A&A 381, L68–L72 (2002)
DOI: 10.1051/0004-6361:20011696

Astronomy & Astrophysics

The K20 survey

I. Disentangling old and dusty star-forming galaxies in the ERO population*

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Received 12 October 2001 / Accepted 28 November 2001

Abstract. We present the results of VLT optical spectroscopy of a complete sample of 78 EROs with $R-Ks \geq 5$ over a field of 52 arcmin^2. About 70% of the 45 EROs with $Ks \leq 19.2$ have been spectroscopically identified with old passively evolving and dusty star-forming galaxies at $0.7 < z < 1.5$. The two classes are about equally populated and for each of them we present and discuss the average spectrum. From the old ERO average spectrum and for $Z = Z_{\odot}$ we derive a minimum age of ∼3 Gyr, corresponding to a formation redshift of $z_{\rm f} \gtrsim 2.4$. PLE models with such formation redshifts well reproduce the density of old EROs (consistent with being passively evolving ellipticals), whereas the predictions of the current hierarchical merging models are lower than the observed densities by large factors (up to an order of magnitude). From the average spectrum of the star-forming EROs we estimate a substantial dust extinction with $E(B-V) \gtrsim 0.5$. The star formation rates, corrected for the average reddening, suggest a significant contribution from EROs to the cosmic star-formation density at $z \sim 1$.

Key words. galaxies: evolution – galaxies: elliptical and lenticular, cD – galaxies: starburst – galaxies: formation

1. Introduction

Extremely red objects (EROs, here defined with $R-Ks > 5$) were discovered serendipitously a decade ago (Elston et al. 1988), and recent wide-field surveys revealed that they form a substantial population (Thompson et al. 1999; Daddi et al. 2000a, D00 hereafter; McCarthy et al. 2001). Having the colors expected for high-z old and passively evolving galaxies, EROs offer the opportunity to test whether the present-day massive ellipticals formed at early cosmological times ($z_{\rm f} > 2$–3) with a subsequent passive and pure luminosity evolution (PLE), or whether they formed more recently through the merging of spiral galaxies (e.g. Baugh et al. 1996; Kauffmann 1996). Studies on small fields claimed a deficit of EROs, thus favouring the hierarchical merging scenario (e.g. Zepf 1997; Barger et al. 1999; Rodighiero et al. 2001), but recent surveys on wider fields showed that the surface density of EROs is consistent with elliptical galaxy PLE expectations (D00; Daddi et al. 2000b). Since only a few old galaxies have been spectroscopically identified (e.g. Spinrad et al. 1997; Cohen et al. 1999), their fraction among EROs remained still unconstrained. On the other hand, EROs may also be high-z starbursts and AGNs strongly reddened by dust extinction. Such a possibility was confirmed by the identification of this kind of galaxies among EROs, but, again, these results were limited to a handful of objects (e.g. Graham & Dey 1996; Cimatti et al. 1998; Gear et al. 2000; Pierre et al. 2001; Smith et al. 2001; Afonso et al. 2001), thus leaving undetermined the relative fractions of old and dusty galaxies in ERO samples.

Because of the stringent test of galaxy formation scenarios that EROs can provide, it is therefore of prime importance to determine the relative fractions among the two classes of galaxies. In this letter, we report on the first results of deep VLT optical spectroscopy of a

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

Table 1. The ERO spectroscopic identifications.

Sample	$N_{\rm tot}$	$N_{\rm id}$	$N_{\rm u}$	$N_{\rm old}$	$N_{\rm sf}$	N(ambig)
$Ks \leq 20.0$	78	35	43	15	18	2
$Ks \leq 19.2$	45	30	15	14	15	1

complete and sizeable sample of EROs. A cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm m} = 0.3$ and $\Omega_\Lambda = 0.7$ is adopted.

2. The K20 ERO sample

The selection and the observations of the ERO sample were made in the context of the K20 survey (`http://www.arcetri.astro.it/~k20/`). The prime aim of such a survey is to derive the redshift distribution of about 550 K-selected objects with $Ks \leq 20$ in order to constrain the galaxy formation models. The targets were selected from a 32.2 arcmin^2 area of the Chandra Deep Field South (CDFS; Giacconi et al. 2001) using the images from the ESO Imaging Survey public database (EIS; `http://www.eso.org/science/eis/`; the R- and the Ks-band images were reduced and calibrated by the EIS team and by our group respectively), and from a 19.8 arcmin^2 field centered at 0055-269 using NTT+SOFI and VLT-UT2+FORS2 Ks- and R-band images respectively (Fontana et al., in preparation). More details on the photometry will be given in forthcoming papers. From the total sample with $Ks \leq 20.0$, we extracted the subsample of EROs with $R - Ks \geq 5.0$, with the colors measured in $2''$ arcsec diameter corrected aperture to match the color definition of D00. The total sample includes 78 EROs, corresponding to a surface density of 1.50 ± 0.17 arcmin^{-2}, consistent with that of Thompson et al. (1999) (1.88 ± 0.11 arcmin^{-2} over a field of 154 arcmin^2). The ratio between the number of EROs and the total number of objects at $Ks \leq 19.2$ is 0.134 ± 0.021, consistent with the value of 0.127 ± 0.006 of D00.

Multi-object spectroscopy of EROs was made with the ESO VLT UT1 and UT2 equipped with FORS1 (October-November 1999) and FORS2 (November 2000) during $0.5''$–$1.5''$ seeing conditions and with $0.7''$–$1.2''$ wide slits depending on the seeing. The grisms 150I, 200I, 300I were used with typical integration times of 1–3 hours. Dithering of the targets along the slits between two fixed positions was made for most observations in order to efficiently remove the CCD fringing and the strong OH sky lines at $\lambda_{\rm obs} > 7000$ Å. The spectra were calibrated using standard spectrophotometric stars, dereddened for atmospheric extinction, corrected for telluric absorptions and scaled to the total R-band magnitudes.

3. The ERO spectral types and relative fractions

The spectroscopic analysis was done by means of automatic software (IRAF: `rvidlines` and `xcsao`) and through visual inspection of the 1D and 2D spectra. The redshift distributions are shown in Fig. 1.

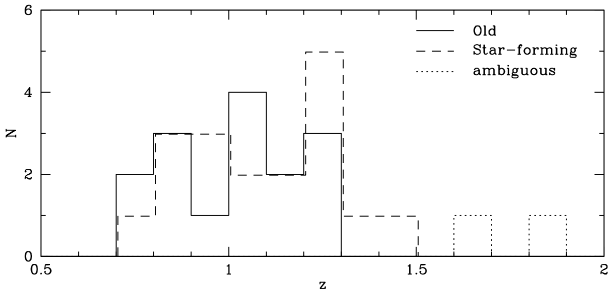

Fig. 1. The redshift distributions of the identified EROs (the distribution of star-forming EROs is slighlty shifted in z to improve the visibility of its difference from that of old EROs). Due to the noise at $\lambda_{\rm obs} > 9000$ Å, our spectroscopy makes it difficult to identify old and star-forming galaxies at $z > 1.3$ and $z > 1.5$ respectively. The redshift distribution of the old EROs is broadly consistent with those discussed by Daddi et al. (2001); McCarthy et al. (2001) and Firth et al. (2001).

According to the observed features, EROs were grouped into two classes: *(1) old* if the spectrum showed no emission lines, a prominent D4000 break, strong CaII H&K absorptions, and the overall shape of the continuum expected in case of an *old passively evolving elliptical*, *(2) star-forming* when the spectrum showed a clear [OII]λ3727 emission and no evidence for a strong D4000 break. Among the 15 old EROs, four present weak [OII]λ3727 emission. We also identified two galaxies at $z > 1.6$ thanks to MgIIλ2800 and FeIIλ2600 absorptions, but their nature remained ambiguous because of the lack of other distinctive spectral features. Table 1 summarizes the results, giving the numbers of spectroscopically identified and unidentified EROs ($N_{\rm id}$ and $N_{\rm u}$), of old ($N_{\rm old}$) and star-forming galaxies ($N_{\rm sf}$).

In this paper, we limited the analysis to the $Ks \leq 19.2$ subsample of EROs because it provides the best compromise between spectroscopic completeness (67% of the EROs identified vs. 44% at $Ks \leq 20$) and significant statistics. In such a subsample, the fractions of old and star-forming galaxies are respectively $N_{\rm old}/N_{\rm tot} = 31\% \div 64\%$ and $N_{\rm sf}/N_{\rm tot} = 33\% \div 67\%$, where the range of such fractions corresponds to assuming that none or all of the unidentified objects belong to the group. Such fractions are generally consistent with the results of HST imaging by Moriondo et al. (2000) and Stiavelli & Treu (2000).

4. The ERO average spectra

In this letter we limit the discussion to the average spectra of the identified galaxy types in order to derive their main properties that would be otherwise difficult to characterize in the individual noisier spectra. The average spectra shown in Fig. 2, obtained deredshifting (with a 5 Å rest-frame bin), normalizing and stacking the equally weighted individual spectra, are relative to all spectroscopically identified EROs with $Ks \leq 20.0$, but they do not significantly change if only the $Ks \leq 19.2$ EROs are used.

4.1. Old EROs

By comparing the average spectrum of old EROs with Bruzual & Charlot (2000, private communication) simple stellar population (SSP) models (Salpeter IMF, $Z = Z_{\odot}$) and no dust extinction, and taking into account the observed average $R - Ks$ color (5.19 ± 0.06), we derive an average age of 3.3 ± 0.3 Gyr (Fig. 3). The amplitude of the average D4000 break (1.92 ± 0.06) is consistent with an age of 2.8 ± 0.3 Gyr. If we adopt an average age of 3.1 ± 0.3 Gyr for $Z = Z_{\odot}$, the mean formation redshift is then $z_{\rm f} = 2.4 \pm 0.3$. If an e-folding time of star formation $\tau = 0.3$ Gyr is adopted, or if a Scalo (1986) IMF is used, the age increases to about 4 Gyr. SSP models with a lower metallicity ($Z = 0.4\ Z_{\odot}$) would further increase the age to ∼5–6 Gyr leading to extremely high $z_{\rm f}$. On the other hand, a higher metallicity with $Z = 2.5\ Z_{\odot}$ would reduce the age to ∼1.1 Gyr and the formation redshift to $z_{\rm f} \sim 1.5$, but it would underestimate the observed $R - Ks$ colors of old EROs at $z > 1$, thus being an inappropriate possibility for the highest redshift objects.

To summarize, being SSP models with an instantaneous burst of star formation rather unrealistic, the age of ∼3 Gyr and $z_{\rm f} = 2.4$ should be considered lower limits if $Z = Z_{\odot}$.

4.2. Star-forming EROs

As a first attempt to investigate the nature of the star-forming EROs, we compared the global shape of their average spectrum with template spectra of star-forming galaxies, although the presence of [NeV]λ3426 emission with an equivalent width $W = 3.6 \pm 0.7$ Å may indicate a more complex picture with also a contribution from dust-obscured AGN activity. A more detailed analysis based on absorption lines with an equivalent width of a few Å is not warranted by our data because of the limited signal to noise ratio. Among the Kinney et al. (1996) templates, a good agreement is found only with their so called SB6 spectrum (i.e. the average spectrum of starburst galaxies with $0.6 < E(B-V) < 0.7$ as derived from the Hα/Hβ ratio), but only if the reddening is increased by an additional $E(B-V) \sim 0.5$ (we adopt the Calzetti et al. 2000 extinction curve throughout the paper). Since the stellar continuum and the ionized gas of dusty starbursts suffer different extinctions ($E(B-V)_{\rm star} \sim 0.44 E(B-V)_{\rm gas}$; Calzetti et al. 2000), the net total extinction of the continuum of the ERO average spectrum is $E(B-V)_{\rm star} \sim (0.65 \times 0.44) + 0.5 \sim 0.8$.

The average spectrum of e(a) VLIGs (Very Luminous Infrared Galaxies; $\log(L_{\rm IR}/L_{\odot}) > 11.5$; Poggianti & Wu 2000) also provides a global satisfactory agreement at $\lambda > 3600$ Å without the need of extra dust extinction (the median reddening estimated for the e(a) galaxies is $E(B-V)_{\rm gas} = 1.1$ based on Hα/Hβ ratio, corresponding to $E(B-V)_{\rm star} \sim 0.5$; Poggianti & Wu 2000).

Finally, a comparison with synthetic spectra of star-forming galaxies with solar metallicity, Salpeter IMF and constant star formation rate (SB99 models, Leitherer et al. 1999 and Bruzual & Charlot 2000 models) showed that the global shape of the continuum and the average $R - Ks$ color can be reproduced with a wide range of ages and with $0.6 < E(B-V) < 1.1$.

The possibility that a fraction of star-forming EROs have an old bulge component contributing to the red colors (e.g. similar to the red massive disk galaxy at $z = 1.34$ of van Dokkum & Stanford 2001) is not ruled out by our data. In fact, HST imaging already showed that the "non-elliptical" EROs are morphologically made by a heterogeneous population ranging from highly irregular systems (likely to be the most dusty starbursts) to disky galaxies (Moriondo et al. 2000; Stiavelli & Treu 2000). The noise in our spectra hampers a detailed analysis of the individual EROs. However, by subtracting the average spectrum of old from that of star-forming EROs, we estimate that at most 30–40% of the total light of the star-forming EROs at ∼4000 Å can be due to an old system. In such a case, the average reddening would decrease to $E(B-V)_{\rm star} \sim 0.7$ using the SB6 template to reproduce the "pure" star-forming component.

5. The density of old EROs and limits on $z_{\rm f}$

Since old EROs have spectra consistent with being passively evolving ellipticals, we compared their density with different model predictions.

5.1. The surface density

The total surface density of EROs with $Ks \leq 19.2$ and $R - Ks \geq 5.0$ in our sample is 0.88 ± 0.13 arcmin^{-2}, consistent with that derived by D00 and Firth et al. (2001) over larger fields. In marked contrast, the surface density of EROs (counted as old plus dusty galaxies) predicted by the hierarchical merging models at $K = 19.2$ presented by Firth et al. (2001) and Smith et al. (2001) are below the observed density by factors of ∼4 and about an order of magnitude respectively.

From the minimum and maximum fractions of old EROs derived in Sect. 3, the implied surface densities of ellipticals at the same magnitude limit should be in the range 0.27–0.55 arcmin^{-2}. Within the uncertainties, such densities agree with those predicted by the PLE models of Daddi et al. (2000b) with $\tau = 0.3$ Gyr (0.24 and 0.54 arcmin^{-2} for $z_{\rm f} = 2.2$ and $z_{\rm f} = 3.5$ respectively), suggesting a *minimum* formation redshift of $z_{\rm f} \sim 2.2$, consistent with the age derived from the average spectrum. The result does not significantly change if the 4 old EROs with weak [OII]λ3727 emission are excluded from the sample. If $\tau = 0.1$ Gyr is adopted, or if the minimum fraction of old EROs (31%) is applied to the surface density of EROs derived by D00 in a much wider field (0.67 arcmin^{-2} over

450 arcmin^2), or if the 2MASS K-band local luminosity function of early type galaxies is used (Kochanek et al. 2001), the *lower limit* becomes $z_f \sim 2$.

5.2. The comoving density

Taking into account the nominal lower redshift limit imposed by the $R - Ks \geq 5.0$ color cut and the upper boundary due to the sensitivity of our spectroscopy ($0.85 \lesssim z \lesssim 1.30$), we derive a comoving density of ellipticals in that redshift range of $(2.16 \pm 0.62) \times 10^{-4}$ Mpc^{-3}. Such a density can be considered a lower limit because some ellipticals can escape the threshold of $R - Ks \geq 5.0$ due to the dispersion of the observed $R - Ks$ colors around the model color prediction. Even so, the densities expected in the Daddi et al. (2000b) PLE model with $\tau = 0.3$ Gyr are in the range of (1.8, 2.7) $\times 10^{-4}$ Mpc^{-3} for $z_f \sim$ (2.2, 2.4), thus being consistent with the observed densities.

6. The role of dusty star-forming EROs

The observed star formation rate (SFR) of each star-forming ERO has been estimated both from the [OII]λ3727 line emission and the 2800 Å continuum luminosities using the relations of Kennicutt (1998). The average SFRs at $z_{\rm mean} = 1.096$ are SFR([OII]) = 3.6 $M_\odot$ yr^{-1} and SFR(L_{2800}) = 1.8$M_\odot$ yr^{-1}. Adopting the comoving volume included between the observed $z_{\rm min}$ and $z_{\rm max}$, the corresponding SFR densities are SFRD([OII]) = 0.0011 and SFRD(L_{2800}) = 0.0005 $M_\odot$ yr^{-1} Mpc^{-3}. Such SFRDs clearly represent *lower limits* because no corrections for dust extinction and for incompleteness have been applied. However, such SFRs may also be partly overestimated if dust-obscured AGN activity is present in some EROs as suggested by the possible [NeV]λ3426 emission (Fig. 1).

If we conservatively adopt an average $E(B - V) \sim 0.5$ (see Sect. 4) and apply the corresponding extinction corrections, the ERO SFRD becomes $\sim$0.015 $M_\odot$ yr^{-1} Mpc^{-3}, formally corresponding to a contribution of about 20% to the global SFRD of the universe at $z \sim 1$ (without counting EROs) corrected for dust extinction (~ 0.08 $M_\odot$ yr^{-1} Mpc^{-3}, as discussed by Somerville et al. 2001). Even if the uncertainties are large because of the assumptions on the SFR estimators and on the adopted extinction curve, our result strongly suggests that EROs may be important in the cosmic star formation budget at $z \sim 1$.

Our results also suggest that the ERO selection provides the possibility to uncover the population of high-z dusty star-forming galaxies in a way complementary to the surveys for submillimeter/millimeter-selected galaxies. In fact, if the dereddened SFRs of star-forming EROs are in the range of 50–150 $M_\odot$ yr^{-1} (possible for $E(B - V) \sim$ 0.5–0.7), this would suggest that their far-infrared luminosities are generally below 10^{12} $L_\odot$ (adopting the relationship SFR[$M_\odot$ yr^{-1}] = $4.5 \times 10^{-44} L_{\rm FIR}$[erg s^{-1}]; Kennicutt 1998). Such a scenario would explain the origin of the low detection rates of EROs in submillimeter/millimeter continuum follow-up observations, typically sensitive to detect ultra-luminous infrared galaxies (ULIGs, $L > 10^{12}$ $L_\odot$) at $z \gtrsim 1$ (e.g. Mohan et al. 2001).

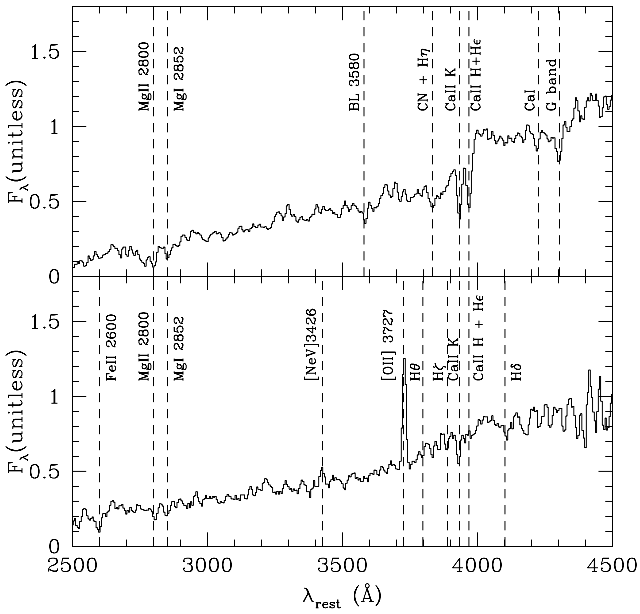

Fig. 2. The average rest-frame spectra (smoothed with a 3 pixel boxcar) of old passively evolving (top; $z_{\rm mean} = 1.000$) and dusty star-forming EROs (bottom; $z_{\rm mean} = 1.096$) with $Ks \leq 20$.

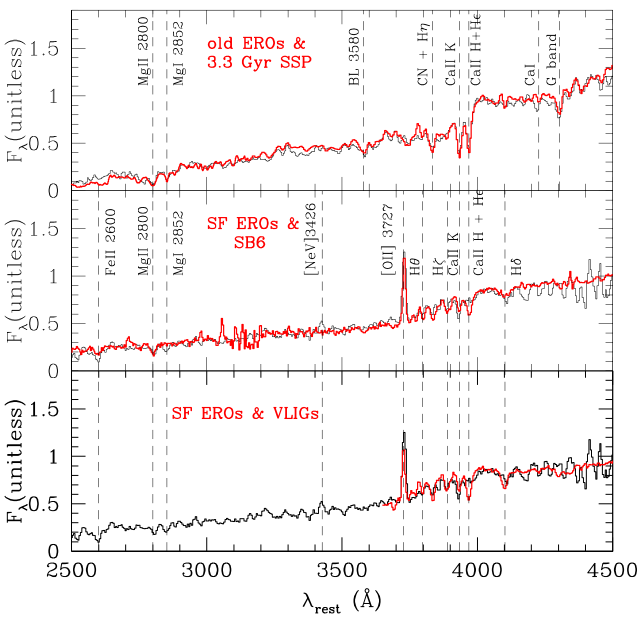

Fig. 3. The average spectra of EROs (thin lines) and template galaxies (thick lines) (see text for details). The spikes at $\lambda \approx 3100$ Å are due to the noise in the SB6 spectrum.

Acknowledgements. We thank the referee, P. McCarthy, for the constructive comments, and the VLT support astronomers for their kind assistance. AC warmly thanks ESO (Garching) for the hospitality during his visits, A. Franceschini for useful discussion and B. Poggianti for providing the VLIG spectrum.

References

Afonso, J., Mobasher, B., Chan, B., & Cram, L. 2001, ApJ, 559, L101
Barger, A. J., Cowie, L. L., Trentham, N., et al. 1999, AJ, 117, 102
Baugh, C. M., Cole, S., & Frenk, C. S. 1996, MNRAS, 283, 1361
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Cimatti, A., Andreani, P., Röttgering, H., & Tilanus, R. 1998, Nature, 392, 895
Cohen, J. G., Hogg, D. W., Pahre, M. A., et al. 1999, ApJ, 120, 171
Daddi, E., Cimatti, A., Pozzetti, L., et al. 2000a, A&A, 361, 535 (D00)
Daddi, E., Cimatti, A., & Renzini, A. 2000b, A&A, 362, L45
Daddi, E., Broadhurst, T., Zamorani, G., et al. 2001, A&A, 376, 825
Elston, R., Rieke, G. H., & Rieke, M. J. 1988, ApJ, 331, L77
Firth, A. E., Somerville, R. S., McMahon, R. G., et al. 2001, MNRAS, submitted [astro-ph/0108182]
Gear, W., Lilly, S., Stevens, J., et al. 2000, MNRAS, 316, L51
Giacconi, R., Rosati, P., Tozzi, P., et al. 2001, ApJ, 551, 624
Graham, J. R., & Dey, A. 1996, ApJ, 471, 720
Kauffmann, G. 1996, MNRAS, 281, 487
Kennicutt, R. C. 1998, ARA&A, 36, 189
Kinney, A. L., Calzetti, D., Bohlin, R. C., et al. 1996, ApJ, 467, 38
Kochanek, C. S., Pahre, M. A., Falco, E. E., et al. 2001, ApJ, 560, 566
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3
McCarthy, Carlberg, R. G., Chen, H.-W., et al. 2001, ApJ, 560, L131
Mohan, N. R., Cimatti, A., Röttgering, H. J. A., et al. 2001, A&A, in press
Moriondo, G., Cimatti, A., & Daddi, E. 2000, A&A, 364, 26
Pierre, M., Lidman, C., Hunstead, R., et al. 2001, A&A, 372, L45
Poggianti, B. M., & Wu, H. 2000, ApJ, 529, 157
Rodighiero, G., Franceschini, A., & Fasano, A. 2001, MNRAS, 324, 491
Scalo, J. M. 1986, Fundam. Cosm. Phys., 11, 1
Smith, G. P., Treu, T., Ellis, R., et al. 2001, ApJL, in press
Smith, G. P., Smail, I., Kneib, J.-P., et al. 2001, MNRAS, in press [astro-ph/0109465]
Somerville, R. S, Primack, J. R., & Faber, S. M. 2001, MNRAS, 320, 504
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., ed. Funes & Corsini [astro-ph/0010100]
Thompson, D., Beckwith, S. V. W., Fockenbrock, R., et al. 1999, ApJ, 523, 100
van Dokkum, P. G., & Stanford, S. A. 2001, ApJ, 562, L35
Zepf, S. E. 1997, Nature, 390, 377