Extremely compact massive galaxies at z~1.4

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ABSTRACT

The optical rest–frame sizes of 10 of the most massive (~5×10^{11}h_{70}^{-2}M_{\odot}) galaxies found in the near–infrared MUNICS survey at 1.2<z<1.7 are analysed. Sizes were estimated both in the J and K' filters. These massive galaxies are at least a factor of 4^{+1.0}_{-1.0} (±1 σ) smaller in the rest–frame V–band than local counterparts of the same stellar mass. Consequently, the stellar mass density of these objects is (at least) 60 times larger than massive ellipticals today. Although the stellar populations of these objects are passively fading, their structural properties are rapidly changing since that redshift. This observational fact disagrees with a scenario where the more massive and passive galaxies are fully assembled at z~1.4 (i.e. a monolithic scenario) and points towards a dry merger scenario as the responsible mechanism for the subsequent evolution of these galaxies.

Key words: Galaxies: evolution; Galaxies: elliptical and lenticular, cD; Galaxies: formation; Galaxies: fundamental parameters; Galaxies: high redshift; Galaxies: structure

1 INTRODUCTION

In the local universe, the population of galaxies with stellar masses larger than 10^{11}M_{\odot} is dominated by passive early–type galaxies that are a factor of ~3 more numerous than late–type galaxies above this mass threshold (Baldry et al 2004). Their stellar populations are old, metal rich and are characterized by a short formation time-scale (e.g. Heavens et al. 2004; Thomas et al 2005; Feulner et al. 2005). In addition, these massive galaxies are large, with sizes (as parametrized by the effective radius) larger than 4 kpc (Shen et al. 2003).

Historically, two different formation scenarios have been proposed in order to explain the properties of these objects: the so–called monolithic collapse model (Eggen, Lynden–Bell & Sandage 1962; Larson 1975; Arimoto & Yoshii 1987; Bressan, Chiosi & Fagotto 1994) and the hierarchical merging model (White & Frenk 1991). In the former scenario, spheroidal galaxies formed at a very early epoch as a result of a global starburst, and then passively evolve to the present. In the merger model, spheroids are formed by violent relaxation during major merger events.

Favoring the monolithic model is the fact that the bulk of stars in massive ellipticals are old (Mannuci et al. 2001) and have high [α/Fe] ratios (i.e. short star formation time scales; Worthey, Faber & González 1992). On the other hand, supporting a hierarchical merger scenario, current observations seem to find a decline in the number of massive galaxies at high–z. The space density of red passively evolving early–type galaxies has moderately increased since z~1 (Daddi et al. 2000; Pozzetti et al. 2003; Bell et al. 2004; Drory et al. 2004; Faber et al. 2005). At even higher redshift, z~1.7, their space density appears to be a factor of 2–3 smaller than that of their local counterparts (Daddi et al. 2005; Saracco et al. 2005; Drory et al. 2005). In addition, new generations of semianalytical models (e.g. de Lucia 2006) are now able to produce results in better agreement with the stellar population properties of ellipticals.

An additional test to check the validity of the above two scenarios is to explore the size evolution of the spheroids through cosmic time. In this sense, the prediction from the monolithic model is that the stellar mass–size relation of these objects should remain unchanged after their formation, with the luminosity–size relation evolving in agreement with the fading of their stellar populations. In the hierarchical model, however, the stellar mass–size relation of these objects should change as a result of the increase in size of the remnants after each merger.

From the observational point of view, the evolution of the luminosity–size and stellar mass–size relations of the early–type galaxies since z~1 is consistent with the passive aging of ancient stellar populations (Trujillo & Aguerri 2004, McIntosh et al. 2005). Consequently, the structural properties of the more massive galaxies seem to not change from z~1 to the present. At z>1 the situation is less clear. Large and deep near–infrared surveys are needed to collect a significative sample of massive passively
evolving galaxies at $z>1$ and to explore the sizes of the galaxies in their optical rest-frame. Using the Faint Infrared Extragalactic Survey (FIRES; Franz et al. 2000), Trujillo et al. (2004;2006) have shown that there is a hint for most massive galaxies ($M_*>7\times10^{10} \, h_{70}^{-2} M_\odot$) at $z<2.5$ being a factor of 2 smaller than present–day counterparts with similar masses. However, the number of galaxies in that sample is not large enough to firmly establish this result. In addition, there has been a recent claim of 4 very compact (r_e<1 kpc in their local UV restframe) and massive ($M_*>10^{11} \, h_{70}^{-2} M_\odot$) passively evolving galaxies at $z<1.7$ in the UDF (Daddi et al. 2005). The few number of objects together with the fact that some of these galaxies could be hosting an AGN make the above claims uncertain.

To shed some light on the above issue, we estimate the sizes (in their local optical rest-frame) of a sample of 10 very massive ($10^{11} < M_* < 10^{12} M_\odot$) galaxies spectroscopically classified as early–type galaxies at 1.2<z<1.7, with no sign of AGN activity in their spectra (except for one object). These objects are consequently good candidates to test whether their sizes are equal or smaller than their local counterparts. Throughout, we will assume a flat $\Lambda$–dominated cosmology ($\Omega_M=0.3$, $\Omega_\Lambda=0.7$ and $H_0=70$ km s$^{-1}$ Mpc$^{-1}$). All magnitudes are provided in the Vega system unless otherwise stated.

2 DESCRIPTION OF THE DATA

The near-infrared images used in this study were taken from the Munich Near-IR Cluster Survey (MUNICS; Drory et al. 2001), and its deeper follow-up project called MUNICS-Deep. MUNICS is a wide-field medium-deep photometric survey taken in the near-infrared and optical filters. Dedicated follow-up spectroscopy is being carried out for a selected sub-sample (Feulner et al. 2003). The main part of the survey consists of 10 fields with a total area of $\sim 0.3 \, \text{deg}^2$. For all these fields photometry in $K^\prime$, $J$, $I$, $R$, $V$, and $B$ is available, with limiting magnitudes ranging from $K^\prime \sim 19.5$ and $J \sim 21$ to $B \sim 24.0$ mag (50% completeness for point sources; Snigula et al. 2002). This is sufficiently deep to detect passively evolving systems up to a redshift of $z<1.4$, and at a luminosity of $0.5L^*$. The final $K^\prime$–selected catalog contains roughly 5000 objects and is described in Drory et al. (2001).

The sample of massive Extremely Red Objects (ERO) studied here was selected in three survey fields (S2F1, S2F5 and S7F5). The primary selection criteria were $K^\prime < 18.5$ and $R - K^\prime > 5$, resulting in a list of 36 objects. Low-resolution near-infrared spectroscopy was carried out for $\sim 60\%$ of them, and ten objects are identified as early-type galaxies at $1.2 < z < 1.7$, with stellar masses well exceeding $10^{11} M_\odot$ (Saracco et al. 2003, 2005; Longhetti et al. 2005).

Seven out of the ten EROs explored here are located in the field S2F1, for which deeper near-infrared images are available from the MUNICS-Deep survey (Goranova et al., in prep.). MUNICS-Deep aims at obtaining a contiguous 1-square-degree field (overlapping the MUNICS patches S2F1 and S2F5) in optical and near-infrared filters to a detection limit 2 mag deeper than MUNICS. To improve the size measurements of these seven EROs in the field S2F1, the deep $K^\prime$ and $J$–band images from MUNICS-Deep were used. These were obtained with Omega2000 at the Calar Alto 3.5-m telescope at a pixel scale of 0.45 arcsec/pixel, with a typical seeing of $\lesssim 1.0$ arcsec, and limiting magnitudes of $K^\prime \sim 21.5$ and $J \sim 23.5$ mag (again 50$\%$ completeness limits for point sources). Basic data reduction (Goranova et al., in prep.) was performed using a modified version of the IRAF external package XDIMSUM.

For the remaining three objects, the sizes were estimated on the $K^\prime$-band and J-band images of the (shallower) MUNICS project. These images, taken with OmegaPrime at the Calar Alto 3.5-m telescope, have a pixel scale of 0.396 arcsec/pixel, a typical seeing of $\sim 1.2$ arcsec, and a limiting magnitude of $K^\prime \sim 19.5$.

Stellar masses have been derived from the $K^\prime$-band absolute magnitudes by means of the mass–to–light ratio $M/L_{K^\prime}$ derived from the best fitting models (see details in Longhetti et al. 2005). The largest uncertainty in the stellar mass computation comes from the variation of $M/L$ according to the age of the stellar population and the adopted IMF. However, it is worth noting that, given the extremely bright $K^\prime$-band magnitudes ($K^\prime<18.4$) and the redshifts ($z>1.2$) of our galaxies, their resulting stellar masses are well in excess of $10^{11} M_\odot$ leaving aside any model assumption. In this paper we use stellar masses derived using a Kroupa IMF. However, to estimate the uncertainty in the stellar masses we used a large set of different IMFs (Longhetti et al. 2005).

3 SIZE ESTIMATION

To estimate the sizes of the galaxies we have used the GALFIT code (Peng et al. 2002). GALFIT convolves Sérsic (1968) $r^{1/n}$ profile galaxy models with the point-spread function (PSF) of the images and then determines the best fit by comparing the convolved models with the science data using a Levenberg–Marquardt algorithm to minimize the $\chi^2$ of the fit.

The spatial resolution of our images does not allow to estimate accurately the shape (index $n$) of the surface brightness profiles. For that reason, and to decrease the number of free parameters in our fits, we have calculated the size of the galaxies by fixing the Sérsic index to $n=1$ (i.e. an exponential profile) and $n=4$ (i.e. a de Vaucouleurs profile). Both models are convolved with the image PSF. The effective radii provided by every fit ($r_{e,1}$ and $r_{e,4}$) are used to estimate a mean effective radius and indicate the range of variation of the sizes of our galaxies. The PSF that was used for every galaxy corresponds to the nearest (bright enough but non-saturated) star to the galaxy.

Neighboring galaxies were excluded from each model fit using a mask, but in the case of closely neighboring galaxies with overlapping isophotes, the galaxies were fitted simultaneously.

3.1 Testing the size estimates: simulations

The results presented in this paper rely on our ability to measure accurate structural parameters. To gauge the accuracy of our size determination we have created 250 artificial galaxies uniformly generated at random in the following ranges: 18\%< J<21, 0.8< $r_e<1.6$ (i.e. 0.8< $r_e<13.5 \, h_{70}^{-1}$ kpc in the local restframe at $z<1.4$) and 0.5<n<8. Simulations were done in J band only, but our results can be extrapolated to the K band data because of their similar signal–to–noise quality. The mock galaxies span a large range of surface brightness shapes (i.e. they are not restricted to n=1 or n=4) to model the different galaxy profiles found in the observations (Trujillo et al. 2006). To simulate the real conditions of our observations, we add a background sky image (free of sources) taken from a piece of the MUNICS–Deep field image in the J band. Finally, the galaxy models used (n=1 and n=4) were convolved with the observed PSF. The same procedure was used to retrieve the structural parameters both in the simulated and actual images.

Fig. 1 shows the comparison between the input and recovered size values in our simulations. The recovered size value, $r_{e,out}$ is evaluated as the mean value between the size recovered using n fixed to 1, and n fixed to 4: $r_{e,out}=(r_{e,out,n=1}+4r_{e,out,n=4})/2$. For that reason, the intrinsic scatter shown in Fig. 1 is independent of the magnitudes and mainly caused by the fact that the index $n$ of
the model galaxies is fixed whereas the mock galaxies span a large range of n. According to the simulations, our sizes for the smallest objects should be considered only as an upper limit. This systematic deviation of the size of the galaxies at small radii is probably an artefact due to the relative large size of the pixel (\(\sim 0.45''\)) compared to the size of the galaxies. Simulations also provide us with a typical uncertainty in the estimation of the sizes of small galaxies of \(\sim 0.1''\). We will use this value to estimate the error bars in our measurements.

### 3.2 Testing the size estimates: crude upper limits and the effect of different images depth

A direct method of establishing a crude upper limit to the size of the objects is by fitting a Gaussian profile to the observed galaxies. Under the assumption that the intrinsic surface brightness profile of the galaxies are also described by a Gaussian profile, the effective radius of the galaxy is given by:

\[
r_e = 1/2 \times \sqrt{FWHM_{obj}^2 + FWHM_{PSF}^2}
\]

In general, galaxies have a surface brightness profile which is much more concentrated than a Gaussian profile, consequently, this method provides us with an upper (very conservative) limit of the object's size. A direct Gaussian fit to our objects provide a typical value of FWHM\(_{obj}\)\(\sim 1.2''\). Using the typical value of seeing that we have in our images, FWHM\(_{PSF}\)\(\sim 1''\), this translates into an upper limit to the sizes of the galaxies of \(r_e \leq 0.8''\) (or \(r_e \leq 6.5\) h\(_{70}^{-1}\) kpc at z\(\sim 1.4\) in the cosmology used). Local galaxies with M\(_{stellar}\)\(\sim 5 \times 10^{11} \ M_{\odot}\) are expected to have sizes of \(\sim 10\) h\(_{70}^{-1}\) kpc (Shen et al. 2003). This crude upper limit estimation (according to our simulations this technique will produce estimates \(\sim 1.5\) larger than the input values) shows that our high-z massive galaxies are more compact than their local counterparts.

The sizes of three galaxies in our sample were estimated using shallower images than the rest of the sample. We have checked whether these shallow observations could introduce any bias in the size estimates of these three objects. For the seven galaxies where we have both shallow and deep observations we estimated the sizes in both cases, and the sizes agree within the error bars. We do not observe, in addition, any systematic difference. This result implies that using deeper observations does not unveil the contribution of light from missing wings in the surface brightness distributions. In other words, our images are catching almost all the light of these galaxies.

### 4 THE OBSERVED STELLAR MASS VS SIZE RELATION

We have estimated the sizes of our galaxies in both the J and the K' band. At z\(\sim 1.4\), this implies estimating the sizes in the local rest–frame V–band and (approximately) I–band. The results of our fitting are shown in Table I. The seeing and the depth are slightly different amongst the near infrared images which allows us to test the reliability of the size estimates. Interestingly, the sizes of individual objects both in J and in K' band are very similar. This reinforces the idea that the sizes presented here are robust.

The stellar mass–size relation for the massive galaxies analysed here are presented in Fig. Overplotted in this figure are the mean and dispersion of the distribution of the Sérsic half–light radii of early–type galaxies from the Sloan Digital Sky Survey (SDSS; York et al. 2000). We use the SDSS sample as the local reference. Local sizes are determined from a Sérsic model fit (Blanton et al. 2003) and the characteristics of the sample described in Shen et al. (2003). SDSS stellar masses were also derived using a Kroupa IMF. The mean of the SDSS galaxies redshift distribution used in this comparison is 0.1. We use the sizes estimated in the observed r'–band and the z'–band (S. Shen, private communication). This closely matches the V–band and I–band restframe filters at z\(\sim 0.1\).

Fig. 2 shows that, at a given stellar mass, the most massive galaxies at z\(\sim 1.4\) are much smaller than local ones. According to our simulations our sizes are upper limits, implying that our high–z galaxies are at least a factor of 4.0\(\pm 1.9\) (\(\pm 1\) \(\sigma\)) smaller in the V–band, and at least 3.2\(\pm 1.1\) smaller in the I–band than local counterparts. This implies that the internal stellar mass density in the most massive galaxies at that redshift is \(\sim 60\) (or at least 33 if considered the measurements obtained in K’-band) times larger than today. To test the robustness of our results we have checked two potential biases. First, following Maraston et al. (2006), we repeat the analysis under the assumption that our masses could be overestimated by a factor of \(\sim 2\). In this case, our galaxies will still be more compact than present-day galaxies of the same masses by a factor of 2.5–3. Second, following the fact that present very massive ellipticals have large index n values, we repeat our analysis using the \(r_e\) values obtained forcing the index n to be fixed to 8 during the fitting. In this case, our galaxies are still more compact than the local galaxies (of equal mass) by a factor of 2.7–3.3.

Most of our galaxies are more than 2 \(\sigma\) away from the local relation. In fact, we have probed whether there is any galaxy in the SDSS sample as massive and compact as the ones we have found. Using the catalogue used by Shen et al. (2003) to build the local SDSS relations (S. Shen, private communication) we have not found any local galaxy with \(r_e < 4\) kpc and \(M_{stellar} > 3 \times 10^{11} \ M_{\odot}\), and only one with \(r_e < 5\) kpc (see also Bernardi et al. 2006). That means a comoving density of \(10^{-7}\text{Mpc}^{-3}\). The selection of our objects (including the spectroscopic follow up) is not biased towards smaller objects. In fact, equally bright objects with sizes four times larger could be observed, and their sizes measured accurately if they were in our sample (see Fig. 1). When considering all the galaxies together the possibility that they are all small by chance is rejected at the 4 \(\sigma\) level.
Table 1. Main physical parameters of the 10 early–type galaxies. Note: sizes of galaxies marked with an asterisk were obtained in the shallow MUNICS images.

| Field ID | $z_{\text{spec}}$ | J | K | $M_*$ | $r_e,J,n=1$ | $r_e,J,n=4$ | $r_e,K,n=1$ | $r_e,K,n=4$ | FWHM J-band | FWHM K'-band |
|----------|-----------------|---|---|-------|-------------|-------------|-------------|-------------|-------------|-------------|
| S2F5*    | 109             | 1.22 | 18.2 | 16.6 | 7.0 | 0.46 | 0.49 | 0.52 | 0.62 | 1.17 | 1.09 |
| S7F5*    | 254             | 1.22 | 19.8 | 17.8 | 7.2 | 0.66 | 0.53 | 0.79 | 0.75 | 1.30 | 1.12 |
| S2F1     | 357             | 1.34 | 19.5 | 17.8 | 9.0 | 0.32 | 0.34 | 0.30 | 0.35 | 0.98 | 0.97 |
| S2F1     | 527             | 1.35 | 20.4 | 18.3 | 3.6 | 0.14 | 0.09 | 0.17 | 0.15 | 1.00 | 0.99 |
| S2F1     | 389             | 1.40 | 20.3 | 18.2 | 4.6 | 0.21 | 0.18 | 0.21 | 0.34 | 1.00 | 1.00 |
| S2F1     | 511             | 1.40 | 19.8 | 18.1 | 1.7 | 0.26 | 0.23 | 0.26 | 0.41 | 0.95 | 0.95 |
| S2F1     | 142             | 1.43 | 19.6 | 18.1 | 5.9 | 0.31 | 0.38 | 0.28 | 0.24 | 0.97 | 1.00 |
| S2F1     | 443             | 1.45 | 20.0 | 18.2 | 5.5 | 0.28 | 0.32 | 0.35 | 0.52 | 0.95 | 0.95 |

Figure 2. Distribution of rest–frame optical sizes vs. stellar mass for massive MUNICS galaxies. Left Panel shows the distribution of galaxies with sizes estimated in the V-band local restframe. Right Panel shows the distribution of galaxies with sizes estimated in the I-band local restframe. Overplotted on the observed distribution of points are the mean and dispersion of the distribution of the S´ersic half–light radius of the SDSS galaxies as a function of the stellar mass. SDSS sizes were obtained in the "V–band" and in the "I–band".

5 DISCUSSION

As stated in the Introduction, it is possible to find in previous works some examples of significantly small massive galaxies at $z \sim 1$. Daddi et al. (2005) have been the first on discussing in detail the nature of these objects. In addition to the four Daddi et al. objects, there is a group of compact ($r_e \lesssim 1$ kpc) and massive galaxies at $z \sim 1$ seen in Fig. 9 from McIntosh et al. 2005. There is also evidence of compact massive galaxies in Trujillo et al. (2006) and di Serego Alighieri et al. (2005). Finally, Waddington et al. (2002) studied two $z \sim 1.5$ radio–selected early–type galaxies and found, using NICMOS imaging, sizes of $\sim 0.3$ arcsec ($\sim 2.5$ kpc). Therefore, the observational existence of these small galaxies appears currently to be well established.

A strong morphological K–correction has been suggested by Daddi et al. (2005) as one of the potential explanation of the compactness of their objects observed in the UV restframe. However, our observations in the optical restframe reject this possibility. Another potential explanation suggested by Daddi et al. (2005) is the presence of an unresolved nuclear component (i.e. an AGN). In fact, two of their 4 objects were detected in X-rays. However, the AGN hypothesis is unlikely to explain our observations.

Only one of our galaxies (S2F1 443) is detected in deep XMM-Newton pointing of the S2 fields (Severgnini et al. 2005) having $L_{2-10keV} \gtrsim 10^{43}$ ergs s$^{-1}$ and the spectral energy distributions of our objects lack AGN features. Consequently, if AGNs are present in the rest of our galaxies, their luminosities should be much fainter than $10^{43}$ ergs s$^{-1}$ or alternatively, they must be heavily obscured (contributing very weakly to the stellar continuum). The quality of our data prevents us to provide a reliable pointlike+S´ersic fit analysis of the surface brightness distributions (as done by Daddi et al. 2005). However, an argument against the biasing of our size estimates due to the AGN contribution (if at all present) is the fact that both at J and K the sizes of our objects are very similar. The AGN should contribute much strongly in J–band (where should be the emission lines H$\beta$ and OIII at $z \sim 1.4$) than in K–band where there is not any significant line. The difference in sizes in J and K in our objects are in agreement (within the error bars). For that reason, we think that the AGN (if present) is not affecting (significantly) the size estimates.

The galaxies analysed in this paper are already very massive at $z \sim 1.4$ and their stellar population properties are consistent with passive fading. However, there is no observational evi-
dence for galaxies as massive and compact as these in the local universe. Consequently, the high-z galaxies have to increase their sizes since that redshift. This observational fact disagrees with a scenario where the most massive and passive galaxies are fully assembled at $z \sim 1.4$ (i.e. a monolithic scenario). It is worth noting that, whatever channel is used for our galaxies to evolve in size, this process should take place quickly (i.e. $\lesssim 2$ Gyr), since galaxies with $M_{\star} > 10^{11} h^{-2}_{70} M_{\odot}$ at $z \sim 0.8$ seem to be all already in place (Cimatti et al. 2006), and to have sizes very similar to their current sizes since that redshift. This observational fact disagrees with a scenario where the most massive and passive galaxies are fully assembled at high redshift. As a consequence, they claim that the remnant should be much smaller in size at high redshift. This will make the discrepancy in sizes very effective but will basically maintain unchanged the sizes (Dekel & Cox 2006). This will make the discrepancy in sizes between the high-z and the local galaxies even larger. So, we think wet merging is disfavoured as an evolutionary path for our objects.

An interesting open question is understanding how galaxies as massive as those we are dealing with can be so compact in the past. Recently Khochfar & Silk (2005) have investigated the effect of dissipation in major mergers within the CDM paradigm. They find that early-type galaxies at high redshifts merge from progenitors that have more cold gas available than their counterparts at lower redshifts. As a consequence, they claim that the remnant should be smaller in size at high redshift. Khochfar & Silk (2006) have predicted that the size of objects at $z > 1.5$ with $M_{\star} \sim 5 \times 10^{11} h^{-2}_{70} M_{\odot}$ is a factor of $\sim 3$ times smaller than local counterparts. These estimates agree very well with our observations. If this scenario is correct, the progenitor galaxies that merge to form massive spheroids galaxies are progressively less and less devoid of gas at lower redshift.

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REFERENCES

Arimoto N, & Yoshii Y., 1987, A&A, 173, 23

Baldry I. K., Glazebrook K., Brinkmann J., Ivezić Ž, Lupton R. H., Nichol R. C. Szalay A. S., 2004, ApJ, 600, 681

Bell E. F. et al., 2004, ApJ, 608, 752

Bernardi M., Hyde J. B., Sheth R. K., Miller C. J., Nichol R. C., 2006, Aj, submitted, astro-ph/0607117

Blanton M. R., et al., 2003, ApJ, 592, 819

Boylan-Kolchin M., Ma C-P., Quataert E., 2006, MNRAS, 369, 1081

Bressan A., Chiosi C., Fagotto F., 1994, ApJS, 94, 63

Cimatti A., Daddi E., Renzini A., 2006, A&A, 453, L29

Cole S. et al., 2001, MNRAS, 326, 255

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

Daddi E. et al., 2005, ApJ, 626, 680

Dekel A., Cox T.J., 2006, MNRAS, 370, 1445

De Lucia, G, Springel V., White S. D. M., Croton D., Kauffmann G., 2006, MNRAS, 366, 499

di Serego Alighieri S., et al., 2005, A&A, 442, 125

Domínguez–Tenreiro, R., Oñorbe, J., Sáiz, A., Artal, H., Serna, A., 2006, ApJ, 636, L77

Drory N., Feulner G., Bender R., Botzler C. S., Hopp U., Maraston C., Mendes de Oliveira C., Snigula J., 2001, MNRAS, 325, 550

Drory N., Bender R., Feulner G., Hopp U., Maraston C., Snigula J., Hill G. J., 2004, ApJ, 608, 742

Drory N., Salvato M., Gabasch A., Bender R., Hopp U., Feulner G., Pannella M., 2005, ApJ, 619, L131

Eggen O. J., Lynden–Bell D., Sandage A. R., 1962, ApJ, 136, 748

Faber S. M., et al. 2005, astro-ph/0506047

Feulner G., Bender R., Drory N., Hopp U., Snigula J., Hill G. J., 2003, MNRAS, 342, 605

Feulner G., Gabasch A., Salvato M., Drory N., Hopp U., Bender R., 2005, ApJ, 633, L9

Heavens A., Panter B., Jimenez R., Dunlop J., 2004, Nature, 428, 625

Khochfar S., Burkert A., 2003, ApJ, 597, L117

Khochfar S., Silk J., 2006a, MNRAS, 370, 902

Khochfar S., Silk J., 2006b, ApJ, in press, astro-ph/0605436

Larson R., 1975, MNRAS, 173, 671

Longhetti M. et al., 2005, MNRAS, 361, 897

Mannucci F., Basile F., Poggianti B.M., Cimatti A., Daddi E., Pozzetti L., Vanzli L., 2001, MNRAS, 326, 745

Maraston C., Daddi E., Renzini A., Cimatti A., Dickinson M., Papovich C., Pasquali A., Pirzkal N., 2006, ApJ, submitted

McIntosh et al., 2005, ApJ, 632, 191

Peng C.Y., Ho L.C., Impey C.D., Rix H.W., 2002, AJ, 124, 266

Pozzetti L. et al. 2003, A&A, 402, 387

Saracco P. et al., 2003, A&A, 398, 127

Saracco P. et al., 2005, MNRAS, 357, L40

Sérsic J.-L. 1968, Atlas de Galaxias Australes (Cordoba: Observatorio Astronomico)

Severgnini P., et al. 2005, A&A, 431, 87

Shen S., Mo H. J., White S. D. M.,Blanton M. R., Kauffmann G.,Voges W.,Brinkmann J., Csabai I., 2003, MNRAS, 343, 978

Snigula J., Drory N., Bender R., Botzler C. S., Feulner G., Hopp U., 2002, MNRAS, 336, 1329

Thomas D., Maraston C., Bender R., de Oliveira C. M., 2005, ApJ, 621, 673

Trujillo I., Aguerri J.A.L., 2004, MNRAS, 355, 82

Trujillo I. et al., 2006, ApJ, in press, astro-ph/0504225

White S.D.M, Frenk C. S., 1991, 379, 52

Worthey G., Faber S. M., Gonzalez J. J., 1992, ApJ, 398, 69

York D., et al. 2000, AJ, 120, 1579