambda_{m\nu}}$$

to explain structures at the present epoch like the Perseus-Pegasus filament. Here we have assumed that $\lambda_{m\nu}$, the wavelength below which density perturbations are viscously damped, is represented by the length of the filament (scaled by h^{-1}). This may be inappropriate if the filament should turn out to be chance alignment of two or more "cell boundaries," as in the simulation results of Melott (1983) and others, in which case $\lambda_{m\nu}$ must be reduced by a factor of 2 or more.

There are four possible problems with the production of such large structures in this hot particle scenario. First, the above mass is about a factor of 4–10 smaller than the canonical number quoted from experimental limits (Lubimov *et al.* 1980). Second, with this small mass for the neutrino, the universe would have to be open, since (Tremaine and Gunn 1979)

$$\Omega = \frac{\rho}{\rho_c} = 0.2 \frac{310 \text{ Mpc}}{\lambda_{m\nu} h^2} .$$

This is in contradiction to the predictions of the inflationary universe model (Guth 1981), a model that is very successful in explaining many of the large-scale characteristics of the universe. Third, according to the results of White, Frenk, and Davis (1983), the low neutrino mass dictated by such large structures would require galaxy and cluster formation to be much too recent to agree with observations of high-redshift quasars, dynamically relaxed clusters, and extremely old globular clusters. (We note here that Heavens 1985 maintains that the N-body simulations of White, Frenk, and Davis 1983 were too coarse to accurately model the galaxy two-point spatial correlation functions that were used to determine the simulation time scales. Thus, this possible problem may disappear when simulations with much larger values of *N* can be run.) Fourth, phase-space constraints would not allow enough of these low-mass particles to bind to galaxies and clusters to explain the dynamically inferred dark matter in these systems (Tremaine and Gunn 1979). Since observed abundances of He, D, and ^{7}Li make baryonic matter unattractive as a "missing mass" candidate (Schramm and Steigman 1981; Olive *et al.* 1981), we are left in the uncomfortable position of requiring two separate "exotic" particles: one to bind clusters and galaxies and another to form superclusters.

c) Cold Particle Models

The third model for the production of large structures also assumes the adiabatic scenario, but it hypothesizes a cold boson (e.g., the axion) that would not have a phase space problem or a more massive fermion such as the gravitino or photino (Blumenthal, Pagel, and Primack 1982; Bond, Szalay, and Turner 1982). Blumenthal *et al.* (1984) provide a thorough review of the mass density fluctuation spectrum that would be expected from such cold particles and the effects that it would have in the formation of galaxies, voids, and superclusters. They show that this spectrum, with its relatively large amount of power at small scales (in comparison to the hot particle model), would result in early formation of galaxies, roughly coeval with the larger structures (i.e., filaments). This spectrum also implies a large variation in structure sizes in the cold particle scenario, and something like the Perseus-Pegasus filament might be possible in this model. In fact, Melott *et al.* (1983) recently reported that simulations using the spectrum of density fluctuations that would result from such cold particles can produce filamentary structures. However, it is not yet clear that ~ 300 Mpc filaments can be formed within this model, because simulations have not yet been performed for this scale size. Also, the density fluctuation spectrum for the cold particles should in general have much less power on the largest scales than what is found in the neutrino model, making long filaments statistically rare. Deeper redshift observations will be needed to determine the frequency distribution of long filaments in order to test this model.

d) Other Models

The difficulties with the above models suggest that some alternative scenario may need to be invoked to explain very large structures in the universe. One other possible model which may naturally predict the existence of long filaments involves cosmic strings (e.g., Vilenkin 1981*a*, *b*). Cosmic strings are one-dimensional defects in the vacuum which can be produced during phase transitions in the early universe. The extremely large, non-Newtonian gravitational fields of these objects and their one-dimensional structures could provide the basis behind the formation of supercluster filaments.

VI. SUMMARY AND CONCLUSIONS

With the data presented in Table 1, all but two of the Abell clusters with $m_{10} < 16.5$ in a large portion of the Southern Galactic Cap now have measured redshifts. The clusters show much apparent structure, with several large voids alternating with regions of high cluster density (our candidate superclusters). Our intention in this paper has been to analyze

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1985ApJ...299....5B

one of these high-density regions, which contains a linear string of galaxy clusters significantly longer than any previously seen. We have five reasons for believing that this apparent filament is a single, real structure:

1. The Abell clusters define a statistically significant filamentary arrangement (at the 0.3% probability level), according to the $|\cos \theta|$ test, with no gaps greater than about $50h^{-1}$ Mpc.
2. Voids of Abell clusters with minimum dimensions of $\lesssim 70h^{-1}$ Mpc effectively isolate the filament.
3. Poor Zwicky clusters show a strong tendency to follow this filament, both in projection (as in Fig. 3) and in three dimensions.
4. Zwicky galaxies also tend to follow the filament in projection.
5. The CfA redshift survey shows that the galaxies in the lower redshift portion of this region that are not obvious cluster member are most often found in bridges that appear to connect the clusters.

If such structures as the Perseus-Pegasus filament are common, then they must strongly influence the direction of theoretical models of galaxy and cluster formation. However, considerable observational work is still required before one can be certain that Perseus-Pegasus is a single, simply connected filament. There are at least two more large observational efforts that must be undertaken. First, the filament region beyond A2634 must be examined in detail to determine whether the apparent string of clusters continues to be a filament of galaxies as well. The gaps between clusters (especially the large gap between A2593 and A2626) should contain bridging galaxies if the filament is to be considered a single structure. This effort must include searching the nearby voids to determine whether they are truly empty of galaxies and clusters. Second, large, deeper surveys of redshifts for individual galaxies and for clusters will be necessary to determine if other structures of such large scale exist. It is important to determine whether the Perseus-Pegasus filament is a statistical fluke among the structures in the near universe. Such observations are important for the differentiation between the hot and cold particle models, or they may even dictate the necessity of using models that involve non-Newtonian gravity (i.e., cosmic strings).

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David J. Batuski and Jack O. Burns: Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131

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