Two new catalogues of superclusters of Abell/ACO galaxy clusters out to redshift 0.15

M. Chow-Martínez, H. Andernach, C. A. Caretta and J. J. Trejo-Alonso

Departamento de Astronomía, DCNE, Universidad de Guanajuato, Apdo. Postal 144, CP 36000, Guanajuato, Gto., Mexico

Accepted 2014 September 15. Received 2014 September 10; in original form 2014 June 3

ABSTRACT
We present two new catalogues of superclusters of galaxies out to a redshift of $z = 0.15$, based on the Abell/ACO cluster redshift compilation maintained by one of us (HA). The first of these catalogues, the all-sky Main SuperCluster Catalogue (MSCC), is based on only the rich (A-) Abell clusters, and the second one, the Southern SuperCluster Catalogue (SSCC), covers declinations $\delta < -17^\circ$ and includes the supplementary Abell S-clusters. A tunable Friends-of-Friends algorithm was used to account for the cluster density decreasing with redshift and for different selection functions in distinct areas of the sky. We present the full list of Abell clusters used, together with their redshifts and supercluster memberships and including the isolated clusters. The SSCC contains about twice the number of superclusters than MSCC for $\delta < -17^\circ$, which we found to be due to (1) new superclusters formed by A-clusters in their cores and surrounded by S-clusters (50 per cent), (2) new superclusters formed by S-clusters only (40 per cent), (3) redistribution of member clusters by fragmentation of rich (multiplicity $m > 15$) superclusters (8 per cent), and (4) new superclusters formed by the connection of A-clusters through bridges of S-clusters (2 per cent). Power-law fits to the cumulative supercluster multiplicity function yield slopes of $\alpha = -2.0$ and $\alpha = -1.9$ for MSCC and SSCC, respectively. This power-law behaviour is in agreement with the findings for other observational samples of superclusters, but not with that of catalogues based on cosmological simulations.

Key words: astronomical data bases: miscellaneous – catalogues – galaxies: clusters: general – cosmology: observations – large-scale structure of Universe.

1 INTRODUCTION
Superclusters are usually defined as ‘clusters of clusters’ given that mainly catalogues of galaxy clusters have been used to identify them. De Vaucouleurs (1953) was the first to present evidence of the existence of a large-scale superstructure now known as the Local Supercluster. The superclustering as a general phenomenon was originally advocated by various authors, beginning with Abell (1961), and followed by Bogart & Wagoner (1973), Hauser & Peebles (1973), and Peebles (1974). Taking this definition of superclusters as aggregates of two or more galaxy clusters (e.g. Bahcall & Soneira 1984), supercluster catalogues have been produced using the pseudo-3D distribution of Abell/ACO clusters (Abell 1958; Abell, Corwin & Olowin 1989) by Rood (1976), Thuan (1980), Bahcall & Soneira (1984), Batuski & Burns (1985), West (1989), Zucca et al. (1993), Kalinkov & Kuneva (1995), and Einasto et al. (1994, 1997, 2001), among others. Zucca et al. (1993) were the first to use the total sample of Abell/ACO A-clusters to construct an all-sky catalogue of 69 superclusters within a redshift of $z \sim 0.1$, with an overdensity of at least twice the average density, and with at least three member clusters. Einasto et al. (2001) used 1663 A-clusters (64 per cent of them with measured spectroscopic redshifts), out to $z = 0.13$, to obtain a catalogue of 285 superclusters via a percolation analysis based on a linking length of $34h_100^{-1}$ Mpc, assumed constant throughout the considered volume. The number of member clusters (commonly called multiplicity, $m$) ranged from 2 to 35. In addition, they also presented the first catalogue of 19 superclusters based on X-ray luminous clusters detected in the ROSAT All-Sky Survey (Voges et al. 1999), on the ROSAT-ESO Flux Limited X-Ray Galaxy Cluster Survey (REFLEX II). Some authors have also used catalogues of individual galaxies based on large-scale surveys to search for superclusters, defining these as significant density enhancement of galaxies (e.g. Gregory & Thompson 1978; Giovanelli & Haynes 1993; Quintana et al. 1995; Barmby & Huchra 1998; Hanks et al. 2001; Einasto et al. 2007b, 2011a).

Superclusters, being immersed in the ‘cosmic web’, generally exhibit irregular or filamentary shapes connected through bridges...
of galaxies and separated by extensive ‘void’ regions where almost no galaxies are found. Properties of the large-scale structure (determined using both observational data and N-body cosmological simulations) have been discussed, e.g. by Jaaniste et al. (1998), Gramann & Shuhonenko (2002), Kolokotronis, Basilakos & Plionis (2002), Wray et al. (2006), Einasto et al. (2007a,c,d, 2011b), Costa-Duarte, Sodré & Durret (2011), Luparello et al. (2011), Soubbie (2011), and Soubbie, Pichon & Kawahara (2011).

Currently there is no evidence that superclusters have reached virialization, since the sizes of these structures range from a few Mpc to ~150 h\(^{-1}\) Mpc, and the crossing time for a member cluster within the system exceeds the age of the Universe (e.g. Oort 1983; Gramann & Shuhonenko 2002). This implies that these systems still preserve a memory of their dynamical history, which makes them worth studying. Furthermore, since they constitute the environment of a considerable fraction of the clusters, groups and galaxies themselves, by comparing their properties with those in lower density environments we can study the effect of this environment on the evolution of such systems. Galaxy clusters are the most massive systems in the Universe that have condensed out of the Hubble flow, and their evolution is still a matter of vital discussion. Finally, superclusters represent regions of significant density enhancement which cause distortions in the local gravitational field that are sometimes noticeable via the bulk motions towards them (e.g. the case of the Great Attractor; Lynden-Bell et al. 1988). They also provide information on the mass distribution in intercluster space, e.g. by measuring their imprint on the cosmic microwave background via the Sunyaev–Zeldovich effect (e.g. Planck Collaboration VIII 2013). All these features allow one to constrain and refine cosmological models of the Universe.

In this work, we describe two new catalogues of superclusters based on the update of late 2012 of the Abell/ACO cluster redshift compilation by one of us (for a description of its content cf. Andernach et al. 2005), restricting ourselves to clusters with redshift \(z \leq 0.15\). For the first catalogue, we consider the distribution of Abell/ACO A-clusters (rich clusters) all over the sky, while the second one is a southern sky catalogue \((s < −17°)\) based on both A-clusters and the supplementary S-clusters (typically poorer than the A-clusters). For the construction of both catalogues, we tuned the linking length as a function of redshift and position on the sky, in order to identify systematic effects and to their position on the sky, separated in redshift by more than \(0.15\) km s\(^{-1}\), we register these as components A, B, C, \ldots in increasing order of redshift. In many cases, the component with the dominant number of redshifts is clearly the one recognized by Abell/ACO, while in other cases these components may be similarly populated, and the identification is not straightforward. In what follows, we shall refer to these as line-of-sight components of a cluster, and we include all the detected ones in our analysis out to \(z = 0.15\).

With the advent of large-scale multi-object spectroscopic surveys, like the Two-Degree Field Galaxy Redshift Survey (Colless et al. 2001), the Six-Degree Field Galaxy Redshift Survey (Jones et al. 2004), and the SDSS (e.g. SDSS-DR7; Abazajian et al. 2009), the source of redshifts for this compilation has gradually changed from surveys of individual clusters to large-area redshift surveys, resulting in more redshifts for cluster members from fewer references per year. We include a number of new spectroscopic redshifts obtained by us for galaxies in 121 clusters. These will be published in a separate paper. Furthermore, for clusters with no spectroscopic redshift as yet, the compilation also includes estimated redshifts, kindly provided by M. J. West (private communication) and based on the relation proposed by Peacock & West (1992).

The current compilation includes all 4076 A- and 1174 S-clusters. For 1011 of the A-clusters, we list a total of 2511 line-of-sight components, resulting in altogether 5576 clusters/components, while 230 S-clusters are split into 551 components, resulting in a total of 1495 S-clusters/components. From these we selected the ones with redshift below 0.15 as the basis for our search for superclusters. These were 3410 A-clusters/components (92 per cent of them having measured spectroscopic redshifts for at least one member, and 76 per cent for at least three galaxies), and 1168 S-clusters/components (91 per cent with at least one galaxy with measured spectroscopic redshift, and 69 per cent with at least three). Beyond this redshift the sample becomes noticeably more incomplete. The redshift distribution for both samples is shown in Fig. 1. The S-clusters represent an important contribution in the southern sky, and they complement the sample towards lower richness clusters in this region at lower redshifts.

In Fig. 2, we divided the entire sample in subsamples according to their position on the sky, in order to identify systematic effects in their global distribution. In the northern sample, the main effect is the presence of the SDSS redshift data: where these data exist (\(z > 0.06\)), the S-clusters affect the southern sample especially at lower redshifts (\(z < 0.08\)) such that the first peak in redshift in the second panel of both Figs 1 and 2 is dominated by them. In the redshift range considered here, the S-clusters are almost exclusively poorer systems than the A-clusters. Thus, we decided to divide our sample into four, rather than two, subsamples, namely two northern subsamples, one for the SDSS region and

### 2 DATA

The Abell/ACO cluster redshift compilation used here (e.g. Andernach et al. 2005) is a collection of individual radial velocities for potential member galaxies of such clusters. The compilation has been updated since 1989 (Andernach 1991; Andernach et al. 1995; Andernach & Tago 1998) by monitoring redshift data of galaxies from the published literature and a few unpublished references. The compilation, as of late 2012, contains redshifts for about 130 000 individual cluster galaxies in 3930 different Abell clusters. Whenever a cluster shows more than one concentration along the line of sight, separated in redshift by more than \(\sim 1500\) km s\(^{-1}\), we register these as components A, B, C, \ldots in increasing order of redshift. In many cases, the component with the dominant number of redshifts is clearly the one recognized by Abell/ACO, while in other cases these components may be similarly populated, and the identification is not straightforward. In what follows, we shall refer to these as line-of-sight components of a cluster, and we include all the detected ones in our analysis out to \(z = 0.15\).

With the advent of large-scale multi-object spectroscopic surveys, like the Two-Degree Field Galaxy Redshift Survey (Colless et al. 2001), the Six-Degree Field Galaxy Redshift Survey (Jones et al. 2004), and the SDSS (e.g. SDSS-DR7; Abazajian et al. 2009), the source of redshifts for this compilation has gradually changed from surveys of individual clusters to large-area redshift surveys, resulting in more redshifts for cluster members from fewer references per year. We include a number of new spectroscopic redshifts obtained by us for galaxies in 121 clusters. These will be published in a separate paper. Furthermore, for clusters with no spectroscopic redshift as yet, the compilation also includes estimated redshifts, kindly provided by M. J. West (private communication) and based on the relation proposed by Peacock & West (1992).

The current compilation includes all 4076 A- and 1174 S-clusters. For 1011 of the A-clusters, we list a total of 2511 line-of-sight components, resulting in altogether 5576 clusters/components, while 230 S-clusters are split into 551 components, resulting in a total of 1495 S-clusters/components. From these we selected the ones with redshift below 0.15 as the basis for our search for superclusters. These were 3410 A-clusters/components (92 per cent of them having measured spectroscopic redshifts for at least one member, and 76 per cent for at least three galaxies), and 1168 S-clusters/components (91 per cent with at least one galaxy with measured spectroscopic redshift, and 69 per cent with at least three). Beyond this redshift the sample becomes noticeably more incomplete. The redshift distribution for both samples is shown in Fig. 1. The S-clusters represent an important contribution in the southern sky, and they complement the sample towards lower richness clusters in this region at lower redshifts.

In Fig. 2, we divided the entire sample in subsamples according to their position on the sky, in order to identify systematic effects in their global distribution. In the northern sample, the main effect is the presence of the SDSS redshift data: where these data exist (\(z > 0.06\)), the S-clusters affect the southern sample especially at lower redshifts (\(z < 0.08\)) such that the first peak in redshift in the second panel of both Figs 1 and 2 is dominated by them. In the redshift range considered here, the S-clusters are almost exclusively poorer systems than the A-clusters. Thus, we decided to divide our sample into four, rather than two, subsamples, namely two northern subsamples, one for the SDSS region and...
In the percolation analysis, the method usually used for identifying superclusters of galaxies, the linking length of the FoF is chosen such that it maximizes the number of systems formed. The result of the percolation analysis depends strongly on the linking length ($\ell$). For smaller linking lengths the FoF yields a smaller number of only the densest systems, while for larger linking lengths these systems start to connect among themselves, lowering the total number of systems until a complete percolation of the sample is reached (e.g. Einasto et al. 1984). For this reason, in the identification of superclusters of galaxies, the linking length of the FoF is often chosen such that it maximizes the number of systems formed in the percolation process. We shall call this the critical linking length, $\ell_c$.

The percolation analysis relies on the fact that the mean density is correctly represented (i.e. the completeness of the sample) in the considered volume. In an ideal (complete and homogeneous) sample, the critical linking length obtained this way should be the same throughout the entire volume. Since the distribution of the clusters in our sample is clearly less complete at higher redshifts (see Figs 1 and 2), and also differs from one subsample to the other, the choice of a single critical linking length for a supercluster search based on Abell/ACO clusters is certainly not the best solution. Therefore, we used a tunable value of $\ell_c$, which is allowed to vary with the selection function and thus corrects for completeness variations in both redshift and position on the sky. This selection function (the fraction of clusters missed as a function of the redshift, due to incompleteness in sampling and the Malmquist bias) is measured directly by estimating the value of $\ell_c$ in the four different subsamples and in different redshift ranges.

To this end, we divided each subsample into seven spherical shells with a width of $\Delta z = 0.03$, (allowing an overlap between them of $\Delta z = 0.01$), inside which the density is not expected to vary significantly. Thus, the first bin ranges from $z = 0.00$ to 0.03, the second one from $z = 0.02$ to 0.05, and so on. We obtained the value of $\ell_c$ for each redshift ‘shell’ and constructed the so-called Percolation Function (PF), i.e. the value of $\ell_c$ as function of the redshift. PFs for each subsample are shown in Fig. 3. Three different PFs were chosen. The first of these is the combination of the northern sample (excluding the SDSS region) and the southern sample (excluding the S-clusters), which we call the Master PF. As expected, these two subsamples show a similar behaviour. The second PF is that for the SDSS region, which we call the SDSS PF. Since it is poorly sampled at lower redshifts ($z < 0.06$), we first freely fitted the data and, then, forced it to coincide with the Master PF at $z = 0.06$, taking the Master PF as the SDSS PF for redshifts lower than this. The third PF is that for the southern subsample including the S-clusters, which we call the Southern PF. This latter one presents smaller critical linking lengths, $\ell_c$, than the Master PF at every redshift, and especially so at the lowest redshifts, obviously due to the higher space density of clusters when S-clusters are included.

The redshift range in which the PFs reach their lowest value may be interpreted as the one of highest completeness, and vice versa: in an undersampled region, the value of $\ell_c$ is larger. Thus, employing these PFs in our FoF compensates for the loss of objects due to selection effects. According to these curves, the best sampled region (excluding the contribution of SDSS and S-clusters) is near $z \sim 0.06$, where the Master PF reaches its minimum. At lower redshifts the sample suffers a deficiency due to the exclusion of clusters at $z \leq 0.02$, as imposed by the authors of the Abell/ACO catalogues. At higher redshifts, the undersampling is due to limiting sensitivity of the sky surveys used to find the clusters and incompleteness in the spectroscopic sampling. The SDSS PF has smaller values than

Figure 1. Redshift distribution for the A-clusters (left-hand panel) and A+S clusters (right-hand panel). The solid lines represent the expected number of clusters in spherical shells of $\Delta z = 0.01$ using a constant space density of clusters corresponding to the most completely surveyed redshifts for each distribution, namely $0.03 < z < 0.07$ for the all-sky distribution of A-clusters, and $z < 0.05$ for the A+S clusters in the southern ($\delta < -17^\circ$) sample. These values are $7.4 \times 10^{-5} h_0^3$ $\text{Mpc}^{-3}$ for only the A-clusters and $2.8 \times 10^{-5} h_0^3$ $\text{Mpc}^{-3}$ for A- and S-clusters together in the south. The first value, $8.9 \times 10^{-6} h_0^3$ $\text{Mpc}^{-3}$, is comparable to the one found by Einasto et al. (1997) for Abell/ACO clusters. The dashed line in the right-hand panel indicates the same function as the solid line in the left-hand panel. These curves grow according to $r^2$ where $r = \tau(z)$ is the comoving distance as described by Hogg (2000).

Figure 2. Redshift distribution for the northern and southern Abell/ACO clusters. For the northern subsample, the solid histogram is for the northern sky without the SDSS region and the dashed histogram is the one for the SDSS region. For the southern subsample, the solid histogram is the distribution for A-clusters and the dashed histogram is the one for A+S clusters.

another for the rest of the northern sky, and another two southern subsamples ($\delta < -17^\circ$), one including both A- and S-clusters and the other only the A-clusters.

3 PERCOLATION ANALYSIS

The Friends-of-Friends algorithm (FoF, e.g. Turner et al. 1976; Huchra & Geller 1982; Zeldovich, Einasto & Shandarin 1982; Einasto et al. 1984) is frequently used to link points when we do not know a priori how they are distributed. In a virialized regime, such as that we expect for at least the cores of the galaxy clusters, the linking length is determined by assuming a spherical gravitational collapse model (e.g. Caretta et al. 2008). However, since the superclusters are probably not in an equilibrium state, we cannot derive the ideal linking length in this way.
4 SUPERCLUSTERS OF ABEll/ACO GALAXY CLUSTERS

4.1 The catalogues

The Master and SDSS PFs were used to produce the Main SuperCluster Catalogue (MSCC) based on the all-sky sample of A-clusters. The MSCC contains 601 superclusters with multiplicities between 2 and 42. The Southern SuperCluster Catalogue (SSCC) was produced using the Southern PF, and contains 423 superclusters with multiplicities between 2 and 38. For the rest of this paper, we shall refer to individual superclusters with their MSCC and SSCC acronyms, followed by their sequence number (see Tables 1 and 2).

For the MSCC, 1152 input clusters (34 per cent of the total number of clusters) turn out to be isolated, while this number is 870 (36 per cent) for the SSCC. The fractions of superclusters with multiplicity \( m = 2 \) (pairs of clusters) are 48 and 52 per cent (containing 17 and 19 per cent of the input clusters), in the MSCC and SSCC, respectively. The richest superclusters, with \( m > 10 \), represent 4 per cent in both MSCC and SSCC, whose member clusters constitute 49 and 45 per cent of the input clusters for MSCC and SSCC, respectively. We also flagged as supercluster candidates the ones which would not be found by our FoF in a test catalogue that excludes the clusters with estimated redshifts. In our Abell/ACO sample limited to \( z \leq 0.15 \), out of 4578 clusters (including A- and S-clusters as well as their line-of-sight components) there are 358 with only estimated redshifts, identified with an ‘e’ following their names in Tables 1 and 2. Using the above definition, 37 (6 per cent) of the MSCC and 38 (9 per cent) of the SSCC superclusters are candidates, identified in the catalogues with a letter ‘c’ following the supercluster sequence number.

We also include in Tables 1 and 2 the supercluster ID of Einasto et al. (2001) for some specific cases (187 for MSCC and 117 for SSCC) where a certain minimum fraction of member clusters (explained below) in that catalogue is linked to the respective supercluster here. From now on, we shall denote Einasto et al. (2001) superclusters ID with the prefix SCL, as chosen by these authors. Tables 1 and 2 only include the cross-identifications when the association was sufficiently clear, with minimum ambiguities by fragmentations or ‘noise’ from subcomponents (divisions of the superclusters due to their member clusters having line-of-sight components). We assumed an entry in SCL to be the same as one in MSCC/SSCC when the number of coincident member clusters exceeded a certain fraction or when the main member cluster of well-known superclusters (e.g. those listed in Section 4.3) was found to be the same. The minimum fraction of member clusters required for the match depended on the multiplicity in MSCC; for pairs, we required both clusters to coincide; for triple and quadruple systems, we required at least two equal member clusters. For higher multiplicities \( (m \geq 5) \), we accepted ‘fragments’ (i.e. a subsample of member clusters) of the original superclusters listed in SCL, and, as we said, in some cases we allowed fractions lower than 50 per cent when the main member clusters were present in some particular MSCC. Where more than one entry in SCL match the same MSCC/SSCC, all SCL ID of these contributors are included (e.g. MSCC 8 in Table 1), in order of decreasing fraction of coincident member clusters (cases for which only one coincident cluster was found are not listed). For SSCC, as we will discuss in Section 5.1, this fragmentation is stronger, so we accepted an identification with SCL when we had at least two coincidences of original member clusters for the fragments of richest superclusters. This was done because fragments usually are accompanied by S-clusters in SSCC. In Section 4.2, we explain...
this matching procedure in more detail, including our treatment of clusters with line-of-sight components. There we also present more complete statistics accounting for more complex cases.

The MSCC and SSCC catalogues (Tables 1 and 2) contain the following columns: (1) the supercluster ID in the respective catalogue followed by the letter ‘c’ if the supercluster is considered a candidate; (2) the matching SCL from Einasto et al. (2001) where applicable; two or more, at most four, SCL ID’s appear if we found these SCL’s identifiable with the same MSCC or SSCC; (3) the multiplicity, m, i.e. the number of member clusters; (4) right ascension and (5) declination (for equinox J2000, in decimal degrees), obtained as the simple arithmetic mean of the member cluster positions and (5) declination (for equinox J2000, in decimal degrees); (6) redshift, $z$; (7) distance, in $h_{100}$ Mpc, of the pair of clusters with the maximum separation in each supercluster; (8) list of member clusters of the supercluster. The full table is available online.

Table 1. First 10 entries in MSCC: (1) MSCC number; (2) SCL identification; (3) multiplicity, $m$; (4,5) right ascension and declination (J2000) in decimal degrees; (6) redshift, $z$; (7) distance, in $h_{100}$ Mpc, of the pair of clusters with the maximum separation in each supercluster; (8) list of member clusters of the supercluster. The full table is available online.

| MSCC | SCL | $m$ | $RA_J$ | $Dec_J$ | $z_{SC}$ | $d_{max}$ | Abell/ACO member clusters |
|------|----|----|--------|---------|---------|----------|----------------|------------------------|
| 1    | 2  | 4  | 0.77   | -26.72  | 0.064   | 50.6     | A0014, A0020, A2682A, A2716, A2726B, A2734, A4038C, A4049B, A4053B |
| 2    | 3  | 2  | 1.09   | +09.77  | 0.098   | 20.2     | A2694, A2706 |
| 3    | 4  | 1  | 1.20   | +16.05  | 0.119   | 41.5     | A0001, A2688A, A2703, A2705 |
| 4    | 3  | 4  | 1.26   | +02.89  | 0.098   | 33.4     | A0003, A2696B, A2698, A2700A |
| 5    | 2  | 1  | 1.31   | -15.32  | 0.102   | 20.3     | A2699, A2710A |
| 6    | 4  | 1  | 1.58   | -64.24  | 0.116   | 37.7     | A2732, A2740A, A2760, A4028 |
| 7    | 5   | 3  | 2.03   | -36.93  | 0.043   | 28.5     | A2717A, A2721A, A4059 |
| 8    | 5.9| 10 | 2.09   | -35.26  | 0.117   | 79.4     | A2715B, A2721A, A2721B, A2724, A2730, A2749B, A2767, A2772, A4035A, A4074A |
| 9    | 2  | 2.35 | -10.57 | 0.110   | 16.2     | A0008A, A2709B |
| 10   | 3  | 3.06 | -34.91 | 0.096   | 22.4     | A2715A, A2749A, A2755 |

Table 2. First 10 entries in SSCC: (1) SSCC number; (2) SCL identification; (3) multiplicity, $m$; (4,5) right ascension and declination (J2000) in decimal degrees; (6) redshift, $z$; (7) distance, in $h_{100}$ Mpc, of the pair of clusters with the maximum separation in each supercluster; (8) list of member clusters of the supercluster. The full table is available online.

| SSCC | SCL | $m$ | $RA_J$ | $Dec_J$ | $z_{SC}$ | $d_{max}$ | Abell/ACO member clusters |
|------|----|----|--------|---------|---------|----------|----------------|------------------------|
| 1    | 2  | 0.20 | -23.73 | 0.097   | 18.8    | A2681, A2719 |
| 2    | 5  | 0.68 | -34.92 | 0.116   | 80.0    | A2715B, A2721A, A2721B, A2730, A2749B, A4035A, A4074A, S0012B, S1161C, S1161D, S1170B |
| 3    | 2  | 0.80 | -44.78 | 0.038   | 10.9    | S0005, S1173 |
| 4    | 3  | 1.23 | -38.67 | 0.103   | 24.2    | A4068, S0017e, S1172C |
| 5    | 2  | 2.61 | -39.93 | 0.070   | 14.0    | A2751A, S0006D |
| 6    | 2  | 3.38 | -29.83 | 0.123   | 24.7    | A2759B, S0010 |
| 7c   | 2  | 3.91 | -65.43 | 0.148   | 24.2    | A2737e, A2761e |
| 8    | 5  | 4.23 | -64.81 | 0.114   | 31.7    | A2732, A2740A, A2760, S0018e, S0057e |
| 9    | 2  | 4.24 | -35.03 | 0.095   | 4.2     | A2749A, A2755 |
| 10   | 2  | 3.43 | -23.26 | 0.066   | 11.8    | A0014, A0020 |

Table 3. The first 10 entries of the list of clusters used as input catalogue for MSCC and SSCC. Columns are: (1) Abell/ACO number/ID (including all line-of-sight components within $z \leq 0.15$); (2) measured or estimated redshift; (3) and (4) sequence number of the respective MSCC and SSCC supercluster host, or ‘iso’ if the cluster is isolated in the respective catalogue, a ‘−’ indicates that the cluster was not used in the respective input catalogue (northern clusters for SSCC and S-clusters for MSCC); (5) in the case of line-of-sight components, percentage of galaxies with measured redshift in each component is listed. The full table is available online.

<table>
<thead>
<tr>
<th>Abell/ACO</th>
<th>$z$</th>
<th>MSCC</th>
<th>SSCC</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0001</td>
<td>0.1249</td>
<td>3</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>A0002</td>
<td>0.1225</td>
<td>iso</td>
<td>iso</td>
<td>−</td>
</tr>
<tr>
<td>A0003</td>
<td>0.1022</td>
<td>4</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>A0005e</td>
<td>0.1120</td>
<td>iso</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>A0007</td>
<td>0.1030</td>
<td>iso</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>A0008A</td>
<td>0.1092</td>
<td>9</td>
<td>−</td>
<td>62</td>
</tr>
<tr>
<td>A0008B</td>
<td>0.1441</td>
<td>iso</td>
<td>−</td>
<td>38</td>
</tr>
<tr>
<td>A0012</td>
<td>0.1259</td>
<td>iso</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>A0013</td>
<td>0.0946</td>
<td>iso</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>A0014</td>
<td>0.0653</td>
<td>1</td>
<td>10</td>
<td>−</td>
</tr>
</tbody>
</table>

Since not all line-of-sight components are inside the examined volume ($z \leq 0.15$), in a few cases the sum of the fraction is lower than 100 per cent.

The projected sky distributions of both catalogues are displayed in Fig. 4.
Figure 4. Sky distribution in an Aitoff projection of equatorial coordinates of superclusters in MSCC (top panel), and SSCC (bottom panel). The superclusters are coloured according to their location in four redshift intervals (see the legend at top right). The symbol size is proportional to the separation $d_{\text{max}}$ of member cluster pairs in each supercluster (cf. Table 1), and the ratio of symbol size to $d_{\text{max}}$ decreases slightly with increasing redshift interval. In both projections the black dotted line indicates the Galactic plane ($b = 0^\circ$) and ‘G.C.’ denotes the Galactic Centre.

4.2 Comparison with previous supercluster catalogues

A comparison of the MSCC and SCL catalogues should give an idea of the improvements achieved over the last 15 years, mainly due to (a) the inclusion of new redshifts from the recent literature, (b) the extension to a higher redshift limit, and (c) the inclusion of all redshift components for the individual clusters, when they are present. Einasto et al. (2001) found 285 superclusters based on a critical linking length of $\ell_c = 34 h_{70}^{-1}$ Mpc, assumed to be constant throughout the considered volume out to $z_{\text{lim}} = 0.13$. Rather than all line-of-sight components, these authors used only the component with the largest number of spectroscopic redshifts, assuming this one to be the ‘correct’ Abell/ACO cluster. The cluster sample used by Einasto et al. (2001) consisted of 1663 A-clusters, 64 per cent of which had measured redshifts. Of these, 1163 clusters (70 per cent) were found to be members of pairs or superclusters, about 5 per cent more than what we found for MSCC and SSCC.

To compare our MSCC with the SCL catalogue, we performed a cluster-by-cluster cross-matching. In the case of clusters with line-of-sight components, only the dominant component was taken into account for the comparison, defining this as the component with the largest number of spectroscopically measured galaxies (in an attempt to match the definition used by Einasto et al. 2001).

Based on the above, of the total number of clusters (1159) which are members of any of the 285 ‘SCL’ superclusters, 880 (76 per cent) were located within 356 superclusters of MSCC, while another 279 (24 per cent) were found to be isolated in MSCC. Moreover, the remaining 245 MSCC superclusters, which are new compared to SCL, can be divided into: 112 (46 per cent) which are beyond the redshift limit of SCL ($z_{\text{lim}} = 0.13$) and another 14 (6 per cent) which are close to that limit, such that they have members on both sides of that limit; another 47 (19 per cent) resulted to be actually ‘components’ in the line of sight of superclusters, formed mostly by part of the members of the ‘dominant’ supercluster; 35 (14 per cent) are superclusters comprised of line-of-sight components accompanying clusters that were considered isolated in SCL; and finally, 37 (15 per cent) represent completely new superclusters within the volume considered by Einasto et al. (2001).\footnote{One of these cases is the pair MSCC 164, formed by the clusters A0569N and A0569S (e.g. Beers et al. 1991).}

Of the 255 superclusters of SCL whose clusters have a match in some MSCC supercluster, 108 (42 per cent) had a one-to-one match in MSCC, while 106 (42 per cent) were ‘fragmented’ (member clusters were linked into different superclusters in MSCC). Another 41 (16 per cent) SCL were redistributed in more complex ways; their member clusters are part of one unique MSCC supercluster which also have member clusters of one or more other SCL superclusters.
This implies that, in some cases for example, the members of three SCL are redistributed in two MSCC. The statistics of the components, fraction of measured redshift and fraction of isolated clusters for the SCL, MSCC, and SSCC catalogues, are listed in Table 4.

A total of 114 (40 per cent) superclusters in SCL were labelled as candidates (`c`). Only for the sake of comparison, when we use the same criterion for `candidate` as Einasto et al. (2001), we find that 81 candidates in SCL are in fact not superclusters in MSCC (i.e. their members were not linked). Another two SCL superclusters were partially confirmed, i.e. they appear fragmented as two MSCC superclusters, one of them being still a candidate. Another 21 candidates in SCL are confirmed in MSCC, and a further 10 superclusters appear as candidates in both MSCC and SCL. In MSCC, there are 37 (6 per cent) supercluster candidates (according to our definition), of which 25 are new superclusters, with 22 of these 25 exceeding the limit of 0.13 imposed by Einasto et al. (2001).

4.3 Notes on individual superclusters

We searched the literature for previous studies of the richest superclusters in MSCC and SSCC (i.e. those 13 MSCC and 11 SSCC with \( m \geq 14 \)) in order to explore the reliability of these catalogues. Only one of these richest superclusters, SSCC 82, which exceeds \( z = 0.13 \), had not been identified before. This comparison also gave some clues on the differences between MSCC and SSCC caused by the inclusion of S-clusters in SSCC.

**Sculptor (SCL 009).** It is identified as MSCC 33 and SSCC 36, with similar multiplicities (24 and 22, respectively), although more compact in the SSCC where nine A-clusters were not linked while another five S-clusters entered the supercluster. These S-clusters connect the main structure of MSCC 33 with the pair MSCC 47. The main member clusters, A2798, A2801, A2804, A2811, and A2814, studied before by Obayashi, Makishima & Tamura (1998) and more recently by Sato et al. (2010), remain in both catalogues as the possible `core' of Sculptor.

**Pisces–Cetus (SCL 010).** It is one of the four richest superclusters in SCL (together with Shapley, Sculptor, and Aquarius); fragmented in three structures in our analysis: MSCC 39, the northern Pisces–Cetus (with \( m = 11 \)); MSCC 27, the central Pisces–Cetus (\( m = 9 \)); and MSCC 1, the southern Pisces–Cetus (also \( m = 9 \)). The southern Pisces–Cetus is also found as SSCC 417, with \( m = 14 \). It was studied previously by Porter & Raychaudhury (2005) and Porter & Raychaudhury (2007).

**Horologium–Reticulum (SCL 048).** Previously studied by Fleenor et al. (2006), Horologium–Reticulum is MSCC 117, the second richest in MSCC. Fig. 5 shows the distribution of its member clusters in 3D. This supercluster appears significantly fragmented in SSCC, namely as SSCC 110, 117, and 122. This fragmentation is due to the smaller value of \( \epsilon_c \) in the Southern PF (\( \sim 15 h_{70}^{-1} \) Mpc) compared to the master PF (\( \sim 22 h_{70}^{-1} \) Mpc) at \( z \sim 0.06 \) (cf. Fig. 3).

**Ursa Major (SCL 109).** It is a northern supercluster listed as MSCC 310. We found good agreement between the member clusters as listed in MSCC and those listed by Kopylov & Kopylov (2009).

**Shapley (SCL 124).** It is usually described (e.g. Bardelli et al. 1994; Proust et al. 2006) as composed of three concentrations, where the central concentration is the classical Shapley supercluster (in-tergrated by A3556, A3558, A3560, A3564, and A3566, according to Bardelli et al. 1994). This concentration was recognized by us as MSCC 389 and SSCC 249. A second concentration, composed of A3528, A3530, and A3532, is part of MSCC 389 and SSCC 249. The third condensation, called the ‘Front Eastern Wall’, with A3571, A3572, and A3575 as main clusters, was found by us as MSCC 401 (which contains another seven clusters) and SSCC 267 (with another five clusters).

**Boötes (SCL 138).** It is identified as MSCC 414. In a recent analysis of superclusters in the SDSS region, using the member galaxies instead of the member clusters, Einasto et al. (2011a) separated it into two superclusters (SCL 349 and SCL 351 according to their catalogue). These superclusters were joined by us into MSCC 414.

**Corona Borealis (SCL 158).** It is identified as MSCC 463. A recent analysis of Corona Borealis by Pearson, Batiste & Batsuki (2014) suggests that many of the member clusters of MSCC 463 (namely A2056, A2061, A2065, A2067, A2089, and possibly A2092) form the only system, apart from the core of Shapley (MSCC 389 and SSCC 261), that shows conclusive evidence to be a bound supercluster.

SSCC 82. It is the richest supercluster in the SSCC, with \( m = 38 \). This supercluster appears in MSCC as three subsystems, namely MSCC 67 (A0210, A0214A, A2895, A2927B, and A2928C), MSCC 68 (A2923D, A2926B, A2927A, A2928B, A2931A, and A2932B), and MSCC 84 with the remaining A-clusters of SSCC 82. These three superclusters are connected through member clusters S0193 and S0227A in the SSCC. Einasto et al. (2001) included a fraction (nine clusters) of the clusters of SSCC 82 in SCL 232c.

**Aquarius A (SCL 205).** MSCC 576 is known as Aquarius A (Tully et al. 1992), or simply Aquarius (Einasto et al. 2001). It corresponds to SSCC 402 and has the same member clusters in both MSCC and SSCC. This membership is also in accordance with the identification of members made by Caretta et al. (2002).

**Aquarius B (SCL 209).** MSCC 574 is known as Aquarius B (Tully et al. 1992). It is the richest system in the MSCC, with \( m = 42 \). Batsuki, Miller & Slinglend (1999) analysed the region of this supercluster, based only on A-clusters, and suggested it to be ‘the largest supercluster in the Local Universe’ (in fact even connected
Figure 5. Horologium-Reticulum supercluster. The XYZ coordinates are derived from RA, DEC, and z of the individual clusters, where X is pointing towards RA=DEC=0, and Z=0 is pointing to the north celestial pole. Left-hand panel: distribution of clusters in the Horologium-Reticulum region according to the MSCC: solid circles are members of Horologium-Reticulum supercluster (MSCC 117); open circles are member clusters of MSCC 115, a foreground supercluster to Horologium-Reticulum; and open triangles are other clusters in the volume. Right-hand panel: distribution according to SSCC; Horologium-Reticulum is fragmented into three superclusters: SSCC 110 (solid circles), SSCC 117 (solid triangles) and SSCC 122 (solid squares); open circles are other clusters in the volume.

Figure 6. Aquarius B supercluster. XYZ coordinates as in Fig. 5. Left-hand panel: distribution of clusters in Aquarius B according to MSCC: solid circles are members of Aquarius B; open circles are other clusters in the considered volume. Right-hand panel: distribution according to the SSCC; Aquarius B is fragmented into two superclusters: solid circles are clusters in SSCC 401, taken as the main condensation of Aquarius B; solid squares are members of SSCC 396, a filamentary structure towards higher redshifts; open circles are other clusters in the considered volume.

to Aquarius A). In our analysis it was separated into SSCC 401 (m = 20) and SSCC 396 (m = 14), with only a small aggregation of S-clusters to the systems. This separation is consistent with the study of Caretta et al. (2002), who considered both A- and S-clusters, also including poor clusters from other catalogues (namely APMCC, Dalton et al. 1997; and EDCC, Lumsden et al. 1992) and groups, and found that Aquarius B is composed of two structures with only a low probability to be connected: a wall-like structure and a filament.
roughly along the line of sight towards higher redshift. Thus, the inclusion of S-clusters in our sample, the SSCC, reproduces this last result, as can be seen in the 3D map of the member clusters of Aquarius B in both MSCC and SSCC (Fig. 6).

Sloan Great Wall. Another important structure is the Sloan Great Wall (Gott et al. 2005). Einasto et al. (2011b) found this structure to be integrated by the Sextans supercluster (SCL 88), Leo-Sextans supercluster (SCL 91), Virgo-Coma supercluster (SCL 111), and SCL 126. We found the Sextans supercluster as MSCC 225, while in our catalogue Leo-Sextans is fragmented into MSCC 247 and 273, and Virgo-Coma into MSCC 311, 327, 343, and 352. SCL 126 was found by us as MSCC 376.

There are another five MSCC objects with \( m \geq 14 \) that were not the subject of individual studies: MSCC 73 (SCL 229), MSCC 76 (SCL 231), MSCC 84 and 94 (SCL 232c), and MSCC 123 (SCL 53, also known as Fornax–Eridanus supercluster). MSCC 238 has a multiplicity \( m = 21 \), and its member clusters are line-of-sight components of clusters in SCL 256c, but they are not dominant components (they do not have significantly high fractions of galaxies with measured redshift along the respective observing cone), except for A1028A. Another supercluster, MSCC 248, has most of the dominant components of members of SCL 256c and was identified as its equivalent. Another three superclusters with \( m \geq 14 \) in SSCC have not been studied in particular: SSCC 56 (SCL 22), SSCC 87 (SCL 232c), and SSCC 300 (MSCC 505 with \( m = 13 \); SCL 174, also known as Microscopium supercluster).

5 PROPERTIES OF THE SUPERCLUSTERS

5.1 The effect of the inclusion of S-clusters

A comparison of the MSCC and SSCC catalogues should give us hints on how the inclusion of S-clusters affects our description of the nearby large-scale structure. We cross-matched them to identify A-clusters in both catalogues, in order to see how the S-clusters affected their supercluster hosts. The MSCC includes 211 (35 per cent) superclusters with \( \delta \leq -17 \). Using the sample of A-clusters with \( \delta < -17 \), we found that only 132 (62 per cent) of these 211 have an unambiguous match with only one supercluster in SSCC (the member clusters of one MSCC supercluster were distributed in only one SSCC object). Another 29 (14 per cent) superclusters appear divided in two or more parts in SSCC, which is likely a consequence of the fact that the critical linking length, \( \ell_c \), is smaller for the southern sample than for the Master PF. These fragments are not necessarily less rich than their MSCC counterparts, and often the inclusion of S-clusters as members maintains their multiplicities almost equal, but their physical sizes are usually smaller, as pointed out in Section 3. This ‘fragmentation’ is more dramatic in the richest superclusters (\( m > 15 \)). As an example, in Section 4.3 we observed a certain degree of fragmentation in the richest structures such as Aquarius B and Horologium-Reticulum, into more compact or filamentary structures. Another 50 (24 per cent) MSCC superclusters disappeared in SSCC because their member clusters were not connected by the smaller linking length. 47 A-clusters, members of some supercluster in MSCC, are only accompanied by S-clusters in SSCC. We shall refer to this effect as ‘nucleation’.

We found that 290 isolated A-clusters of MSCC are also isolated in SSCC. Another 91 A-clusters that are isolated in MSCC became members of superclusters in SSCC. Of the total number of 423 superclusters in SSCC, 194 are considered new superclusters, i.e. they do not have an unambiguous counterpart in MSCC nor do they arise from fragmentation. Of these, 83 (42 per cent) represent nucleation of isolated clusters in MSCC, 3 (2 per cent) are bridges of S-clusters, i.e. isolated clusters in MSCC connected by S-clusters in SSCC, and 108 (56 per cent) are new superclusters formed by only S-clusters (including cluster pairs with \( m = 2 \)).

Although the SSCC covers only about 35 per cent of the whole sky (excluding the Galactic plane, \( |b| < 10 \)) the number of superclusters is about twice that in the MSCC in the same volume. As explained before, the main contributions to this enhancement of the number of superclusters are nucleation (50 per cent), considering both, nucleation of disconnected A-clusters being members of MSCC superclusters, as well as nucleation of isolated A-clusters in the south), S-cluster systems (40 per cent), fragmentation (8 per cent), and S-cluster bridges (2 per cent).

If S-clusters are poorer systems, it may be expected that they inhabit lower density regions. To test this hypothesis, we determined the local number density of A- and S-clusters within 20 \( h^{-1}_{70} \) Mpc for each cluster in the southern sky (\( \delta < -17 \)) with redshift \( z \leq 0.06 \). Out to this redshift, based on an examination of Fig. 1, the sample seems to be reasonably complete. Fig. 7 shows the histograms for the local density of southern clusters. It is apparent that S-clusters tend to inhabit lower density regions than A-clusters. Three statistical tests were applied to corroborate this visual impression, the Kolmogorov–Smirnov (KS), Cramér, and Tukey tests. The p-values are listed in Table 5, and suggest a low probability that both distributions are drawn from the same population. This is in agreement with the scenario where the main effect of S-cluster is the nucleation, the fact that A-clusters are surrounded by S-clusters in the external regions of superclusters, or in filaments, where the density is lower.

On the other hand, we did find 108 superclusters formed only by S-clusters, but none of those has \( m > 4 \), and indeed 71 per cent of these are pairs (\( m = 2 \)).
Table 5. Statistical tests for density distributions between A and S clusters shown in Fig. 7.

<table>
<thead>
<tr>
<th>Test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS</td>
<td>0.01</td>
</tr>
<tr>
<td>Cramér</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Tukey</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

5.2 Multiplicity functions

The MF is the distribution of multiplicities (the amount of member clusters) of the superclusters. The cumulative MFs of MSCC and SSCC catalogues are shown in Figs 8(a) and (b). Both follow very closely a power law, for which we obtained the slope, α, defined as \( N(m) \propto m^{-\alpha} \), whose values are listed in each panel of that figure. We compared the MF obtained for MSCC and SSCC with the ones obtained for two other observational samples, as well as for two mock catalogues. We also compared them to one generated from a completely random sample.

The two other observational samples are the supercluster catalogues of Einasto et al. (2001), the equivalent all-sky supercluster catalogue based on Abell/ACO clusters before our MSCC (Fig. 8c), and the catalogue of 2MASS groups (Fig. 8d; Crook et al. 2007), to which we applied our FoF algorithm to create a comparison supercluster catalogue including lower mass systems. Einasto et al. (2001) show the MF for SCL, but these authors did not attempt a cumulative log–log plot of the MF which would show a power-law distribution. The SCL superclusters also follow a power law, though with a slightly higher dispersion than our MSCC and SSCC catalogues. The MFs of the three supercluster samples (MSCC, SSCC, and SCL) have similar slopes: \( \alpha \sim 1.9 \). Fig. 8(d) shows the MF for a supercluster catalogue based on 2MASS ‘groups’ (Crook et al. 2007), which dominantly consists of systems of lower mass than the S-clusters in SSCC, but includes the few rich Abell clusters that exist within its redshift limit (\( z_{\text{lim}} \sim 0.033 \)). This catalogue, only produced to check the presence of a power law in its MF, was obtained using a PF similar to the ones generated for MSCC and SSCC in order to compensate for the selection effects with the redshift.

The power law seems to apply to systems of very different mass, and, since the SCL was produced using a single critical linking length, \( \ell_c \), for the entire volume, it also seems to be independent of the selection of \( \ell_c \) to produce the catalogue.

Can the mock catalogues based on simulated data reproduce the MFs of the observational samples? The distribution generated from mock catalogues come from the Millennium simulation (Fig. 8e;...
Springel et al. 2005) and Bolshoi simulation (Fig. 8d; Klypin, Trujillo-Gomez & Primack 2011).

The Millennium project is a cold dark matter (CDM) N-body simulation of the evolution, since redshift \( z = 127 \), of 2160 cold dark matter particles within a box of side 500 Mpc based on \( H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1} \). For the FoF calculations in this paper, all cosmological parameters were scaled to \( H_0 = 70 h_{70} \text{ km s}^{-1} \text{ Mpc}^{-1} \), thus the box side corresponds to 521 \( h_{70} \text{ Mpc} \). The mass of the individual particles is \( M/M_{\odot} = 8.89 \times 10^8 h_{70}^{-1} \). We selected all dark matter haloes obtained from the internal FoF of the Virgo-Millennium Database (http://gavo.mpa-garching.mpg.de/Millennium/) with the condition \( M/M_{\odot} \geq 10^{13} h_{70}^{-1} \geq 1136 \) particles per dark matter halo. The dark matter halo sample obtained in this way has a density of similar order as that obtained for the sample of 2MASS groups (Table 6). We applied our own FoF to the 51 998 massive dark matter haloes that follow the mass condition within the complete volume of the Millennium simulation, which corresponds to a redshift limit of \( z \sim 0.12 \). Since the mean density is by construction the same throughout the Millennium volume, we assumed a constant value of \( \epsilon_c \) throughout the volume. Thus, \( \epsilon_c \) was obtained considering the total volume and not parts of it as MSCC and SSCC (and the sample of 2MASS group). However, it is clear from Fig. 8(e) that the distribution of superclusters obtained from such haloes does not follow the power law obtained for observational samples.

The other mock catalogue (Fig. 8f) is based on the sample of dark matter haloes of the Bolshoi simulation, a CDM N-body simulation that uses 2048 dark matter particles within a box of side 250 \( h_{70}^{-1} \text{ Mpc} \). It has the largest resolution for a cosmological simulation of this type, not only in space but also in time evolution. For comparison, Millennium is based on 11 000 time steps per particle while Bolshoi was evolved since \( z = 80 \) in \( \sim 400,000 \) time steps. The simulation was obtained with the adaptive-mesh refinement (AMR)-type code (Kratsov, Klypin & Khokhlov 1997) instead of the gadget code (Springel, Yoshida & White 2001) used for Millennium. For Bolshoi, we extracted from the MultiDark Database (http://www.multidark.org/MultiDark/) such haloes with \( M/M_{\odot} \geq 10^{13} h_{70}^{-1} \) (haloes were determined by an internal FoF of the MultiDark Project). The particle density of Bolshoi is, again, comparable to that of the 2MASS group sample, and similar to the sample of massive haloes of Millennium we used (cf. Table 6). We applied our FoF to these haloes, using the same procedure as for Millennium. The MF for superclusters we obtained in this way follows more closely the power law than the mock catalogue obtained with Millennium, but yet it is evident that neither of the two mock catalogues produce a cumulative MF that resembles the power-law distribution of multiplicities for the real superclusters.

While the observational MF distributions for higher mass systems are relatively well fitted by a power law with \( \alpha = 2.0 \), the simulated ones do not follow closely a power law, presenting a more curved distribution (lower fraction of superclusters with low and high multiplicities, and larger for intermediate multiplicities than in a power-law regime), resulting in lower values for \( \alpha \).

What would one expect from a completely random sample of particles? Fig. 8(g) is the average of the MF of one thousand simulated catalogues based on randomly distributed points that represent Abell/ACO clusters. These distributions were produced assigning random coordinates to each point. Each distribution contains 7329 points in a spherical volume of ‘radius’ \( z = 0.15 \). This condition simulates the mean density of the best-sampled region of MSCC. In each sample, the value of the critical linking length, \( \epsilon_c \), was found, and an FoF algorithm was applied. We produced one thousand mock supercluster catalogues, from which the number of frequency of each richness was averaged (note that this resulted in high-richness systems having fractional values of frequency in Fig. 8g). Again, as for the other distributions, the slope \( \alpha \) is shown, but neither the cosmological simulations nor the random distribution reproduces the shape of the cumulative MF of the observational samples. Actually, the completely random sample appears more similar to the distribution based on the Millennium data.

The hump in the curves based on mock catalogues, much stronger in the random and Millennium MF, can be interpreted as a lower probability to obtain high-richness superclusters from such samples. We can see this in the random distribution, where the structures are in a Poissonian regime and the value of the power spectrum is expected to be zero. However, in a gravitational regime one may expect to obtain structures (power spectrum >0), that drive the superclusters towards the richest systems, which would explain why in the MF of cluster-based catalogues the curves do not decay (at the rich end) as abruptly as in the random case.

Power laws have also been fitted in the literature for the number of galaxies within groups of SDFS by Berlind et al. (2006) and Nurmi et al. (2013). Berlind et al. (2006) found values for \( \alpha = 2.49 \pm 0.28, 2.48 \pm 0.14, \) and 2.72 \( \pm 0.16 \) for different volume–limited samples of absolute magnitude limits of \( M_r \lesssim -18 \), and \( -19,-20 \). On the other hand, Nurmi et al. (2013) found \( 2.02 \pm 0.18, 2.12 \pm 0.17, 2.26 \pm 0.19 \) for these luminosity ranges, and \( 3.29 \pm 0.24 \) for \( M_r \leq -21 \). Since these distributions are based on ‘particles’ (galaxies) of much lower mass we do not expect a direct relation with those obtained here, except, as we said, that the power law will be a natural distribution for systems in gravitational regimes.

### 6 Conclusions and Summary

We summarize our conclusions as follows.

(1) We constructed two new supercluster catalogues based on the optically selected Abell/ACO clusters, which not only reach deeper in space (\( z \leq 0.15 \)) than previous ones, but also contain a much higher fraction (\( >5 \%) \) of clusters with spectroscopically confirmed redshifts. Different from previous works, we include in our analysis the different line-of-sight components for the clusters (up to the above-mentioned redshift limit). One of these catalogues is the all-sky MSCC, based on only the rich Abell A-clusters, the other is the SSCC covering declinations \( \delta < -17^\circ \) and including the supplementary Abell S-clusters.
(2) A tunable linking length was used to generate these supercluster catalogues, taking into account the undersampling at higher redshift and the different selection functions in different regions of the sky. The area covered by SDSS is clearly better sampled than the rest of the sky, and a special PF was fitted for this region. Also, for the southern sky, the inclusion of the S-clusters required an independent correction for the selection function. We conclude that the ‘PF’ is an efficient tool for detecting and correcting the selection function for samples of galaxy clusters.

(3) For the all-sky main sample of A-clusters, we found that the maximum completeness is reached near $z \sim 0.06$, which leads to a critical linking length of $\ell_c \sim 22.5 \, h_{100}^{-1} \, \text{Mpc}$, while for the south ($\delta < -17^\circ$) the S-clusters provide the best sampling at $\sim 0.02$, leading to $\ell_c \sim 11.5 \, h_{100}^{-1} \, \text{Mpc}$.

(4) The MSCC and the SSCC contain 601 and 423 superclusters, respectively. Considering the probability for a cluster to be member of a supercluster or not, we found the following: 35 per cent of the clusters tend to be isolated, 18 per cent form pairs, and 47 per cent are hosted by a supercluster with $m \geq 3$. Of the superclusters found, the fraction of pairs $(m = 2)$ is $\sim 50$ per cent, while the fraction of very rich superclusters $(m > 10)$ is $\sim 4$ per cent of the systems. The complete catalogues and input lists of clusters are available in the electronic version of this paper.

(5) By comparing our MSCC directly with the one by Einasto et al. (2001), we find: (i) a slightly higher fraction of isolated clusters (35 per cent compared to 30 per cent in SCL); (ii) 37 new superclusters identified in the same volume investigated previously; (iii) 126 new superclusters near and beyond $z = 0.13$; (iv) 70 per cent of Einasto et al.’s candidate superclusters were not confirmed as such. The fraction of candidate superclusters was reduced from 40 to 6 per cent, thanks to the much higher fraction of clusters with spectroscopically confirmed redshifts in our sample.

(6) The MSCC and SSCC reveals that the S-clusters seem to prefer to inhabit the surroundings of richest clusters. The lower critical linking length in SSCC only breaks up the MSCC systems with $m \geq 15$, and since these systems represent only $\sim 2.0$ per cent of the MSCC, and only 1.2 per cent of them are in the declination range of SSCC, these fragmentation effects are not significant. More important effects of the inclusion of S-clusters on the distribution are new superclusters (with multiplicities $m \geq 2$) of only S-clusters and the ‘nucleation’ of A-clusters surrounded by S-clusters.

(7) The distributions of supercluster ‘richness’ (the MF) of the MSCC and SSCC follow a power law of slope $\alpha \sim -2.0$. A very similar behaviour is seen in other catalogues based on observational data, namely the SCL (Einasto et al. 2001) and a catalogue generated from 2MASS groups (Crook et al. 2007), the latter being far more complete for lower mass systems. However, when similar supercluster catalogues are generated from mock data, namely using the Millennium (Springel et al. 2005) and the Bolshoi (Klypin et al. 2011) N-body cosmological simulations, the MFs change from a power law to a convex curve, predicting less superclusters in both the low- and high-multiplicity regimes. A similar behaviour, even farther from a power law, is found for an entirely random distribution of input clusters.

ACKNOWLEDGEMENTS

We thank Kristin Riebe and the people of the MultiDark Project as well as Gerard Lemson and the people of the Virgo Consortium for the access to the data bases of the cosmological simulations used in this paper. We also thank the R Core Team (2013) and other developers of R Project libraries: Ligges & Mächler (2003), Franz (2006), Hothorn, Bretz & Westfall (2008), Warnes et al. (2014), and Zeileis (2004). All graphics and statistics in this work were generated using these tools. MC-M acknowledges a CONACyT grant for a Master thesis, and CC and HA a Guanajuato University grant #219/13. CC and HA are also grateful to the staffs of the following observatories, where some of the spectroscopic data used in this paper were obtained: Observatorio Astronómico Nacional (Ensenada, Mexico), Observatorio do Pico dos Dias (Brasópolis, Brasil), South African Astronomical Observatory (Cape Town, South Africa), and Indian Astronomical Observatory (Hanle, India).

REFERENCES


MNRA 445, 4073–4085 (2014)
Two new catalogues of superclusters

Hohlfenter, Breitl, Wesslaff 2008, Biometirical J. 50, 346
Springel V. et al., 2005, Nature, 435, 629

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. The Main SuperCluster Catalogue (MSCC) (1) MSCC number; (2) SCL identification; (3) multiplicity, \( m \); (4,5) right ascension and declination (J2000) in decimal degrees; (6) redshift, \( z \); (7) distance, in \( h_{70}^{-1} \) Mpc, of the pair of clusters with the maximum separation in each supercluster; (8) list of member clusters of the supercluster.

Table 2. The Southern SuperCluster Catalogue (SSCC) (1) SSCC number; (2) SCL identification; (3) multiplicity, \( m \); (4,5) right ascension and declination (J2000) in decimal degrees; (6) redshift, \( z \); (7) distance, in \( h_{70}^{-1} \) Mpc, of the pair of clusters with the maximum separation in each supercluster; (8) list of member clusters of the supercluster.

Table 3. The list of clusters used as input catalogue for MSCC and SSC.

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the paper.

This paper has been typeset from a \TeX/\LaTeX\ file prepared by the author.