A&A 384, L1–L5 (2002)
DOI: 10.1051/0004-6361:20020112

Astronomy & Astrophysics

The K20 survey

II. The different spatial clustering of $z \sim 1$ old and dusty star-forming EROs*

E. Daddi[1,10], A. Cimatti[2], T. Broadhurst[3], A. Renzini[1], G. Zamorani[4], M. Mignoli[4], P. Saracco[5], A. Fontana[6], L. Pozzetti[4], F. Poli[7], S. Cristiani[8,9], S. D'Odorico[1], E. Giallongo[6], R. Gilmozzi[1], and N. Menci[4]

[1] European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
[2] Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[3] Racah Institute for Physics, The Hebrew University, Jerusalem 91904, Israel
[4] Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
[5] Osservatorio Astronomico di Brera, via E. Bianchi 46, Merate, Italy
[6] Osservatorio Astronomico di Roma, via Dell'Osservatorio 2, Monteporzio, Italy
[7] Dipartimento di Astronomia, Università "La Sapienza", Roma, Italy
[8] ST, European Coordinating Facility, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
[9] Osservatorio Astronomico di Trieste, via Tiepolo 11, 34131 Trieste, Italy
[10] Dipartimento di Astronomia, Università di Firenze, Largo E. Fermi 5, 50125 Firenze, Italy

Received 21 December 2001 / Accepted 21 January 2002

Abstract. We compare the 3D clustering of old passively-evolving and dusty star-forming $z \sim 1$ EROs from the K20 survey. With detailed simulations of clustering, the comoving correlation length of dusty star-forming EROs is constrained to be less than $r_0 \sim 2.5\ h^{-1}$ Mpc. In contrast, the old EROs are much more positively correlated, with $5.5 \lesssim r_0/(h^{-1}\ \mathrm{Mpc}) \lesssim 16$, consistent with previous claims for $z \sim 1$ field early-type galaxies based on analyses of ERO angular clustering. The low level of clustering of dusty star-forming EROs does not support these to be major mergers building up an elliptical galaxy, or typical counterparts of SCUBA sources, but it is instead consistent with the weak clustering of high redshift blue galaxies and of luminous local IRAS galaxies. Current hierarchical merging models can explain the large r_0 for $z \sim 1$ field early-type galaxies, but fail in matching their high number density and overall old ages.

Key words. galaxies: evolution – galaxies: elliptical and lenticular, cD – galaxies: starburst – galaxies: formation – large-scale structure of Universe

1. Introduction

Extremely red objects ($R - K > 5$, EROs hereafter) are providing increasingly stringent constraints on our understanding of the formation of galaxies in general, via their spectral evolution and clustering properties. The very red colors of EROs are well known to be both consistent with old passively evolving distant ($z > 0.8$) elliptical galaxies (e.g. Cohen et al. 1999; Spinrad et al. 1997) or dust-reddened starburst galaxies (e.g. Cimatti et al. 1998; Smail et al. 1999). Purely passive evolution of the present day population of elliptical galaxies is consistent with the measured surface density of faint EROs with $K \sim 17$–22, while current renditions of the semianalytical hierarchical merging models fail to reproduce the surface density of EROs by a large factor (Daddi et al. 2000a; Smith et al. 2001; Firth et al. 2001).

Recently, we have completed a relatively large deep survey of very red galaxies covering 700 arcmin^2 (Daddi et al. 2000b, D00 hereafter), concluding that EROs are strongly clustered in projection, by an order of magnitude more than all galaxies at the same limits of $K \leq 18$–19.2. With careful attention to the measurement uncertainty inherent in narrow field data, Daddi et al. (2001, D01 hereafter) showed that the angular clustering of EROs implies a spatial correlation length of $r_0 = 12 \pm 3\ h^{-1}$ comoving Mpc, consistent with the assumption that the ERO population is dominated by elliptical galaxies.

Send offprint requests to: E. Daddi,
e-mail: `edaddi@eso.org`

[*] Based on observations made at the European Southern Observatory, Paranal, Chile (ESO LP 164.O-0560).

This large clustering amplitude is not at odds with recent hierarchical merging models, which require that the most massive galaxies are clustered more strongly than the general galaxy population at high z (e.g. Mo & White 1996). Our results on the angular and spatial clustering of EROs have been substantially confirmed by the Las Campanas Redshift Survey data (McCarthy et al. 2001; Firth et al. 2001; Moustakas & Somerville 2001).

In our recent large K20 redshift survey of a flux limited sample of ~500 galaxies with $K \leq 20$ (Cimatti et al. 2002, C02 hereafter), we obtained redshifts for a subsample of 35 EROs. For red objects with $R-K > 5$ and $K \leq 19.2$, about 1/3 were identified as old systems (consistent with being passively evolving elliptical galaxies), 1/3 were found to be dusty starburst galaxies and 1/3 remain unidentified. While the derived fraction of early-type galaxies, 50 ± 20%, is consistent with previous estimates based on morphology (Moriondo et al. 2000; Stiavelli & Treu 2000), C02 showed that the dusty star-forming (SF) objects do contribute significantly to the ERO population at faint magnitudes, thus complicating the interpretation of both ERO surface density and clustering, as measured in earlier analyses. In particular, given the strong interest in the clustering amplitude of early-type galaxies, it is important to estimate separately the clustering properties of the old and of the dusty-SF EROs, hence their relative contribution to the clustering of the whole ERO population. This is attempted in this letter, where we adopt a cosmology with $\Omega_\Lambda = 0.7$, $\Omega_\mathrm{m} = 0.3$ and $H_0 = 100\ h\ \mathrm{km\,s^{-1}/Mpc}$.

2. Clustering analysis

2.1. The sample and the diagnostic method

Table 1 shows the redshifts of the EROs identified in the K20 survey (C02) and classified as old passively evolving or dusty-SF galaxies, sorted with increasing redshift and divided between the two survey fields (32.2 arcmin^2 from CDFS and 19.8 arcmin^2 from 0055-27). The classification of EROs as old galaxies is based on the detection of the 4000 Å break and CaII H&K absorption with undetected (or very weak) [OII]λ3727 emission, while objects with strong [OII]λ3727 emission and an absence of a distinctive 4000 Å break were assigned to the dusty-SF class (see C02 for details).

Despite being by far the largest sample of EROs with identified redshifts, standard methods for evaluating the full two point correlation function cannot be still applied because of the small number of objects. Nevertheless the clustering properties of the old and dusty-SF samples can be investigated by studying the frequency of close pairs. This kind of approach has been applied in regimes with limited amount of information, e.g. to early studies of QSO clustering (Shaver 1984, cf. also Hartwick & Schade 1990), or to analyses of the arrival directions of ultra high energy cosmic rays (Tinyakov & Tkachev 2001), and relates to the integral under the correlation function on small scales, where most of the amplitude lies.

Table 1. ERO redshifts in the K20 survey. All but four EROs have $K \leq 19.2$. The redshift measurement errors are preliminarily estimated to be of the order of $\sigma \sim$ 100–200 km s^{-1}.

CDFS		0055-27	
Old	*Dusty-SF*	*Old*	*Dusty-SF*
0.726	0.796	0.790	0.820
1.019[1]	0.863	0.864	0.996
1.039	0.891	0.896	1.210
1.096	0.974	0.896	1.240
1.215	0.996[1]	0.935	1.300[1]
1.222	1.030	1.050	1.419
1.222	1.094	1.104	
	1.109[1]	1.166	
	1.149		
	1.221		
	1.294		
	1.327		

[1] Objects with $19.2 < K \leq 20$.

From Table 1, it can be noted that the sample of old EROs contains two pairs that, within the observational redshift accuracy, have the same redshift ($z = 0.896$ in the 0055-27 field and $z = 1.222$ in the CDFS), with an additional object close to the second pair at $z = 1.215$. On the other hand, the sample of dusty-SF EROs contains no really close pair, the closest pair having a relatively large redshift separation $\Delta z = 0.015$ ($z = 1.094$ and $z = 1.109$ in the CDFS, corresponding to $\Delta v \sim 4500$ km s^{-1}). The two old ERO pairs with the same redshift have also quite small angular separations ($\lesssim 1'$), implying spatial separations of 0.51 and 0.82 h^{-1} Mpc, while the two closest dusty-SF pairs are separated by 24 and 40 h^{-1} Mpc, respectively. The number of independent pairs in the samples is 81 for the dusty-SF EROs and 49 for the old EROs, thus immediately suggesting a higher intrinsic clustering amplitude for the old EROs.

To assess the significance of observed pair counts we first generate random samples. The selection functions are constructed from the observed redshift distributions of the two ERO populations. Simulated samples were built by assigning at random a redshift (rounded to $\Delta z = 0.001$ to match the data redshift measurements) extracted from the appropriate selection function, with sky positions within boundaries matching the area of each of our fields, and number of objects as in the relative observations (Table 1). The resulting probability of finding by chance ≥2 pairs of old EROs within a separation ≤0.82 h^{-1} Mpc is about 5×10^{-5}, a clear evidence of clustering among the sample of old EROs. On the other hand, the probabilities of finding the closest dusty-SF ERO pair at ≤24 h^{-1} Mpc and the two closest pairs at ≤40 h^{-1} Mpc are both ~97%, consistent with purely random chance.

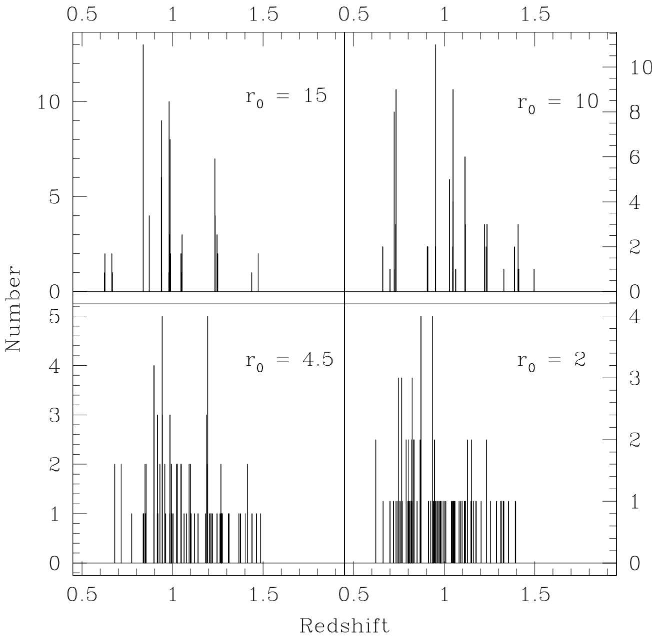

Fig. 1. For each panel we show the redshift distribution of 100 objects extracted from our simulations, that incorporates a given correlation length r_0, as indicated on the figure, illustrating the influence of the correlation amplitude on the overall smoothness of pencil beam redshift surveys (see text).

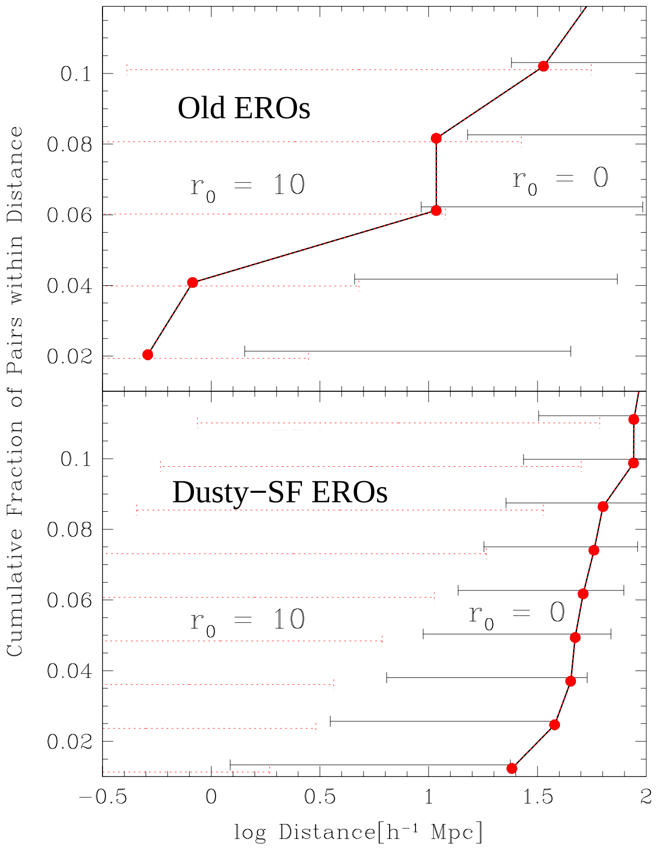

Fig. 2. Top panel: the cumulative distribution of pair separations observed for the old EROs (heavy line with filled circles). The horizontal error bars show the 2σ range estimated from our simulations with random (solid lines) and clustered (dotted lines, $r_0 = 10\ h^{-1}$ Mpc) realizations. Bottom panel: the same but for the dusty-SF EROs. This comparison shows that while the error on the estimate of the correlation length of either sample is quite broad, it is clear that the dusty-SF EROs as a class are completely inconsistent with a correlation length of order 10 h^{-1} Mpc, estimated from projected samples of EROs (D01, Firth et al. 2001).

2.2. Comparison to clustered samples

We now proceed a step further and generate simulated samples incorporating a known 2-point clustering amplitude, in order to derive information on the clustering of the two classes, and to obtain meaningful estimates of the variance inherent in the pairs statistics in the sample. We follow the recipe described in D01, based on the Soneira & Peebles (1977, 1978) prescription, allowing us to generate many samples with a given value of r_0 over very large volumes. We adopt the canonical parameterisation $\xi(r) \propto r^{-\gamma}$ with a slope of $\gamma = 1.8$ (justified by the observed angular slope $\delta = 0.8$, D00) for the 2-point correlation function and allow the amplitude to vary.

For these simulations one has also to account for the redshift space distortion, which tends to decrease the numbers of small scale pairs, and for the measurement error in the redshift. For the pairwise peculiar velocity dispersion we adopt the local value of $\sigma_{12} = 360$ km s^{-1} (Landy et al. 1998, see also Peacock et al. 2001) and their functional parameterisation, which is assumed not to evolve significantly over the redshift range of our data (e.g. Kauffmann et al. 1999). For the redshift error $\sigma = 150$ km s^{-1} is adopted (cf. Table 1), and we note that its contribution is small compared to the peculiar velocity term. To each simulated object, an error in the redshift measurement and a peculiar velocity is added in quadrature, chosen randomly from the appropriate distributions, before rounding its redshift to $\Delta z = 0.001$ to match the data redshift measurements.

As expected, the close pairs statistics is strongly dependent on the correlation length. For example, Fig. 1 shows that in the case of strong clustering almost all the objects reside in spikes with 2 or more objects in each $\Delta z = 0.001$ bin, and therefore even with our small number of objects we would expect to find a number of very close pairs (as indeed we do find for the old EROs). In fact, with the clustered samples the probability to find $\geq$2 pairs within $\leq$0.82 h^{-1} Mpc increases strongly with r_0 and at the 1σ level the observed close pairs statistics requires the correlation length of the present sample of old EROs to lie in the broad range $5.5 \lesssim r_0/(h^{-1}\ \mathrm{Mpc}) \lesssim 16$. On the other hand, for the dusty-SF EROs, the observation of the two closest pairs within 40 h^{-1} Mpc constrains $r_0 < 2.5\ h^{-1}$ Mpc at the 3σ confidence level. Figure 2 summarises concisely the comparison between the fraction of observed pairs below a given scale compared with the random ($r_0 = 0$) and clustered ($r_0 = 10\ h^{-1}$ Mpc) expectations for a range of scales.

2.3. Spatial and angular clustering of $K \leq 19.2$ EROs

If we assume $r_0 < 2.5\ h^{-1}$ Mpc for the observed sample of dusty-SF EROs, this results in an angular clustering amplitude $A(1^o) \lesssim 0.002$ at $K \sim 19$. We recall that EROs as a whole (including both old and dusty-SF objects) have a factor of 10 larger angular amplitude than this (D00). A solid result of this analysis is therefore that the dusty-SF EROs cannot be the cause of the strong angular clustering of EROs reported by D00, in agreement with the considerations of D01. It is clear from our redshift survey that a significant fraction of EROs are weakly clustered dusty-SF galaxies which therefore dilutes the true angular clustering amplitude of the early-type galaxies population responsible for the majority of the clustering signal. A detailed estimate of the amplitude of this dilution effect would need a more precise knowledge of the relative fractions of both classes and a measure of the cross correlation between the two ERO species. In fact, two dusty-SF EROs are in close redshift pairs with old EROs (see Table 1), with $\Delta z \leq 0.002$ and distances within $3.2\ h^{-1}$ Mpc, with a probability of only 2% to happen by chance. This is evidence of some positive cross-correlation bewteen the two ERO species, an intriguing result considering the different physical properties of the two populations. We defer a discussion of this aspect as a part of the ongoing analysis of the clustering of the whole K20 sample (Daddi et al. 2002, in preparation). The cross correlation term will tend to reduce the dilution effect of the dusty-SF EROs to the angular clustering of all EROs. In any case, although for $z \sim 1$ early-type galaxies the spatial clustering amplitude of $r_0 = 12 \pm 3\ h^{-1}$ Mpc (derived in D01) is more secure, being based on a relatively large sample, and consistent with the present analysis, it is likely that such amplitude should be revised upward in light of the findings presented here.

2.4. Analysis of systematic effects

We tested the stability of these results with respect to the statistical uncertainty in the shapes of the selection functions, which mostly influences the numbers of widely separated pairs. A change in the pairwise peculiar velocity dispersion σ_{12} by 20%, would result in a change of only about 10% for the estimated r_0 values, influencing of course the analysis of both ERO species in the same direction and thus leaving the result unchanged. Figure 2 shows that the two closest pairs for the old EROs in our survey are expected at $\lesssim 5\ h^{-1}$ Mpc separation at the 2σ level for $r_0 \sim 10\ h^{-1}$ Mpc, thus demonstrating that our result would hold correctly even if, because of redshift errors and roundings, the two closest pairs had been found at $\Delta z = 0.001$–0.002. The effect of redshift errors is in fact negligible for the dusty-SF ERO pairs, being all of them at $>20\ h^{-1}$ Mpc separation. Finally, we tested that the result is stable to variations of the color threshold at least up to $R - K > 4.5$.

3. Discussion

3.1. The clustering of dusty-SF EROs

The clustering of dusty-SF EROs is small, and maybe consistent with the values of $1 \lesssim r_0/(h^{-1}\ \mathrm{Mpc}) \lesssim 2.5$ measured for star-forming galaxies at $z \sim 1$ (Le Fevre et al. 1996; Carlberg et al. 1997; Hogg et al. 2000). This would suggest the former to be a subclass of the latter, but with stronger dust extinction. Locally, dusty galaxies detected by IRAS are also known to have a relatively weak clustering (e.g. Saunders et al. 1992).

The low level of clustering seems also to be at odds with the idea that the dusty-SF EROs are in a starburst phase following a major merger event, eventually expected to produce an elliptical galaxy, as in this case one would expect to find a correlation length somewhat lower than, but similar, to that of the ellipticals at the same redshift.

SCUBA sub-mm selected sources are also thought to be dusty objects at high redshift detected by virtue of the emission from dust warmed by star-formation or AGN activity. This population is expected (Magliocchetti et al. 2001) and tentatively observed (Scott et al. 2001) to show strong angular clustering at the level of $A(1^o) \sim 0.01$ (see also Ivison et al. 2000; Chapman et al. 2001). Therefore our result suggest the dusty-SF EROs are a different population with respect to SCUBA galaxies, with small overlap, in agreement with the latter being typically fainter and more distant ($K > 20$, median redshift $z \sim 2.5$–3, Smail et al. 2000, see also C02, Mohan et al. 2001, and Dannerbauer et al. 2002 for MAMBO sources).

Finally, we note that the class of dusty-SF EROs could be internally inhomogeneous: some of them maybe spirals with moderate extinction (e.g. van Dokkum & Stanford 2001) and there could also be a mixture of dust-enshrouded AGNs and starburst galaxies (C02).

3.2. Field $z \sim 1$ early-type galaxies

Observations of samples of faint ERO galaxies have led to three key conclusions regarding bright early-type galaxies with $L \gtrsim L_*$, at $z \sim 1$. Firstly, their space density is consistent with that of local luminous early-type galaxies, when account is made of minimal pure luminosity evolution (PLE) (C02). Secondly, spectroscopy implies age $\gtrsim$3 Gyr for their stellar populations (assuming solar metalicity, C02); and thirdly, a comoving correlation length $r_0 \gtrsim 12\ h^{-1}$ Mpc (this paper and D01) has been measured comparable with the local value for luminous early-type galaxies.

A large correlation length, $r_0 \gtrsim 10\ h^{-1}$ Mpc, is anticipated theoretically for the hierarchical merging paradigm for which a rapidly increasing bias is predicted for massive galaxies by $z \sim 1$ (e.g. Mo & White 1996; Moscardini et al. 1998). Such a large correlation length is not expected for the PLE (galaxy conservation) scenario (D01). However, also current semi-analytical renditions of the hierarchical models seem to be at odds with the observed results.

For example, the Cole et al. (2000) model predicts a comoving density (Fig. 1 of Benson et al. 2001) of *all* the $z \sim 1$ galaxies with 10^{11} $M_\odot$ (consistent with our $K \leq 19.2$ selection) which is a full order of magnitude below the density of just the old EROs observed by C02. Similarly, the Kauffmann et al. (1999) model[1] predicts a comoving density of $z \sim 1$ EROs ($R - K \geq 5$, $K \leq 19.2$) that is 3(6) times lower than observed by C02 for old(all) EROs. In addition, in these models $z \sim 1$ galaxies qualified as field early-types appear to have experienced recent star-formation, while the present sample of old EROs is dominated by an old stellar population. We conclude that to our knowledge no semianalytical rendition of the hierarchical merging models can yet account for all the 3 key observed properties of $z \sim 1$ field early type galaxies described above.

Acknowledgements. We thank the referee, Rob Ivison, for constructive remarks, and Huub Röttgering and Sperello di Serego Alighieri for useful comments to the manuscript.

References

Benson, A. J., Ellis, R. S., & Menanteau, F. 2001, MNRAS, submitted [`astro-ph/0110387`]

Carlberg, R., Cowie, L., Songaila, A., & Hu, E. 1997, ApJ, 484, 538

Chapman, S. C., Lewis, G. F., Scott, D., et al. 2001, ApJ, 548, L17

Cimatti, A., Andreani, P., Röttgering, H., & Tilanus, R. 1998, Nature, 392, 895

Cimatti, A., Daddi, E., Mignoli, M., et al. 2002, A&A, 381, L68 (C02)

Cohen, J. G., Hogg, D. W., Pahre, M. A., et al. 1999, ApJ, 120, 171

Cole, S., Lacey, C., Baugh, C., & Frenk, C. 2000, MNRAS, 319, 168

Daddi, E., Cimatti, A., & Renzini, A. 2000a, A&A, 362, L45

Daddi, E., Cimatti, A., Pozzetti, L., et al. 2000b, A&A, 361, 535 (D00)

Daddi, E., Broadhurst, T., Zamorani, G., et al. 2001, A&A, 376, 825 (D01)

Dannerbauer, H., Lehnert, M. D., Lutz, et al. 2002, submitted to ApJ [`astro-ph/0201104`]

Firth, A. E., Somerville, R. S., McMahon, R. G., et al. 2001, MNRAS, submitted [`astro-ph/0108182`]

Hartwick, F. D., & Schade, D. 1990, ARA&A, 28, 437

Hogg, D., Cohen, J., & Blandford, R. 2000, ApJ, 545, 32

Kauffmann, G., Colberg, J. M., Diaferio, A., & White, S. D. M. 1999, MNRAS, 307, 529

Ivison, R. J., Dunlop, J. S., Smail, I., et al. 2000, ApJ, 542, 27

Landy, S., Szalay, A., & Broadhurst, T. 1998, ApJ, 494, L133

Le Fevre, O., Hudon, L., Lilly, S., et al. 1996, ApJ, 461, 534

Magliocchetti, M., Moscardini, L., Panuzzo, P., et al. 2001, MNRAS, 325, 1553

McCarthy, P. J., Carlberg, R. G., Chen, H.-W., et al. 2001, ApJ, 560, L131

Mo, H., & White, S. D. M. 1996, MNRAS, 282, 347

Mohan, N., Cimatti, A., Röttgering, H., et al. 2002, A&A, in press [`astro-ph/0112342`]

Moriondo, G., Cimatti, A., & Daddi, E. 2000, A&A, 364, 26

Moscardini, L., Coles, P., Lucchin, F., & Matarrese, S. 1998, MNRAS, 299, 95

Moustakas, L. A., & Somerville, R. S. 2001, submitted to ApJ [`astro-ph/0110584`]

Peacock, J. A., Cole, S., Norberg, P., et al. 2001, Nature, 410, 169

Saunders, W., Rowan-Robinson, M., & Lawrence, A. 1992, MNRAS, 258, 134

Scott, S., Fox, M., Dunlop, J., et al. 2001, submitted to MNRAS [`astro-ph/0107446`]

Shaver, P. 1984, A&A, 136, L9

Smail, I., Ivison, R. J., Kneib, J.-P., et al. 1999, MNRAS, 308, 1061

Smail, I., Ivison, R. J., Owen, F. N., et al. 2000, ApJ, 528, 612

Smith, G. P., Smail, I., Kneib, J.-P., et al. 2001, MNRAS, in press [`astro-ph/0109465`]

Soneira, S., & Peebles, P. J. E. 1977, ApJ, 211, 1

Soneira, S., & Peebles, P. J. E. 1978, AJ, 83, 845

Spinrad, H., Dey, A., Stern, D., et al. 1997, ApJ, 484, 581

Stiavelli, M., & Treu, T. 2000, in Galaxy Disks and Disk Galaxies, ASP Conf. Ser. [`astro-ph/0010100`]

Tinyakov, P. G., & Tkachev, I. I. 2001, JETP Lett., 74, 1

van Dokkum, P., & Stanford, S. 2001, ApJ, 562, L35

---

[1] `http://www.mpa-garching.mpg.de/GIF/`