Supercluster properties as a cosmological probe

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ABSTRACT

We investigate the supercluster shape properties of the all-sky observed (Abell/ACO) and simulated (Virgo data) cluster catalogues using an approach based on differential geometry. We identify rich superclusters by applying the percolation algorithm to both observed and mock cluster populations, the latter being constructed following the observational selection of the Abell/ACO sample, extended out to $z_{\text{max}} \leq 0.114$. We apply a set of shape diagnostics in order to study the morphological features of superclusters with \( \geq 8 \) cluster members. Our results demonstrate that filamentarity is the dominant supercluster shape feature. On comparing data and models, we show that the $\Lambda$CDM ($\Omega_\Lambda = 1 - \Omega_m = 0.7$) model performs better than $\tau$CDM, which is excluded at a relatively high confidence level, in agreement with other recent large-scale structure studies.

Key words: galaxies: clusters: general – cosmology: theory – large-scale structure of Universe.

1 INTRODUCTION

Superclusters of galaxies occupy an eminent position in the structure hierarchy, being the largest mass units that we observe today. Since they have been seeded by density perturbations of the largest scale ($\sim 100 \text{h}^{-1} \text{Mpc}$), they therefore constitute objects with which one can study the details of the fluctuations that gave rise to them (West 1989; Einasto et al. 1997). Additionally, we can obtain fruitful clues regarding the formation and evolution of the large-scale structure of the Universe and test cosmological models (Bahcall & Soneira 1984; Bahcall 1988; Frisch et al. 1995).

Numerous studies have been devoted not only to delineating the geometrical pattern of the Universe as a whole (Zel’dovich, Einasto & Shandarin 1982; de Lapparent, Geller & Huchra 1991), confirming the picture of a well-designed web-like network, but also to extracting statistically complete supercluster catalogues in order to analyse their spatial distribution and morphological characteristics (Einasto et al. 2001a,b, and references therein). However, only very recently (Sathyaprakash et al. 1998a; Basilakos, Plionis & Rowan-Robinson 2001, hereafter BPR) has any significance been given to cosmological inferences from supercluster shape statistics. Sathyaprakash et al. (1998a) and BPR have used infrared galaxy samples (1.2-Jy and PSCz, respectively), whereas we presently consider Abell/ACO clusters (Abell 1958; Abell, Corwin & Olowin 1989).

A substantial number of geometrical and topological techniques have been applied to observational data to explore and assess clustering and superclustering at large scales (see Weinberg, Gott & Melott 1987; Coles & Plionis 1991; Mecke, Buchert & Wagner 1994; Sahni & Coles 1995; Yess & Shandarin 1996; Dave et al. 1997; Kerscher et al. 1997; Kerscher et al. 2001a,b and references therein). Nevertheless, an innovative method was devised recently (Sahni, Sathyaprakash & Shandarin 1998; Sathyaprakash, Sahni & Shandarin 1998b; Sahni & Habib 1999; Schmalzing et al. 1999) and has been used with success, so far, to describe in detail the geometrically complex features of large-scale structure. The first time this new scheme was applied to astronomical data was in BPR, where it was used to ascertain that the prominent feature of the large-scale structures we see today is filamentarity, as has also been observed in $N$-body simulations of gravitational clustering (Sathyaprakash et al. 1998b, and references therein).

The aim of the present work is not to produce a reliable all-sky supercluster list. Such attempts have been copiously presented by other authors over the last 25 years or so, based on either optical or X-ray (ROSAT) cluster data (Bahcall & Soneira 1984; Batutski et al. 1985; Postman, Huchra & Geller 1992; Cappi & Maurogordato 1992; Zucca et al. 1993; Kalinkov & Kuneva 1995; Einasto et al. 2001a,b, and references therein). The present analysis will focus on:

(i) whether or not superclusters verify the dominance of filamentarity as the basic trait of large-scale structure; and,
(ii) if so, whether or not supercluster shape and size statistics can be used to test cosmological scenarios.

The layout of the paper is as follows. The observed and simulated data sets are presented in Section 2. In Section 3, we discuss the selection parameters of the observed sample, give a brief exposé on the method used to investigate supercluster shape...

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properties, and comment on its stability. In Section 4, we derive the morphological parameters of the real (Abell/ACO) and mock (based on Virgo simulations) supercluster data, and in Section 5 we compare data and models in an attempt to discriminate between two possible structure formation scenarios. Finally, our concluding remarks are presented in Section 6.

2 THE DATA SETS

2.1 The Abell/ACO cluster catalogue

In the present analysis we make use of the combined optical Abell/ACO cluster list (Abell 1958; Abell, Corwin & Olowin 1989), which contains 2712 and 1364 entries in the northern and southern hemispheres respectively, but excludes the 1174 supplementary poor southern systems. We are utilizing a redshift-updated version of the catalogue up to a maximum redshift of $z_{\text{max}} \leq 0.114$ and restrict ourselves to $|b| \geq 30^\circ$ to avoid severe selection biases (cf. sections 2 and 5 of Einasto et al. 2001b) and light absorption in the zone of avoidance (ZoA). After taking into account the double cluster entries, our final list includes 926 objects (523 Abell and 403 ACO), $\sim 80$ per cent of which (733/926) have measured redshifts and are also in accordance with the above observational limits. Estimated redshifts are taken from Plionis & Valdarnini (1991).

All the above redshifts are heliocentric and transformed to the Local Group frame using the latest estimates for the galactic coordinates and velocity of the Sun. Redshifts are converted to proper distances using a spatially flat background cosmology with $H_0 = 100 \, h \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$ and $q_0 = 0.5$. Thus the redshift cut-off corresponds to a limiting distance $R_{\text{max}} \leq 315 \, h^{-1} \, \text{Mpc}$.

2.2 The Hubble volume simulations

For the purpose of our study it is necessary to use the largest up-to-date cosmological $N$-body simulations. This is the reason for utilizing the Virgo Consortium structure formation models (Frenk et al. 2000). Details of the simulations have been presented in Colberg et al. (2000) and Evrard et al. (2001, and references therein), so we only briefly discuss the main points here.

The Hubble Volume simulations follow the evolution of $10^9$ particles in volumes comparable to the whole observable Universe. We consider two spatially flat cold dark matter (CDM) structure formation models, namely $\Lambda$CDM with $\Omega_\Lambda = 0.7$ and $\tau$CDM (resembling a massive $\tau$-neutrino contribution). Further details of the two models are given in Table 1. The lengths of the boxes are 3 and $2 \, h^{-1} \, \text{Gpc}$ for the two cosmologies respectively. In both cases, the particle mass is $m_p \approx 2.2 \times 10^{12} \, h^{-1} \, M_\odot$ and both models are normalized to the abundance of rich clusters at $z = 0$, i.e. $\sigma_8 = 0.55 \Omega_m^{0.6}$ (Eke, Cole & Frenk 1996) and to COBE results.

Galaxy clusters are specified with a variety of methods, one of which is the friends-of-friends algorithm (cf. Evrard et al. 2001). The sizes of simulation boxes certify that an appreciable number of independent ‘observers’ will be identified within these vast volumes, and the large number of simulated clusters ($>10^8$) will ensure better statistics when supercluster shape properties are measured (see Sections 4 and 5).

Since the Abell/ACO cluster distances are uncorrected for redshift-space distortions and in order to compare simulation and data reliably, we transform the simulated cluster positions to redshift space.

3 GEOMETRICAL AND SHAPE FORMALISM

3.1 Selection parameters

The supercluster catalogues for both observed and simulated data are constructed by using a constant-size neighbourhood radius, i.e. the percolation radius (Zel’dovich et al. 1982), a scheme that has been successfully applied to similar kinds of studies. We place a sphere of a certain size around each cluster and then find all neighbouring spheres having an overlap region. In doing so, we join all clusters falling within the spheres that have common areas, and do this for all clusters in the sample. In order to choose the optimal percolation radius, we have repeated the procedure by successively increasing the size of the sphere. At the end, we identify the radius that yields the maximum number of superclusters, which obviously occurs before the percolation of the superclusters themselves. The choice of this percolation radius (hereafter $p_t$) has been based on criteria similar to those of Einasto et al. (1994, 2001a,b, and references therein).

To this end, we plot in Fig. 1 the dependence of the number of superclusters on $p_t$ for a variety of percolation radii for both data and models. The solid line corresponds to the Abell/ACO supercluster data, whereas the long-dashed and short-dashed lines denote $\Lambda$CDM and $\tau$CDM respectively. Note that this plot accounts for superclusters with at least eight members, i.e. with multiplicity $k \geq 8$. As $p_t$ increases, the supercluster number increases accordingly, reaching a maximum at radii between 25 and $32 \, h^{-1} \, \text{Mpc}$. At larger radii, superclusters start connecting with each other, and at even larger radii we reach the point of superconnectivity with only a few (≤5) huge objects pervading the total volume available. We therefore choose to work with $p_t = 27 \, h^{-1} \, \text{Mpc}$, which is a value well away from the

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The number of superclusters $N_{\text{scl}}$ as a function of $p_t$ for both data and the two dark matter models. The solid line denotes the observational sample, while the long-dashed and short-dashed lines correspond to the two models ($\Lambda$CDM, $\tau$CDM). Note that the superconnectivity limit is similar in all three data sets, occurring at depths $>33 \, h^{-1} \, \text{Mpc}$. Error bars ($\pm 1\sigma$) are shown only for one set of data for clarity.
superconnectivity limit (\(\approx 33 \, h^{-1} \text{Mpc}\)). Note that our value is consistent with other recent analyses (Einasto et al. 1994, 1997).

In order to construct realistic Abell/ACO simulation lookalikes we need to compute the number density of the Abell and ACO cluster samples. We do so by using 10 equal-volume shells (\(\delta V = 3 \times 10^8 \, h^{-3} \text{Mpc}^3\)) up to \(R_{\text{max}} \approx 315 \, h^{-1} \text{Mpc}\) and calculate, as a function of radial depth, their densities separately. The corresponding average-over-shells densities for the two samples are \(n_{\text{Abell}} \approx 1.62 \times 10^3 \, h^{-3} \text{Mpc}^{-3}\) and \(n_{\text{ACO}} \approx 2.55 \times 10^3 \, h^{-3} \text{Mpc}^{-3}\), giving rise to intercluster separations of order \(\sim 39.5\) and \(\sim 34 \, h^{-1} \text{Mpc}\) respectively. For completeness, we note that the number density of the combined catalogue is \(\sim 1.82 \times 10^3 \, h^{-3} \text{Mpc}^{-3}\), corresponding to a mean separation of \(\sim 38 \, h^{-1} \text{Mpc}\) in accordance with other estimates of the same population.

### 3.2 The shapefinders

An appreciable number of geometrical and topological tools have been developed recently for identifying correctly and quantifying the rich texture of large-scale structure as it appears in large angular or redshift surveys and \(N\)-body simulations (Babul & Starkman 1992; Luo & Vishniac 1995; Sahni & Coles 1995; Sathyaprakash et al. 1998b; Sahni & Habib 1999; Schmalzing et al. 1999, and references therein). In contrast to traditional schemes (low-order statistics) which bear no relation to either topology or angular or redshift surveys and the rich texture of large-scale structure as it appears in large scale simulations, we investigate the performance of our shape-finding method, we utilize a Monte Carlo (MC) approach. In particular, given as input parameters the three axes \(I_1, I_2\) and \(I_3\) of an ellipsoid with equation

\[
\frac{x^2}{I_1} + \frac{y^2}{I_2} + \frac{z^2}{I_3} \leq 1
\]

for \(k \geq 5\), the question we answer is ‘what are the most probable measured \(K_1\) and \(K_2\) recovered by our shape algorithm?’

In Fig. 2, we compare theoretical predictions with MC-estimated values of \(K_1\) and \(K_2\) as a function of multiplicity \(k\). Horizontal solid lines correspond to the input values for an ideal pancake (upper and lower) and an ideal triaxial structure (middle) and are taken from Sahni et al. (1998, their table 1). Upper \((K_1)\) and lower \((K_2)\) dashed lines with error bars denote the derived values for the pancake,
Table 2. List of the Abell/ACO superclusters using $p_1 = 27 \ h^{-1} \ Mpc$. The columns are as follows: index number, multiplicity, axes of triaxial ellipsoid, distance from us, $K_1$, $K_2$, their ratio $\mathcal{R}$, the morphological classification type and finally the supercluster name (see Einasto et al. 2001a, their table A1). F denotes filaments, P is for pancakes and eF and eP symbolize extremely elongated or planar superclusters. Note that $I_1$, $I_2$, $I_3$ and $R$ have units of $h^{-1} \ Mpc$. We also report that, because of our cut in $b$, only part of the Shapley supercluster has been detected.

| Index | $k$ | $I_1$ | $I_2$ | $I_3$ | $R$ | $K_1$ | $K_2$ | $\mathcal{R}$ | Type  | Name              |
|-------|-----|-------|-------|-------|-----|-------|-------|-----------|-------|-------------------|
| 1     | 16  | 91.6  | 26.8  | 14.1  | 267.9| 0.1405| 0.2622| 0.54      | F     | Pegasus-Pisces   |
| 2     | 22  | 63.0  | 30.6  | 25.1  | 291.0| 0.0416| 0.0773| 0.54      | F     | Sculptor         |
| 3     | 11  | 37.1  | 20.5  | 14.8  | 184.1| 0.0454| 0.0644| 0.71      | F     | Pisces-Aries     |
| 4     | 9   | 31.1  | 23.6  | 12.1  | 129.1| 0.0723| 0.0463| 1.56      | P     | Pisces           |
| 5     | 24  | 56.7  | 23.8  | 14.1  | 174.1| 0.0945| 0.1429| 0.66      | F     | Pisces-Cetus     |
| 6     | 8   | 30.8  | 20.4  | 3.1   | 302.4| 0.4551| 0.1194| 3.81      | eP    | Fornax-Eridanus  |
| 7     | 18  | 84.9  | 19.0  | 11.7  | 117.8| 0.1206| 0.3355| 0.36      | eP    | Sextans+Leo      |
| 8     | 8   | 34.5  | 21.2  | 7.7   | 204.3| 0.1778| 0.0972| 1.83      | P     | Leo–Sextans      |
| 9     | 13  | 55.9  | 22.3  | 12.6  | 185.6| 0.1074| 0.1614| 0.67      | F     | Ursa Majoris     |
| 10    | 9   | 44.8  | 22.5  | 10.3  | 298.0| 0.1356| 0.1218| 1.11      | P     | Leo–Virgo        |
| 11    | 19  | 63.1  | 34.6  | 17.9  | 225.5| 0.1004| 0.0937| 1.07      | P     | Virgo–Coma       |
| 12    | 9   | 36.1  | 22.1  | 7.7   | 275.3| 0.1913| 0.1001| 1.91      | P     | Leo A             |
| 13    | 16  | 42.0  | 27.1  | 18.2  | 295.5| 0.0431| 0.0458| 0.94      | F     | Draco             |
| 14    | 15  | 47.7  | 33.0  | 13.5  | 135.1| 0.1333| 0.0712| 1.87      | P     | Shapley (part)   |
| 15    | 16  | 55.7  | 37.1  | 20.2  | 184.8| 0.0742| 0.0570| 1.30      | P     | Bootes           |
| 16    | 10  | 35.0  | 14.3  | 9.9   | 210.6| 0.0713| 0.1336| 0.53      | F     | Corona Borealis  |
| 17    | 15  | 56.5  | 19.3  | 13.2  | 116.2| 0.0835| 0.1843| 0.45      | eF    | Hercules         |
| 18    | 10  | 37.6  | 13.7  | 10.3  | 240.6| 0.0680| 0.1545| 0.44      | eF    | Aquarius B       |
| 19    | 9   | 27.1  | 11.5  | 9.6   | 168.0| 0.0488| 0.1048| 0.47      | eF    | Aquarius–Cetus   |
| 20    | 20  | 71.9  | 38.7  | 28.3  | 233.8| 0.0460| 0.0081| 0.68      | F     | Aquarius         |
| 21    | 8   | 33.1  | 18.3  | 5.1   | 190.5| 0.2757| 0.1317| 2.09      | eP    | Horologium–Reticulum |
| 22    | 46  | 79.6  | 59.3  | 32.4  | 189.7| 0.0638| 0.0428| 1.49      | P     | Caelum           |
| 23    | 8   | 33.9  | 19.4  | 6.6   | 285.2| 0.2069| 0.1141| 1.81      | P     | Caelum           |
| 24    | 12  | 43.5  | 10.9  | 8.0   | 263.3| 0.0892| 0.2733| 0.33      | eF    | Microscopium     |
| 25    | 13  | 45.2  | 30.7  | 12.8  | 205.9| 0.1306| 0.0726| 1.80      | P     | –                |
| 26    | 8   | 31.3  | 17.3  | 10.3  | 277.8| 0.0737| 0.0806| 0.91      | F     | Grus             |

Figure 3. Two-dimensional whole-sky map of the 26 Abell/ACO superclusters (crosses). Open symbols denote the clusters associated with superclusters with $k \geq 8$. Note that we have detected 11 superclusters in the north and 15 in the south.

while the middle one ($K_1$) indicates the triaxial object. For the latter case, we observe that our MC-computed values always approximate extremely well (within 5 per cent) the input ones for all multiplicities used. Similar results are also obtained for $K_2$ in the case of the pancake (upper lines). However, it is evident that our $K_2$ estimated values lie systematically above the input ones, although asymptotic convergence is gradually achieved with increasing multiplicity. This systematic trend effectively means that our algorithm tends to make pancakes less planar, a feature which is more pronounced at small multiplicities. Exactly the opposite event occurs in the case of filaments for the input and MC-estimated values of $K_1$, thus producing less elongated filaments than it should. This effect tends to produce a slightly distorted shape spectrum of superclusters, keeping, however, the shape identity of the superclusters unchanged (filaments remain filaments and pancakes remain pancakes).

We have concluded that, for $k < 8$, our input results differ significantly from the MC-computed values for the study cases of the pancake ($K_2$) and the filament ($K_1$). This is also in line with previous analyses on shape determination, thus proving the caveat of the technique for superclusters with a few cluster members.

4 MORPHOLOGICAL PROPERTIES

4.1 The Abell/ACO superclusters

We investigate supercluster characteristics according to the observational requirements and the definitions of shape diagnostics set out in Section 3. Taking the optimum value of $p_1 = 27 \ h^{-1} \ Mpc$ for the combined Abell/ACO sample, we end up with 26 superclusters with $k \geq 8$. The relevant information is presented in Table 2. In Fig. 3, we show a 2D schematic representation of superclusters (crosses) superimposed on to the related cluster distribution (open symbols) for the Abell/ACO sample. The absence of objects in the central stripes of the plot is due to the ZoA restrictions that we have placed. Note that only superclusters with $k \geq 8$ and their member clusters are plotted.

As is evident from Table 2, there are no spherical superclusters (crosses) superimposed on to the related cluster distribution (open symbols) for the Abell/ACO sample.
in concordance with numerical N-body simulations of gravitational clustering and similar studies on observed data (Plionis, Valdarnini & Jing 1992; Sathyaprakash et al. 1998a,b; Sahni et al. 1998; BPR). More than half of the systems (54 per cent or 14/26) reveal filamentary structure (cf. Section 5.2), five of which are dubbed as extreme filaments ($R \leq 0.5$). The rest of the objects (12 or 46 per cent) are estimated to be pancakes, with two of them being extreme cases ($R \geq 2$).

We plot in Fig. 4 the results of this study, where the ratio $R$ as a function of $k$ is shown for all 26 real superclusters. The equilibrium between filamentarity and planarity, however, seems to be perturbed if we extend the $k$-infinum from 8 to 10 members. In this case, we find 71 per cent (12/17) filaments, while for $k \leq 10$ superclusters we obtain 64 per cent (7/11) pancakes. We attribute this to the ill-defined shapes of superclusters with $k \leq 10$, as evidenced from the analysis of Section 3.3 (cf. Fig. 2). Statistically speaking, the larger the multiplicity, the more accurately supercluster morphologies are defined, and the more filaments are revealed.

### 4.2 The simulated distributions

The task of constructing mock supercluster catalogues based on the two aforementioned dark matter models ($\sigma$CDM and $\Lambda$CDM) is accomplished by using the selection parameters of the Abell/ACO population presented earlier. Since the lengths of the simulated boxes are 2 and $3 h^{-1}$ Gpc for the two models respectively, we can easily define several mock cluster distributions as seen by a variety of totally independent observers. The number of these observers per simulation box can then be computed as $N_{obs} = (L_{box}/2R_{\text{max}})^3$.

We have defined 27 such observers for $\sigma$CDM and 64 for $\Lambda$CDM, each of them having exactly the same observational features as the initial Abell/ACO population (i.e. number density, number of clusters, selection function, geometry and $R_{\text{max}}$).

We furthermore make use of the percolation parameter $p_c$ that maximizes the mock supercluster numbers for each model (see Fig. 1). We have computed $p_c = 32 h^{-1}$ Mpc for $\sigma$CDM and $p_c = 28 h^{-1}$ Mpc for $\Lambda$CDM. The latter values correspond to $\sim 22 \pm 3.5$ superclusters for $\sigma$CDM and $\sim 24 \pm 4$ for $\Lambda$CDM, where means and scatters emanate from the 27 and 64 observers respectively.

It is evident that the choice of $p_c$ for both the models and the observational data, is essential not only for the detection of rich superclusters, but also for getting a better handle on cosmic variance effects (see next section). To this end, we have cross-checked our findings using the nearest-neighbour statistical measure (critical radius $R_{\text{cr}}$) for clustered distributions (Peebles 2001),

$$R_{\text{cr}} = \left[\frac{3 - \gamma}{\omega_0(n)r_0^2}\right]^{1/(3-\gamma)},$$

where $\omega_0$ and $n$ are the solid angle and mean number density, and $r_0$ and $\gamma$ correspond to the correlation length and the slope of the correlation function of the sample under study. Using a plausible set of parameters for the clustering properties (correlation lengths, amplitudes and slopes) of the two models (see section 3.2 of Colberg et al. 2000) and the average values from the literature for the observed sample, we find that our values are in excellent agreement with those predicted by equation (5).

### 5 SUPERCLUSTER STATISTICS

#### 5.1 Cosmological implications

We compare the shape and volume (size) spectral distributions between the data and two cosmological models via a standard Kolmogorov–Smirnov (KS) statistical test. We then compute the corresponding probabilities of consistency between models and data ($P_{\text{KS}}$) and place these results in Table 3. In order to investigate whether the above two statistics can be used as a cosmological discriminant, we first use the KS test to compare the two model distributions. It is evident from Table 3 that the shape spectrum fails to discriminate between the two models, probably echoing the Gaussian initial conditions common to both cosmologies. The volume spectrum constitutes a useful tool, since it yields a zero probability ($\sim 10^{-19}$) that $\sigma$CDM and $\Lambda$CDM are being selected from the same parent population.

We display in Fig. 5 the results from the shape (left-hand plots) and volume (right-hand plots) spectra. Upper panels correspond to the $\sigma$CDM model and lower panels to $\Lambda$CDM. Hatched areas and open symbols denote the observed data and filled circles the two dark matter cosmologies. Error bars in all panels are the $\pm 1\sigma$ scatter between the independent observers and the vertical solid lines in the left-hand panels mark the transition limits between filaments and pancakes. A characteristic worth observing is that in both models the percentage of filaments exceeds that of pancakes. The latter finding is in accordance with $N$-body results (Sathyaprakash et al. 1998a,b). A clear indication of the discriminative power of the volume spectrum test is presented in the right-hand panels of Fig. 5. It is apparent that the $\sigma$CDM distribution gives the worst fit to the observed data, with the
shown for the PSC$^k$ superclusters for Figure 6.

Shape distributions for Abell/ACO (hatched areas) and PSC$^k$ (left) and prominent in our optical sample for dominance is confirmed by both kinds of data, although it is less optical data (hatched histograms) for superclusters with $k \geq 8$ (left) and $k \geq 10$ (right). Poissonian errors are only shown for the PSC$^k$ sample, for clarity.

Figure 5. Comparison between data (hatched areas and open circles) and models (filled symbols). Shape spectra are plotted in the left-hand panels and multiplicity functions in the right-hand panels for $\Omega_{CDM}$ (top) and $\Lambda$CDM (bottom) respectively.

Figure 6. Shape distributions for Abell/ACO (hatched areas) and PSC$^k$ superclusters for $k \geq 8$ (left) and $k \geq 10$ (right). Poissonian errors are only probability of consistency being 0.007. In contrast to this, the $\Lambda$CDM supercluster volume spectrum represents better that of the Abell/ACO supercluster sample ($P_{KS} = 0.43$). This can probably be explained as a natural outcome of the different clustering pattern of the two cosmologies considered here [see Jenkins et al. (1998) and Colberg et al. (2000) for a comparison between optical data and Virgo models].

To validate our findings, we further explore the selection parameters presented in Section 3 and test the reliability of our methods. On choosing reasonable values for $p_c$, the multiplicity infimum and finally a smaller set of independent observers, we have verified that our results remain remarkably robust.

5.2 Optical versus infrared supercluster shapes

We compare the shape spectra of the optical (Abell/ACO) and the infrared (PSC$^k$) superclusters in order to probe whether or not the prominence of filamentarity is retained by all-sky data with diverse global geometrical and selection properties. For this purpose, we have resorted to the recently constructed all-sky PSC$^k$ supercluster catalogue (BPR) based on $\sim 12$ 000 infrared galaxies out to $240\, h^{-1}$ Mpc.

We display in Fig. 6 the shape distributions of infrared and optical data (hatched histograms) for superclusters with $k \geq 8$ (left) and $k \geq 10$ (right). It is obvious that the filamentarity dominance is confirmed by both kinds of data, although it is less prominent in our optical sample for $k \geq 8$ (cf. Fig. 4 and discussion in Section 4.1). In fact, for $k \geq 10$, we observe that infrared and optical data yield almost identical values for the fractions of filaments ($\sim 70$ per cent) and pancakes ($\sim 30$ per cent). Note, however, that the PSC$^k$ superclusters are identified from the galaxy density field, smoothed on a grid having a cell size of $10^3\, h^{-3}$ Mpc$^3$. In this case, $k$ is the cell multiplicity of the detected superclusters.

A final word of caution is due here. The above argument is not intended to cast any shadow on the results based on the use of the nominal $k$ infimum applied to the present analysis. Had we used superclusters with $k \geq 10$, we would have obtained qualitatively the same results in the data--model comparison, but would run the risk of being too close to the validity limit of the KS test.

6 CONCLUDING REMARKS

We have explored the shape parameters of superclusters identified in the Abell/ACO and simulated (Virgo dark matter models) cluster populations, up to a depth of $315\, h^{-1}$ Mpc. Superclusters were identified using the percolation algorithm and an optimal percolation radius, $p_c$. The simulated supercluster samples were constructed by applying the Abell/ACO cluster catalogue selection functions to the mock cluster samples of two cosmological models (CDM and $\Lambda$CDM). The investigation of supercluster morphologies was based on the differential geometry method devised by Sahni et al. (1998).

We have found that filamentary supercluster shapes dominate over pancake morphologies, in both data and models. This further supports the idea that filamentarity is the main structural feature of the large-scale structure, since it has been born out of the analyses of the available infrared and optical samples.

A standard KS statistical test of consistency between the size distributions of the Abell/ACO and the two model superclusters has clearly given a preference to the $\Lambda$CDM ($\Omega_m = 0.7$) cosmology. In contrast, CDM is rejected at a relatively high (99.3 per cent) significance level. Finally, the shape spectrum is insensitive to the different cosmologies, probably reflecting their common Gaussian initial conditions. The latter findings are in concordance with a similar analysis of the PSC$^k$ supercluster shapes (see BPR).

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REFERENCES

Abell G., 1958, ApJS, 3, 211
Abell G., Corwin H., Olowin R., 1989, ApJS, 70, 1
Babul A., Starkman G., 1992, ApJ, 401, 28
Bahcall N., 1998, AR&A, 26, 631
Bahcall N., Soneira R., 1984, ApJ, 277, 27
Basilakos S., Plionis M., Rowan-Robinson M., 2001, MNRAS, 223, 47 (BPR)
Batutski D., Burns J., 1985, AJ, 90, 1413
Cappi A., Maurogordato S., 1992, A&A, 259, 423
Colberg J. et al., 2000, MNRAS, 319, 209

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Coles P., Plionis M., 1991, MNRAS, 250, 75
Davé R., Hellinger D., Primack J., Norlihenius R., Klypin A., 1997, MNRAS, 284, 607
de Lapparent V., Geller M. J., Huchra J. P., 1991, ApJ, 369, 273
Einasto M., Einasto J., Tago E., Dalton G., Andernach H., 1994, MNRAS, 269, 301
Einosto M., Tago E., Einasto J., Andernach H., 1997, A&AS, 123, 119
Einasto M., Einasto J., Tago E., Mueller V., Andernach H., 2001a, AJ, 122, 2222
Einasto M., Einasto J., Tago E., Andernach H., Dalton G., Mueller V., 2001b, astro-ph/0012538
Eke V. Cole S., Frenk C. S., 1996, MNRAS, 282, 263
Evrard A. et al., 2001, ApJ, submitted (astro-ph/0110246)
Frenk C. et al., 2000, pre-print (astro-ph/0007362)
Frisch P. et al., 1995, A&A, 296, 611
Jaaniste J., Tago E., Einasto M., Einasto J., Andernach H., Mueller V., 1998, A&A, 336, 35
Jenkins A. et al., 1998, ApJ, 449, 20
Kalinkov M., Kuneva I., 1995, A&AS, 113, 451
Kerscher M. et al., 1997, MNRAS, 284, 73
Kerscher M., Mecke K., Schmalzing J., Beisbart C., Buchert T., Wagner H., 2001a, A&A, 373, 1
Kerscher M. et al., 2001b, A&A, 377, 1
Luo S., Vishniac E., 1995, ApJS, 96, 429
Mecke K., Buchert T., Wagner H., 1994, A&A, 288, 697
Peebles P. J. E., 2001, ApJ, 557, 495
Plionis M., Valdarnini R., 1991, MNRAS, 249, 46
Plionis M., Barrow J. D., Frenk C. S., 1991, MNRAS, 249, 662
Plionis M., Valdarnini R., Jing Y. P., 1992, ApJ, 398, 12
Postman M., Huchra J., Geller M., 1992, ApJ, 384, 404
Sahni V., Habib S., 1999, in Sato K., eds, Proc. IAU Symp. 183, Cosmological Parameters and the Evolution of the Universe. Kluwer, Dordrecht
Sahni V., Coles P., 1995, Phys. Rep., 262, 1
Sahni V., Sathyaprakash B. S., Shandarin S. F., 1998, ApJ, 495, L5
Sathyaprakash B. S., Sahni V., Shandarin S. F., Fisher B. K., 1998a, ApJ, 507, L109
Sathyaprakash B. S., Sahni V., Shandarin S. F., 1998b, ApJ, 508, 551
Schmalzing J., Buchert T., 1997, ApJ, 482, L1
Schmalzing J., Buchert T., Melott A. L., Sahni V., Sathyaprakash B. S., Shandarin S. F., 1999, ApJ, 526, 568
Weinberg D. H., Gott J. R., III, Melott A. L., 1987, ApJ, 321, 2
West J. M., 1989, ApJ, 347, 610
Yess C., Shandarin S. F., 1996, ApJ, 465, 2
Zeldovich Ya. B., Einasto J., Shandarin S., 1982, Nat, 300, 407
Zucca E., Zamorani G., Scaramella R., Vettolani G., 1993, ApJ, 407, 470

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