Stellar populations in superclusters of galaxies

M. V. Costa-Duarte,1,2★ L. Sodré Jr1 and F. Durret3

1Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, Brazil
2LUTH, Observatoire de Paris, CNRS, Université Paris Diderot, Place Jules Janssen, F-92190 Meudon, France
3UPMC Université Paris 06, UMR 7095, Institut d’Astrophysique de Paris, 98 bis Bd Arago, F-75014 Paris, France

Accepted 2012 September 26. Received 2012 September 4; in original form 2012 July 16

ABSTRACT

A catalogue of superclusters of galaxies is used to investigate the influence of the supercluster environment on galaxy populations, considering galaxies brighter than $M_v < -21 + 5 \log h$. Empirical spectral synthesis techniques are applied to obtain the stellar population properties of galaxies which belong to superclusters and representative values of stellar population parameters are attributed to each supercluster. We show that richer superclusters present denser environments and older stellar populations. The galaxy populations of superclusters classified as filaments and pancakes are statistically similar, indicating that the morphology of superclusters does not have a significative influence on the stellar populations. Clusters of galaxies within superclusters are also examined in order to evaluate the influence of the supercluster environment on their galaxy properties. Our results suggest that the environment affects galaxy properties but its influence should operate on scales of groups and clusters, more than on the scale of superclusters.

Key words: galaxies: evolution – galaxies: formation – large-scale structure of Universe.

1 INTRODUCTION

Large scale structures are an important tool to study the Universe, presenting several useful features to constrain the cosmology. Groups and clusters of galaxies represent two fundamental classes of objects in this scenario, providing information on galaxy evolution and structure formation. Many cluster catalogues have been compiled, presenting properties for hundreds or even thousands of objects (Abell, Corwin & Olowin 1989; Koester et al. 2007; Wen, Han & Liu 2009). Beyond group and cluster scales, the large scale structure is traced by the largest type of object known: superclusters of galaxies, extending to tens of megaparsecs and presenting a variety of morphologies. The first galaxy redshift surveys have allowed the compilation of the first supercluster catalogues, presenting data for about a hundred structures (Zucca et al. 1993; Einasto et al. 1994). Since then, the completion of new surveys led to a new generation of catalogues. For example, the Las Campanas Galaxy Redshift survey (Shectman et al. 1996) and the 2-degree Field Galaxy Redshift Survey (Colless et al. 2001), with tens to hundreds of thousands of galaxies, have produced catalogues with several hundreds of superclusters (Einasto et al. 2007a). Nowadays, the Sloan Digital Sky Survey (SDSS, Abazajian et al. 2009) provides a data base with roughly one million galaxy spectra, making possible a detailed study of a variety of supercluster properties. A detailed map of the Universe has been produced, showing, among others, the most prominent supercluster known, the Sloan Great Wall (Gott et al. 2005). Besides, much effort is being applied to provide deeper galaxy surveys, such as ZCOSMOS Redshift Survey (Lilly et al. 2007) and The Great Observatories Origins Deep Survey/VIMOS (Popesso et al. 2009). Deep surveys make possible the identification of structures beyond the local Universe, reaching $z \sim 1–3$ (Tanaka et al. 2001; Gal & Rubin 2004; Kuiper et al. 2012).

We have compiled a supercluster catalogue using the SDSS/DR7 data base (Costa-Duarte, Sodré & Durret 2011, hereafter CD11). Our analysis has shown that superclusters classified as filaments tend to be richer and more luminous. Using mock lightcones (Croton et al. 2006) we also concluded that peculiar velocities do not represent a significative influence on supercluster morphologies. Einasto et al. (2011a, 2011b) also used the SDSS/DR7 data base to discuss the relation between morphology and evolution in these structures. Luparello et al. (2011) presented a detailed study of the future of superclusters, collapsing into future virialized structures. Recently, Einasto et al. (2012) have shown that the cluster population in superclusters depends on their richness, with richer clusters being preferentially located in the high density regions of rich superclusters.

It is well known that galaxy environment has an important role on galaxy evolution, affecting galaxy morphology and stellar populations (Davis & Geller 1976; Dressler 1980; Whitmore, Gilmore & Jones 1993). High density environments are usually populated by early-type galaxies, presenting old stellar populations, while late-type galaxies, with younger stellar populations, are mostly found in low density environments. Environmental processes may act even...
at very large scales (Mo et al. 1992; Mateus et al. 2007). Several studies have shown this effect by considering the environmental effect on colours, morphology and luminosity function of galaxies (see Croton et al. 2005; Park et al. 2007; Carollo et al. 2012). Einasto et al. (2007b) have compared the galaxy population properties of rich and poor superclusters in the 2-degree Field Galaxy Redshift Survey by using colour index and spectral features, concluding that richer structures present a higher fraction of early-type galaxies than the poorer ones. They also show that main galaxies of rich superclusters are more luminous than the main galaxies in poor structures. Recently, Lietzen et al. (2012) have shown that groups of galaxies belonging to superclusters evolve faster than groups in the field or in voids, presenting higher luminosities and higher fractions of passive galaxies.

In this paper, we investigate the connection between stellar populations of galaxies and supercluster properties. We have obtained parameters useful to characterize the stellar population of galaxies using empirical spectral synthesis of SDSS spectra obtained with the STARLIGHT code of Cid Fernandes et al. (2005). This technique aims at reproducing an observed galaxy spectrum with a linear combination of simple stellar populations (SSPs), taking into account extinction and line broadening due to the stellar velocity dispersion. It allows us to estimate physical properties of galaxies, such as star formation and chemical enrichment histories and mean stellar ages and metallicities (e.g. Cid Fernandes et al. 2004; Tojeiro et al. 2007).

This paper is organized as follows. In Section 2, we present the data analysed here: the supercluster catalogue and the results of the spectral synthesis of supercluster galaxies. In Section 3, we discuss the connection between stellar population parameters and supercluster properties, as well as that between galaxy clusters and superclusters. Finally, in Section 4, we summarize our main results and discuss their main implications for our knowledge of large scale structures.

2 THE DATA

In this section, we describe the supercluster catalogue (CD11) and the supercluster parameters (morphology, richness, total luminosity). We also present the quantities associated with the stellar populations (mean stellar ages and metallicities) and galaxy environment (local density), describing how they were obtained.

We assume a standard ΛCDM cosmology, when necessary, with Ω_m = 0.3, Ω_Λ = 0.7 and the Hubble parameter H_0 = 100 h^{-1} \text{km s}^{-1} \text{Mpc}^{-1}.

2.1 Supercluster identification

The supercluster catalogue analysed in this work is discussed in detail in CD11. We identified superclusters by using a volume-limited sample of galaxies extracted from the main footprint of the SDSS (SDSS/DR7; Abazajian et al. 2009), containing 120 013 galaxies brighter than M_v < -21 + 5 \log h in the redshift range 0.040 ≤ z ≤ 0.115. Here we present a brief description of our approach, referring the reader to CD11 for more details.

We have adopted the density field method to find high density regions in the galaxy distribution. The luminosity density at a point \( r \) is given by

\[ L(r) = \sum_{i} K(r - r_i, \sigma) L_i(r_i), \]

where \( K(r, \sigma) \) is the Epanechnikov kernel, \( L_i \) is the luminosity of the \( i \)-th galaxy within the kernel radius, and \( W_i \) is a statistical weight taking into account the selection effects. The density field grid has cells with length \( l_{\text{cell}} = 4 \ h^{-1} \text{Mpc} \) and the kernel smoothing parameter is \( \sigma = 8 \ h^{-1} \text{Mpc} \). The luminosity density, which is used to find superclusters, is also useful for characterizing the local galaxy environment in investigations of stellar populations (see the next section).

To evaluate the influence of the threshold density on the supercluster identification, our analysis has been performed with two thresholds, \( D_1 = 3.0 \times D_0 \) and \( D_2 = 6.0 \times D_0 \), where \( D_0 \) is the mean luminosity density. The first threshold maximizes the number of structures and the second is based on the Einasto et al. (2007a) criterion, assuming that the largest supercluster has length \( \sim 120 h^{-1} \text{Mpc} \).

The morphology of superclusters was determined with Minkowski functionals. We have considered the parameters of planarity (\( K_1 \)) and filamentarity (\( K_2 \)) to classify superclusters as filaments (\( K_1/K_2 \leq 1.0 \)) or pancake-like objects (\( K_1/K_2 > 1.0 \)) (Sahni, Sathyaprakash & Shandarin 1998). This ratio increases monotonically from filaments to pancakes. The richness \( (R) \) and total luminosity \( (L_{\text{tot}}) \) have been measured for all superclusters in our catalogue (see CD11 for more details).

Table 1 shows some properties of the supercluster samples associated with each threshold. This table presents the number of filamentary and pancake-like superclusters, the number of clusters (see Section 3.2) within each morphological group and the number of galaxies for each threshold. Obviously, some of these galaxies are in both samples: 10 953 of them. The total number of galaxies in this analysis is 50 422.

We have verified that, qualitatively, the results of the next sections summarized in Figs 1 to 4 are not affected by the choice of the threshold and, hereafter, all our results will refer to \( D_1 \).

Table 1. Supercluster samples. For each threshold density, we give the number of filaments \( (N_f) \), the number of pancakes \( (N_p) \), the number of clusters in filaments \( (N_{cf}) \), the number of clusters in pancakes \( (N_{cp}) \) and the number of galaxies \( (N_g) \).

| Threshold | \( N_f \) | \( N_p \) | \( N_{cf} \) | \( N_{cp} \) | \( N_g \) |
|-----------|-----------|-----------|-------------|-------------|-----------|
| \( D_1 \) | 436       | 444       | 74          | 59          | 39 469    |
| \( D_2 \) | 215       | 194       | 64          | 60          | 22 817    |

Figure 1. The median ages weighted by mass \( \langle (\log(t))_{M} \rangle \) of superclusters as a function of their richness \( (R) \). The size of the symbols is proportional to the median supercluster density contrast \( (D/D_0) \). Superclusters classified as filaments and pancakes are shown as circles (red) and crosses (blue), respectively. The vertical dashed lines represent the median and quartiles of richness, which we use to define the samples \( R_1, R_2, R_3 \) and \( R_4 \) (see the text).
Figure 2. Top: spatial distribution of two superclusters from our sample with different richness. The radii of the circles are proportional to the local luminosity density of each galaxy and the galaxy ages weighted by mass \( \langle \log(t) \rangle M \) follow the grey (colour) scale. Bottom: histogram of \( \langle \log(t) \rangle M \) of galaxies which belongs to the superclusters, showing the median value and the fraction of galaxies with \( \langle \log(t) \rangle M \) greater than 10 Gyr.

Figure 3. The richness of clusters (\( R_{\text{clus}} \)) as a function of supercluster richness (\( R \)). The size of the symbols is proportional to the density contrast ((\( D/D_0 \))). Clusters in superclusters classified as filaments and pancakes are shown in circles (red) and crosses (blue), respectively.

2.2 Spectral synthesis

The parameters related to the stellar populations of the galaxies in the sample were obtained through an analysis of the galaxy spectra with the STARLIGHT code (Cid Fernandes et al. 2005), which makes the use of techniques of empirical population synthesis and evolutionary models to fit each observed spectrum with a combination of SSPs.

We adopted a spectral library with \( N_\star = 150 \) components (SSPs) from Bruzual & Charlot (2003), with the initial mass function of Chabrier (2003), evolutionary tracks of Padova 1994 (Alongi et al. 1993; Girardi et al. 1996) and the STELIB library (Le Borgne et al. 2003). The spectral library contains 25 ages in the range \( 10^6 \leq t \leq 18 \times 10^9 \) yr, 6 metallicities in the range \( 0.0001 \leq Z \leq 0.05 \) and the extinction parameter \( A_V \) was constrained to the interval \( -1.0 \leq A_V \leq 4.0 \). The STARLIGHT code provides several interesting parameters useful for this paper and we select for our analysis the mean stellar ages and metallicities weighted by light and by mass. Cid Fernandes et al. (2005) defined the mean ages and metallicities weighted by the light vector \( \{x\} \) as follows:

\[
\langle \log(t) \rangle_L = \sum_{i=1}^{N_\star} x_i \log(t_i) \\
\langle Z \rangle_L = \sum_{i=1}^{N_\star} x_i Z_i.
\]
Stellar populations in superclusters of galaxies

Figure 4. Left: median profiles of ages weighted by mass and light of clusters in filaments (red) and pancakes (blue). Right: median metallicity profiles of clusters. The parameters weighted by mass and light are presented in the top and bottom panels, respectively. The thick lines represent the median values and the dashed lines represent the quartiles for each radius.

In a similar way, the mean age and metallicity weighted by mass are defined using the mass vector \((\mu)\). The spectral synthesis was carried out for 50 422 galaxies and the relevant stellar population properties were calculated for each object.

Using the SDSS spectral classification, we identified 420 objects in our sample as QSOs. Seyfert I galaxies frequently present a spectral continuum difficult to be fitted by stellar populations. We then carried out a visual inspection of the spectral fitting of these objects, finding that spectral synthesis produced bad fittings for 259 objects, which were consequently excluded from our stellar population analysis.

For each supercluster in our sample, we computed the median values of the stellar ages and metallicities of their galaxies. These median values are the stellar population parameters that we will ascribe to each supercluster. It is worth mentioning that these parameters were obtained for galaxies brighter than \(M_r < -21 + 5\log h\) and, hence, they are not representative of the whole stellar population. However, we use the same luminosity threshold for all structures and consequently the properties of bright galaxies can be compared between superclusters with different properties.

3 PROPERTIES OF SUPERCLUSTERS

In this section, we first study the relation between stellar population parameters and other supercluster properties, and then we address the relation between galaxy clusters and superclusters.

3.1 Stellar populations

To evaluate the influence of supercluster properties on the stellar population of galaxies, we have investigated the correlations between supercluster richness \((R)\), total luminosity \((L_{\text{tot}})\), median galaxy overdensity \((D/D_0)\) and morphology \((K_1/K_2)\) and the representative values of mean ages and metallicities of galaxies belonging to each supercluster. The strength of each correlation is evaluated with the non-parametric Spearman rank-order correlation coefficient (Press et al. 1992). The parameter \(r_s\) represents the rank correlation, a number between \(-1\) (anti-correlation) and \(+1\) (correlation), and \(P(H_0)\) is the null-hypothesis probability of the absence of correlation. Table 2 summarizes the results of this analysis.

The first result to note is that stellar populations do not depend at all on the supercluster morphology, as indicated by the large values of \(P(H_0)\) in relation to the morphological indicator \(K_1/K_2\). This result indicates that the morphology does not have a significant influence on the stellar population of galaxies.

There are significant correlations (i.e. with low values of \(P(H_0)\)) between supercluster richness, total luminosity and mean density with mean ages: richer, more luminous and denser superclusters tend to harbour older stellar populations. These correlations, however, are weak, as indicated by the small (absolute) values of \(r_s\).

There are no significant relations between the supercluster properties and the mean metallicities of their galaxies. It is interesting to note in Table 2 that age and metallicity correlation coefficients have always opposite signs. This may be an indication of the age–metallicity degeneracy and, since our results are more sensitive to ages than to metallicities, it is possible that a trend with metallicity is weakened and at the same time the trend with age is strengthened due to this degeneracy.

To evaluate the significance of the absence of rich, luminous and high density superclusters with ages as young as those found for low-richness structures (Fig. 1) and verify whether this is only an observational effect due to the relatively small number of...
high-density structures, we divided the galaxies in four bins of richness (and also of luminosity and of overdensity). We computed the median and quartiles of the distribution and defined the four richness bins \((R_1, R_2, R_3, \text{ and } R_4)\) by the quartiles of the distribution. The Kolmogorov–Smirnov test was then applied to compare the samples of superclusters in different richness bins. We verified that there are significant differences in the age distributions of galaxies in the first two richness quartiles with respect to galaxies in the fourth quartile. The same is true if we analyse the behaviour of age distribution in bins of \(L_{\text{rot}}\) and \((D/D_0)\). These results indicate that the age distribution of superclusters in different richness/luminosity/density classes can be considered statistically distinct (mostly by comparing samples of galaxies in bins 1 and 4). Thus, the absence of rich, luminous and denser superclusters with young stellar populations seems to be indeed an environmental effect.

Richer superclusters present higher density regions than less rich structures. Invoking the morphology–density relation, we may expect that richer superclusters present, on average, galaxies with older stellar populations. High density regions strongly affect star-forming galaxies, quenching the star formation by several processes, such as starvation, ram pressure, etc. As a consequence, an older stellar population dominates in these regions after roughly 1 Gyr after the arrival of (infalling) star-forming galaxies. Since high-density structures are much more common in high-richness objects, it is reasonable to expect that these structures present, on average, an older stellar population. Fig. 2 shows the galaxy distribution of two superclusters with different richness. The top figures show filaments of galaxies linking the high density regions, which are mostly populated by galaxies with old stellar populations, while the fraction of young stellar population increases in low density regions. The poorer supercluster shown in this figure does not have regions with densities as high as those found in the richer structure and, consequently, has a significantly younger stellar population. The bottom figures show histograms of \((\log(t))_b\) of galaxies for these superclusters. The median values and the fractions of galaxies with age higher than 10 Gyr also indicate different stellar populations. Thus, the influence of the environment on stellar populations will be distinct for each supercluster, according to its richness and consequently total luminosity.

### 3.2 Clusters in superclusters

Superclusters are, actually, formed by groups and clusters of galaxies and it is then interesting to verify whether the properties of, for example, galaxy clusters are related to the properties of the supercluster which they inhabit.

For this investigation, we have adopted the cluster catalogue of Wen et al. (2009), which contains 39 668 objects from SDSS/DR6 in the redshift range 0.05 < \(z\) < 0.6. Clusters are identified as supercluster members if their centres are within a supercluster. Table 1 presents the number of clusters identified in superclusters classified as filaments and pancakes. The cluster catalogue contains several cluster properties, such as richness \((R_{\text{clus}})\) and \(r\)-band luminosity \((L_{\text{rot}})\), which are useful proxies of cluster mass (e.g. Wen, Han & Liu 2010).

We verified that galaxy cluster properties are not related to the supercluster morphology. Indeed, the distribution of cluster richness and luminosity is statistically the same for filaments and pancakes. We have also verified that richer and denser clusters are preferentially located in richer superclusters, confirming the Einasto et al. (2012) results, as shown in Fig. 3.

We have also evaluated the effect of environment on galaxies in clusters and in their outskirts. For this, we calculated, for each cluster, the mean values of ages and metallicities of galaxies inside spherical shells with radii varying from 0.1 \(h^{-1}\) to 10 \(h^{-1}\) Mpc for each cluster. At small radii, only cluster galaxies contribute to these means, and the results indicate the prevalence of an older and more metallic population than those found at larger radii: as the radii increase, the mean values of ages and metallicities decrease, due to an increasing contribution of late-type galaxies, which present a higher fraction of younger and less enriched stellar populations.

Fig. 4 shows the median profiles of ages and metallicities weighted by light and mass for clusters in filaments and pancakes. The trends indicate that clusters affect the parameters probed by spectral synthesis up to a radius of \(8 h^{-1}\) Mpc. These profiles, however, do not present any significant difference between clusters in filaments or in pancakes, nor depend on supercluster richness, suggesting that the environmental effect on galaxies is driven fundamentally by clusters more than by the superclusters.

### 4 SUMMARY AND DISCUSSION

In this work, we have analysed some properties of supercluster of galaxies, making use of the supercluster catalogue described in CD11 which considers galaxies brighter than \(M_r < -21 + 5 \log h\). The results focused on connections between supercluster properties and their stellar populations. We have also examined some links between galaxy clusters and superclusters.

Our main results can be summarized as follows:

(i) the stellar populations of galaxies in superclusters are not affected by supercluster morphology;

(ii) richer and more luminous superclusters have higher density regions;

(iii) richer and more luminous superclusters have, on average, older stellar populations;

(iv) we do not find any significative correlation between supercluster properties and the metallicity of the stellar populations; we
suggest that this may be an artefact produced by the age–metallicity
degeneracy;
(v) rich clusters tend to inhabit rich superclusters;
(vi) the behaviour of stellar population parameters around clusters
seem to be independent of supercluster richness and morphology.

It is worth stressing that most of the correlations discussed in this
paper are not strong but the trends are statistically significant.

The supercluster morphology is a tracer of the processes of struc-
ture formation and evolution (Shandarin, Sheth & Sahni 2004;
Einasto et al. 2011a, 2011b) and there is evidence that filamen-
tary structures tend to be richer, larger and more luminous than
pancakes (e.g. CD11, Einasto et al. 2011a), suggesting an evolu-
tionary track where pancakes evolve to filaments. We do not find,
however, any significant correlation between supercluster morphol-
gy and the properties of stellar populations. On the other side,
the influence of the environment on galaxy properties is well de-
scribed by various authors (cf. Dressler 1980; Mateus et al. 2007).
Our results might be indicating that the supercluster morphology is
not strongly correlated with the inner environment of these struc-
tures, at least to the point of affecting the stellar populations of their
galaxies. So, although our results are all consistent with the idea
that the environment affects galaxy properties, this influence should
operate on scales of groups and clusters, more than in the scale of
superclusters.

ACKNOWLEDGMENTS

MVCD thanks FAPESP and CAPES scholarships that allowed
him to develop this project. LSJ acknowledges the support of
FAPESP and CNPq to his work. This work is also supported by
the CAPES/COFECUB project 711/11.

REFERENCES

Abazajian K. N. et al., 2009, ApJS, 182, 543
Abell G. O., Corwin H. G., Jr, Olowin R. P., 1989, ApJS, 70, 1
Alongi M. et al., 1993, A&AS, 97, 851
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
Carollo C. M. et al., 2012, preprint (arXiv:1206.5807)
Chabrier G., 2003, PASP, 115, 763
Cid Fernandes R. et al., 2004, MNRAS, 355, 273
Cid Fernandes R., Mateus A., Sodrê L., Stasińska G., Gomes J. M., 2005,
MNRAS, 358, 363
Colless M. et al., 2001, MNRAS, 328, 1039
Costa-Duarte M. V., Sodré L., Jr, Durret F., 2011, MNRAS, 411, 1716
(CD11)
Croton D. J. et al., 2005, ApJ, 356, 1155
Croton D. J. et al., 2006, MNRAS, 365, 11
Davis M., Geller M. J., 1976, ApJ, 208, 13
Dressler A., 1980, ApJ, 236, 351
Einasto M., Einasto J., Tago E., Dalton G. B., Andernach H., 1994, MNRAS,
269, 301
Einasto J. et al., 2007a, A&A, 462, 811
Einasto M. et al., 2007b, A&A, 464, 815
Einasto M. et al., 2011a, A&A, 532, A5
Einasto M. et al., 2011b, A&A, 535, A36
Einasto M. et al., 2012, A&A, 542, A36
Gal R. R., Lubin L. M., 2004, ApJ, 607, L1
Girardi L., Bressan A., Chiosi C., Bertelli G., Nasi E., 1996, A&AS, 117, 113
Gott J. R. et al., 2005, ApJ, 624, 463
Koester B. P. et al., 2007, ApJ, 660, 239
Kuiper E., Venemans B. P., Hatch N. A., Miley G. K., Rottgering H. J. A.,
2012, MNRAS, 425, 801
Le Borgne J.-F. et al., 2003, A&A, 402, 433
Lietzen H. et al., 2012, A&A, 545, A104
Lilly S. J. et al., 2007, ApJS, 172, 70
Luparello H., Lares M., Lambas D. G., Padilla N., 2011, MNRAS, 415, 964
Mateus A., Sodrê L., Cid Fernandes R., Stasińska G., 2007, MNRAS, 374,
1457
Mo H. J., Einasto M., Xia X. Y., Deng Z. G., 1992, MNRAS, 255, 382
Park C., Choi Y.-Y., Vogeley M. S., Gott J. R. III, Blanton M. R., 2007,
SDSS Collaboration, ApJ, 658, 898
Poppesso P. et al., 2009, A&A, 494, 443
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, Nu-
merical Recipes, 2nd edn. Cambridge Univ. Press, Cambridge
Sahni V., Sathyaprakash B. S., Shandarin S. F., 1998, ApJ, 495, L5
Shandarin S. F., Sheth J. V., Sahni V., 2004, MNRAS, 353, 162
Shectman S. A. et al., 1996, ApJ, 470, 172S
Tanaka I., Yamada T., Turner E. L., Suto Y., 2001, ApJ, 547, 521
Tojeiro R., Heavens A. F., Jimenez R., Panter B., 2007, MNRAS, 381, 1252
Wen Z. L., Han J. L., Liu F. S., 2009, ApJS, 183, 197
Wen Z. L., Han J. L., Liu F. S., 2010, MNRAS, 407, 533
Whitmore B. C., Gilmore D. M., Jones C., 1993, ApJ, 407, 489
Zucca E., Zamorani G., Scaramella R., Vettolani, 1993, ApJ, 407, 470

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