Detection of Strong Clustering of the Extremely Red Objects: Implications for the Density of z > 1 Ellipticals

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Abstract. We present the results of a wide–field survey for extremely red objects (EROs hereafter), the widest so far, based on $K$ and $R$ band imaging. The survey covers 701 arcmin\textsuperscript{2} and it is 85\% complete to $K_s \leq 18.8$ over the whole area and to $K_s \leq 19.2$ over 447.5 arcmin\textsuperscript{2}. Thanks to the wide field covered, a complete sample of 422 EROs with $R - K_s \geq 5$ was selected. The distribution of the EROs on the sky is strongly inhomogeneous, being characterized by overdensities and large voids. We detect at the 8\sigma level a strong clustering signal of the EROs which is about an order of magnitude larger than the clustering of K–selected field galaxies in the same magnitude range. A smooth trend of increasing clustering amplitude with the $R - K_s$ color is observed. These results are a strong piece of evidence that the largest fraction of EROs is made of high–$z$ ellipticals, of which we detect for the first time the $z \gtrsim 1$ large scale structure clustering signal. We show how the surface density variations of the ERO population found in our survey can explain the origin of the discrepant results obtained so far on the density of $z > 1$ ellipticals, and we discuss the main implications of our results on the question of the evolution of elliptical galaxies. The number counts and the colors the K–selected field galaxies are also presented and briefly discussed.

1. Introduction

Near-infrared surveys prompted the discovery of a population of objects with very red optical-infrared colors (Extremely Red Objects, EROs hereafter; e.g. Elston et al. 1988, McCarthy et al. 1992, Hu & Ridgway 1994; Thompson et al. 1999; Yan et al. 2000; Scodeggio & Silva 2000).

In general, objects have been classified EROs when they had redder colors than late type galaxies (with negligible dust extinction) at any redshift. However, depending on the depth of the photometry and on the available filters, different selection criteria have been used to select EROs. In this paper, EROs are defined as objects with $R - K_s \geq 5$ (see Section 5 for more details on this choice).

The red colors of EROs are consistent with two classes of galaxies: they could be old, passively evolving elliptical galaxies at $z \gtrsim 1$ which are so red because of the large $K$–correction. EROs may also be strongly dust–reddened, star–forming galaxies or AGN. The observational results of the last few years showed that both classes of galaxies are indeed present in the ERO population: on one hand, a few objects were spectroscopically confirmed to be $z > 1$ ellipticals (Dunlop et al. 1996, Spinrad et al. 1997, Liu et al. 2000, and marginally, Soifer et al. 1999), or to have surface brightness profiles consistent with being dynamically relaxed early type galaxies (e.g. Stiavelli et al. 1999, Benitez et al. 1999). On the other hand, other EROs have been detected in the sub–mm (Cimatti et al. 1998, Dey et al. 1999, Smail et al. 1999, Andreani et. al. 2000), thus providing examples of high–redshift starburst galaxies reddened by strong dust extinction and characterized by high star formation rates. The relative contribution of the two classes of objects to the whole ERO population is still unknown, but there are preliminary indications that ellipticals may represent the largest fraction based on near-IR and optical spectroscopy and on surface brightness analysis (e.g. Cimatti et al. 1999, 2000; Liu et al. 2000; Moriondo et al. 2000). A small fraction of low-mass-stars and brown dwarfs among EROs is also expected in case of unresolved objects (e.g. Thompson et al. 2000, Cuby et al. 1999).

The importance of studying EROs is clear especially for the clues that they could provide on the formation
and evolution of elliptical galaxies. For instance, existing realizations of the hierarchical models of galaxy formation predict a strong decline in the comoving density of the ellipticals with \( z \), as they should form through merging at \( z \gtrsim 2 \) (Kauffmann 1996, Baugh, Cole & Frenk 1996), so that a measure of their comoving density would provide a stringent proof of these models. Conflicting results have been found so far about such issue: some works claim the detection of a deficit of \( z > 1 \) ellipticals (e.g. Kauffmann, Charlot & White 1996, Zepf 1997, Franceschini et al. 1998, Barger et al. 1999, Menanteau et al. 1999), whereas others find the opposite result, i.e. a constant comoving density of ellipticals up to \( z \sim 2 \) (Totani & Yoshii 1997, Benitez et al. 1999, Broadhurst & Bowens 2000, Schade et al. 1999). A potential serious problem in these studies is suspected to be the influence of the field-to-field variations in the density of EROs due to the small fields of view usually covered in the near-infrared. For instance, Barger et al. (1999) found a very low surface density of EROs in a 60 arcmin \( ^2 \) survey to \( K = 20 \), while on a similar area McCracken et al. (1999) observed a density three times larger at the same \( K \) level.

Similar uncertainties have been found in the trials of deriving the fraction of high redshift galaxies among IR selected samples, which is believed to be a stringent test for the formation of the massive galaxies (Broadhurst et al. 1992, Kauffmann & Charlot 1998). Fontana et al. (1999), using photometric redshifts, found that the fraction of high–\( z \) galaxies in a collection of small deep fields complete to \( K = 21 \) was low and comparable with the predictions of the cold dark matter (CDM) models but not with passive evolution (PLE) models. The preliminary results of Eisenhardt et al. (2000) give the opposite conclusion, estimating a much higher fraction of high–\( z \) galaxies, consistent with both CDM and PLE models.

The main aim of the survey presented here was to encompass the difficulties induced by the cosmic variance, obtaining a sample of EROs on a very large area, at moderately deep \( K \) levels, in order to minimize and possibly to detect the effects of their clustering, and to compare the observed density with that expected in the case of passive evolution of ellipticals. Our survey is larger by more than a factor of four than the Thompson et al. (1999) survey, and of more than an order of magnitude of all the other previous surveys for EROs, at the same limiting magnitudes. With the large area covered we aimed also to detect a sample, or place limits to the surface density of the very rare class of extreme EROs with \( R - Ks > 7 \).

In this paper, the observational results of this survey and their main implications are presented. A more detailed interpretation of our findings will be presented in a forthcoming paper (Daddi et al., in preparation, hereafter PaperII).

The paper is organized as follows: we first describe the data reduction and analysis, then we present the counts of field galaxies. In § 3 the sample of EROs is described. § 4 contains the analysis of the clustering of field galaxies and EROs. The main implications of our findings are discussed in § 5 \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) throughout the paper.

### 2. Observations, data reduction and photometry

#### 2.1. \( Ks \)-band imaging

The \( Ks \) observations were made with the ESO NTT 3.5m telescope in La Silla, during the nights of 27–30 March 1999, using the SOFI camera (Moorwood et al. 1998) with a field of view of about 5′×5′. SOFI is equipped with a Hawaii HgCdTe 1024x1024 array, with a scale of 0.29 arcsec/pixel. The \( Ks \) filter has \( \lambda_c = 2.16 \) \( \mu m \) and \( \Delta \lambda \sim 0.3 \) \( \mu m \) and it is slightly bluer than the standard \( K \) filter in order to reduce the thermal background.

The center of the observed field is at \( \alpha = 14^h49^m29^s \) and \( \delta = 09^\circ00'00'' \) (J2000). The observed field is one of the fields described in Yee et al. (2000) to which we refer for the detail on how it was selected, that mainly were based on not to have any apparent nearby clusters and to be at high galactic latitude.

The images were taken with a pattern of fixed offsets of 14″ (about half of the SOFI field of view) over a grid of 9×13 pointings. The total area covered by the observations was about 24×34 arcmin, with a local integration time of 12 minutes in the central deepest region of the field. In the shallower region, the effective integration time is reduced up to 6 minutes. The total amount of time required to cover the whole field was about 5.5 hours.

The data reduction was carried out using the IRAF software. The images were flat-fielded with twilight flats. The sky background was estimated and subtracted for each frame using a clipped average of 6–8 adjacent frames (excluding the central frame itself). The photometric calibration was achieved each night with the observation of 5–7 standard stars taken from Persson et al. (1998). The zero-points have a scatter of ~ 0.015 mags in each night and a night-to-night variation within 0.02 mags. Each frame was scaled to the same photometric level correcting for the different zero-points and airmasses. Accurate spatial offsets were measured for each frame using the area in common with the adjacent frames. The images were then combined, masking the known bad pixels, in order to obtain the final mosaic. The cosmic rays were detected and replaced by the local median using the task cosmicrays of the IRAF package ccddred. The effective seeing of the final coadded mosaic ranges from 0.9″ to 1.1″.

#### 2.2. \( R \)-band imaging

The \( R \)-band data were taken in May 19–21 1998 with the 4.2m William Herschel Telescope on La Palma. The observations were done using the prime focus camera, equipped with a thinned 2048x4096 pixels EEV10 chip, with a scale of 0.237″/pixel. This gives a field of view of...
about 8.1′ × 16.2′. A standard Johnson $R$-filter was used. The whole field has been covered by a mosaic of 6 pointings. Each pointing consisted of at least 3 exposures of 1200s taken with small offsets. The total integration times per pointing was therefore 3600s, with the exceptions of two pointings with 4800s and 6000s.

The photometric calibration was achieved with standard stars taken from Landolt (1992) with a scatter in the zeropoints, from the different stars used, below 0.01 magnitudes. The images were de-biased and then flatfielded, using a master flatfield constructed from the science exposures, scaled to the same zeropoint and then combined. The seeing of the final $R$-band mosaic was between 0.7″ and 0.8″.

2.3. Sample selection and $Ks$ photometry

The software SExtractor (Bertin & Arnouts 1996) was run on the $Ks$ mosaic with a background weighted threshold in order to take into account the depth variations across the area, as defined by SExtractor. Among the detected objects, all those with $S/N>5$ in a 2″ circular aperture (twice the average seeing FWHM) were selected and added to the catalog. A few spurious detections (e.g. close to image defects) have been excluded after a visual inspection of the image. The final catalog includes 4585 objects. In the central deepest region, the $5\sigma$ limiting aperture magnitude is $Ks(2″)=19.6$, whereas in the remaining area such limit is $Ks(2″)\sim19.2$ because of the reduced integration time.

Isophotal magnitudes were measured with a limiting threshold of about $0.7\sigma_{sky}$ corresponding in the central area to a surface brightness limit of about $\mu_{lim} \sim 21$ arcsec$^{-2}$. The aperture correction from 2″ to total magnitudes was estimated throughout the area by measuring the difference between the isophotal and the 2″ aperture magnitudes for the stars with $Ks <16$. A differential correction, in the range of 0.16–0.30 magnitudes, was measured for different regions of the mosaic with a typical scatter of <0.03 magnitudes. For the bright objects the isophotal magnitudes were on average consistent with the Kron automatic aperture magnitudes. However, the isophotal magnitudes were adopted because the Kron magnitudes are rather unstable at faint flux levels where the low signal often does not allow to define the correct automatic aperture.

The total $Ks$ magnitudes were defined as the brightest between the isophotal and the corrected aperture magnitude. This allowed to assign safely a total magnitude for both the faint and the bright objects. The typical $Ks$ magnitude where the corrected aperture magnitude begins to be adopted as the total one is $Ks\sim18$ in the central deepest region.

The completeness of our catalog has been estimated by adding artificial objects to the $Ks$ mosaic in empty positions, using the IRAF package artdata. Point-like sources as well as objects with De Vaucouleurs and exponential profiles (convolved with the seeing PSF) were simulated, and SExtractor was run with the same detection parameters as for the real data. The 85% completeness magnitude for the deepest area is $Ks\sim19.2$ for point-like sources. The completeness decreases to $\sim70\%$ for the worst case that we have recovered, i.e. for the exponential galaxies with $0.7″$ half-light radius. In the shallower area the corresponding limiting magnitude is $Ks \leq 18.8$. Most of the $Ks \geq 18.5$ galaxies are anyway expected to be only barely resolved with the $Ks 1″$ seeing (Saracco et al. 1997), and this certainly occurs for the distant $z \geq 1$ ellipticals, and thus their completeness limits can be assumed to be similar to those for stars.

2.4. $R$-band photometry and colors

In order to recover the $R$-band counterparts of the $Ks$-selected objects, a coordinate mapping between the $Ks$ and the $R$ images was derived. SExtractor was then run in ASSOC mode with a search box of 2×FWHM$_R$. The regions around bright stars or defects in the $R$ and $Ks$ band images were excluded from this analysis. The final effective area is 701 arcmin$^2$ at $Ks \leq 18.8$ and 447.5 arcmin$^2$ at $Ks \leq 19.2$.

Whenever an object had $S/N<3$ in the $R$-band image $3\sigma$ limits were assigned. The $3\sigma$ limiting magnitude in a 2″ diameter aperture is $R > 26.2$ for most of the area, reaching $R > 26.5$ in the deepest pointing. When $S/N>3$, 2″ diameter corrected aperture magnitudes were assigned to each object. The aperture correction was derived in the same way as for the $Ks$-band, with slightly smaller corrections because of the better $R$-band seeing. The magnitudes were dereddened for Galactic extinction. At the Galactic coordinates of the center of our field ($l \sim 5^\circ.5$, $b \sim 5^\circ$), the extinction coefficient from Burstein & Heiles (1982) and from Schlegel et al. (1998) are $A_B = 0.04$ and $A_B = 0.13$ respectively. As the two values are derived in different ways, none of the two can be discarded. The average was therefore adopted, obtaining a correction of 0.052 magnitudes in $R$ and negligible in $Ks$. This introduce an uncertainty of 0.028 magnitudes in the dereddened $R$ magnitudes.

Finally, the $R - Ks$ colors are defined for all the objects as the difference between the $R$ and $Ks$ corrected aperture magnitudes. Thanks to the depth of the $R$-band data, colors as red as $R - Ks = 7$ could be measured down to the $Ks$ magnitude limits of our survey. Because of the long integrations used in the $R$-band the objects with $R \geq 20$ were saturated. As we are interested in the extremely red galaxy population, this problem has no impact on our results.
2.5. Star–Galaxy classification

The star–galaxy (S/G) separation was done by means of the SExtractor CLASS\_STAR parameter in both the $R$ and $Ks$ band. This classification was found to be reliable for objects with $Ks \lesssim 17.5$ and $R \lesssim 24$. Because of the seeing variations through the area in both bands, a variable CLASS\_STAR threshold was adopted in different subareas. Given the better seeing of the $R$-band, the classification was based mostly on such band, switching to the $Ks$ CLASS\_STAR for objects close to the saturation level in $R$. This means that in principle a S/G separation can be provided only for objects with colors $R - Ks < \sim 5$ at $Ks=19$, $R - Ks \lesssim 6$ at $Ks=18$, and so on (see Fig. 5). From Fig. 1 it can be seen that this has no effect on the total star number counts (and therefore on the galaxy number counts), but it does not allow to classify properly all the EROs selected. For the objects where both classifiers were applicable, a reasonable agreement between the two CLASS\_STAR values was found. At the limiting magnitudes of our survey a very small fraction of very compact and not resolved galaxies, such as for instance AGN or compact narrow emission line galaxies (e.g. Koo & Kron 1988), could have been incorrectly classified as stars.

Figure 1. The observed number counts for both stars and galaxies of our survey. The error bars indicate the poissonian uncertainties.

3. $Ks$-band number counts

Galaxy number counts in the $Ks$ band can provide more advantages in studying galaxy evolution and cosmological geometry than optical counts because they are not much sensitive to the evolution of stellar population and to the dust extinction. Our survey, which covers the magnitude range $14 < Ks < 19.2$, represents the widest among the previous deep surveys at level fainter than $Ks > 18$.

| $Ks$ range | Area[2] | Galaxies | Stars |
|------------|---------|----------|-------|
| 11.7 – 12.2 | 701     | -        | 4     |
| 12.2 – 12.7 | "       | -        | 7     |
| 12.7 – 13.2 | "       | -        | 9     |
| 13.2 – 13.7 | "       | -        | 17    |
| 13.7 – 14.2 | "       | 4        | 21    |
| 14.2 – 14.7 | "       | 6        | 38    |
| 14.7 – 15.2 | "       | 16       | 37    |
| 15.2 – 15.7 | "       | 30       | 62    |
| 15.7 – 16.2 | "       | 74       | 73    |
| 16.2 – 16.7 | "       | 100      | 88    |
| 16.7 – 17.2 | "       | 178      | 128   |
| 17.2 – 17.7 | "       | 372      | 127   |
| 17.7 – 18.2 | "       | 633      | 144   |
| 18.2 – 18.7 | "       | 892      | 185   |
| 18.7 – 18.8 | "       | 200      | 32    |
| 18.8 – 19.2 | 447.5   | 631      | 84    |

The last bin includes only the objects in the deepest region. [2]

Table 1 summarizes the number of galaxy and star detected in each $Ks$ bin. Figure 2 shows the differential counts in 0.5 magnitude bins for both stars and galaxies. No correction for incompleteness was applied. Star counts increase smoothly to faint levels, confirming the reliability of our star classification. At $Ks \sim 16.5$ galaxies begin to dominate over stars.

The slope of the galaxy number counts were derived over the magnitude range covered by our survey. At bright magnitudes a slope of $\gamma = 0.53 \pm 0.02$ is found in the range $14 < Ks < 17.5$. We confirm that the $K$-band galaxy counts show a flattening at $Ks > 17.5$, and the slope changes from $\gamma = 0.53$ to $\gamma = 0.32 \pm 0.02$ (see Fig. 2). The leveling off of the counts below a slope of 0.4 indicates that the differential contribution to the extragalactic background light (EBL) in the $K$ band peaks at $Ks \sim 17$ and then begins to decrease at fainter fluxes. The contribution to the EBL over the magnitude range $14 \leq Ks \leq 19.2$ sampled by our survey is about 4.20 nW/m$^2$/sr, which constitutes about 53% of EBL from discrete source in the $K$-band (cf. Pozzetti et al. 1998, Madau & Pozzetti 2000).

Figure 2 shows differential galaxy number counts in our survey compared with a compilation of $K$-band published surveys. No attempt was made to correct for different filters. Our counts are broadly consistent with the average counts of previous surveys (Hall & Green 1998).
Counts of galaxies from our survey compared to a collection of published data. The solid and dotted lines are PLE models with $\Omega_0 = 0.1$ and $\Omega_0 = 1$ respectively (see text and Pozzetti et al. 1996). The dashed line is a number evolution model with $(1+z)^{\eta}$ and $\eta = 2.0$.

In Fig. 2, our data are compared with the predictions of some evolutionary models from Pozzetti et al. (1996): a PLE model, with $\Omega_0 = 0.1$ and with $\Omega_0 = 1$, and a number luminosity evolution (NLE) model with $\Omega_0 = 0.1$ and number evolution as $(1+z)^{\eta}$ with $\eta = 2.0$. At bright magnitudes ($K_s < 16$) the PLE models seem to overestimate our observed counts, favoring lower normalizations for the local LFs (which are uncertain up to a factor of two, Tresse 1999), or a stronger luminosity evolution. Considering the slopes, which are independent from the normalization of the LFs, we find that at $K_s > 16$ both cases of the PLE model are rather consistent with our data, while the NLE model gives a worse fit to the observed steep slope of the counts. A more detailed comparison with models is beyond the aim of this paper.

In Fig. 3 the $R-Ks$ vs. $Ks$ color magnitude diagram is plotted for both stars and galaxies in our sample. Figure 4 shows the distribution of colors for galaxies fainter than $Ks > 16.5$, from which the median color at different $Ks$ magnitude levels have been calculated (see Table 2). The faintest bin with $18.8 < Ks \leq 19.2$ includes only the objects detected in the deeper region. The median $R-Ks$ color of the galaxies increases by 0.5 magnitudes from $Ks = 16.5$ to $Ks \sim 18$ and then it remain almost constant up to the limits of our survey ($Ks = 19.2$). This trend is similar to what found by Saracco et al. (1999) for the median galaxies $J-Ks$ color which also reach it maximum at $Ks = 18-19$ and then it becomes bluer, while the median $B-K$ color gets significantly bluer before, at $K > 17$ (Gardner et al. 1993).

Our wide-field survey allows us to select a statistically significant and complete sample of EROs which can provide stringent constraints on the density of high-z ellipticals (see Section 1). For this reason, EROs are defined as objects with $R-Ks \geq 5$ because this corresponds to select passively evolving ellipticals at $z > 0.9$ (see Fig. 13). Table 3 shows the results of the selection for different magnitude and color thresholds. Among the others, the threshold $R-Ks \geq 5.3$ is used because it corresponds to
Table 3. The Sample of EROs

| $K_s$ limits | N  | Frac. | Dens. | N  | Frac. | Dens. | N  | Frac. | Dens. | N  | Frac. | Dens. |
|--------------|----|-------|-------|----|-------|-------|----|-------|-------|----|-------|-------|
| $K_s \leq 17.0$ | 701 | 2 | 0.006 | 0.003 | – | – | – | – | – | – | – | – |
| $K_s \leq 17.5$ | 701 | 15 | 0.025 | 0.02 | 5 | 0.008 | 0.007 | – | – | – | – | – |
| $K_s \leq 18.0$ | 701 | 58 | 0.051 | 0.08 | 19 | 0.017 | 0.027 | – | – | – | – | – |
| $K_s \leq 18.5$ | 701 | 158 | 0.084 | 0.23 | 75 | 0.040 | 0.11 | 7 | 0.004 | 0.01 | – | – |
| $K_s \leq 18.8$ | 701 | 279 | 0.111 | 0.40 | 150 | 0.060 | 0.21 | 30 | 0.012 | 0.04 | 2 | 0.0008 | 0.003 |
| $K_s \leq 19.0$ | 474.5 | 220 | 0.116 | 0.49 | 133 | 0.070 | 0.30 | 33 | 0.017 | 0.07 | 4 | 0.0021 | 0.009 |
| $K_s \leq 19.2$ | 474.5 | 281 | 0.126 | 0.63 | 173 | 0.079 | 0.39 | 44 | 0.020 | 0.10 | 5 | 0.0023 | 0.011 |

We present in detail the cumulative number (N) of EROs selected at each $K_s$ limiting magnitude, the fraction of EROs with respect to the whole field galaxies (Frac.) and the corresponding surface density (Dens., in objects/arcmin$^2$).

**Fig. 4.** Distributions of the $R - K_s$ colors for the galaxies of our sample.

The selection of $z > 1$ elliptical galaxies (see Fig. 3). We detected 279 EROs with $K_s \leq 18.8$ from the whole area and 143 EROs with $18.8 < K_s \leq 19.2$ in the deeper area, yielding a total sample of 422 objects (see Fig. 3). This is by far the largest sample of EROs obtained to date. A small but complete sample of EROs with $R - K_s \geq 7$ has been selected, and we estimate for the first time their surface density to be $\sim 0.01$ arcmin$^{-2}$ at $K_s \sim 19$.

A comparison of the surface densities of EROs that we have detected can be directly done with Thompson et al. (1999), after taking into account the different filters used. For the $K'$ filter used by Thompson et al. (1999), $K_s \sim K' - 0.2$ (adopting $H - K = 1$), and then their limit at $K' \leq 19$ corresponds to $K_s \leq 18.8$ which is the shallower limit of our survey, while their $R - K'$ color is bluer than our $R - K_s$ of about 0.1 mags for the redder objects (Thompson, private communication). At the level of $K_s \leq 18.8$ we find a density of $0.042 \pm 0.008$ arcmin$^{-2}$ of EROs with $R - K_s \geq 6$, to be compared with the value of $0.039 \pm 0.016$ that they find (these errors are poissonian). Thus, the density that we find is in good agreement with the Thompson et al. survey. A more detailed comparison with Thompson et al. (1999) and other published data on the surface density of EROs will be presented in Paper II. We also verified that...
the average $R - K_s$ color of all our objects with $17.8 < K_s < 18.8$ is $R - K_s = 3.70 \pm 0.03$ (determined with a Kaplan-Meier estimator), in agreement with the average $R - K' = 3.73 \pm 0.04$ in $18 < K' < 19$ by Thompson et al. (2000).

5. The angular correlation functions

Statistical measurements of the clustering of faint galaxies are important for studying the evolution of galaxies and the formation of structures in the Universe. In fact, the amplitude of clustering in 2D space is a useful probe of the underlying 3D structure (e.g. Connolly et al. 1998, Efstathiou et al. 1991, Magliocchetti & Maddox 1999). The clustering of galaxies on the sky has been studied extensively especially in the optical but also in the near-infrared (e.g. Roche et al. 1998 and 1999, Postman et al. 1998, Baugh et al. 1996). Our survey, as noted before, is the widest at the limits of $K_s \sim 19$. It is therefore interesting to estimate the clustering of our sample of galaxies.

5.1. Calculation technique

The angular two-point correlation function $w(\theta)$ is defined as the excess probability (over a poissonian distribution) of finding galaxies separated by the apparent distance $\theta$:

$$dP = N^2[1 + w(\theta)]d\Omega_1 d\Omega_2$$

(1)

where $N$ is the mean density per steradian (Groth & Peebles, 1977).

Several methods for estimating $w(\theta)$ from a set of object positions have been proposed and used, but the most bias-free and suitable for faint galaxies samples resulted to be the Landy & Szalay technique (Landy & Szalay 1993, see also Kerscher et al. 2000). This technique (adopted for the calculations in this paper) consists in deriving the counts of objects binned in logarithmic distance intervals, for the data-data sample $[DD]$, the data-random sample $[DR]$ and the random–random sample $[RR]$. These counts have to be normalized, i.e. divided for the total number of couples in each of the 3 samples. From them we can estimate $w_b(\theta)$ as:

$$w_b(\theta) = \frac{[DD] - 2[DR] + [RR]}{[RR]}$$

(2)

which is biased to lower values with respect to the real correlation function $w(\theta)$:

$$w(\theta) = w_b(\theta) + \sigma^2$$

(3)

Where $\sigma^2$ is the “integral constraint” (Groth & Peebles, 1977):

$$\sigma^2 = \frac{1}{\Omega^2} \int \int w(\theta) d\Omega_1 d\Omega_2$$

(4)

Assuming that the angular correlation function $w(\theta)$ can be described by a power law of the form $w(\theta) = A\theta^{-\delta}$, then, following Roche et al. (1999), using the random–random sample we can estimate:

$$C = \frac{\sigma^2}{A} = \frac{\sum N_{rr}(\theta)\theta^{-\delta}}{\sum N_{rr}(\theta)}$$

(5)

The real two-point correlation function $w(\theta)$ can thus be estimated by fitting to the measured $w_b(\theta)$ to the function:

$$w_b(\theta) = A(\theta^{-\delta} - C)$$

(6)

The errors can be estimated, following Baugh et al. (1996), as:

$$\delta w_b(\theta) = 2 \sqrt{(1 + w_b(\theta))/DD}$$

(7)

where $DD$ is the non normalized histogram of $[DD]$. Eq. (7) is equivalent to assume $2\sigma$ poissonian errors for the correlations, and it gives estimates that are comparable to the errors obtained with the bootstrap technique (Ling, Frenk & Barrow 1986). This is necessary because it is known that, as the counts in the different bins are not completely independent, assuming the $1\sigma$ poissonian errors would result in an underestimate of the true variance of the global parameters of the angular correlation (see Mo, Jing & Börner 1992).

In case of the presence of a randomly distributed spurious component among the analyzed sample of objects (an example of this case could be a residual stellar component among the galaxy sample), the resulting amplitudes are apparently reduced by a factor $(1 - f)^2$, where $f$ is the fraction of the randomly distributed component (see e.g. Roche et al. 1999), and the corresponding correction should be applied.

The random samples used in our analysis were obtained using the pseudo–random number generator routine of the C Library function drand48. Random samples with up to 200 000 objects were used. Typically the number of objects in the random samples were a factor of 100–200 larger than the number of observed objects. The random sample was generated to fulfill the same geometrical constraints of the data sample, avoiding for instance to place objects in the regions excluded around the brightest stars.

5.2. The clustering of the $K$-selected field galaxies

In our analysis a fixed slope of $\delta = 0.8$ was assumed, as this is consistent with the typical slopes measured in both faint and bright surveys (e.g. Baugh et al. 1996, Roche et al. 1996, Maddox et al. 1990), and because it gives us the possibility to compare our results with the published ones that are typically obtained adopting such a slope. The factor $C$ was estimated (with eq. (5)) for both the whole and the deeper areas, resulting to be 4.55 and 5.16 respectively (the angles are expressed in degrees, if
The observed and bias–corrected two-point correlation functions of our $K$–selected sample. The lines plotted are the best–fitted power laws (see Table 4). The error in each bin is two times the poissonian error (see Section 5.1).

In Fig. 6 the observed, bias corrected, two-point correlation functions $w(\theta)$ is showed, recovered by splitting the data in fixed logarithmic width bins ($\Delta \log \theta = 0.2$), with the bin centers ranging from $3.6''$ to $15''$.

We clearly detect a positive correlation signal for our sample with an angular dependence broadly consistent with the adopted slope $\delta = 0.8$ even if the measurements show some deviations, in particular for the brightest samples. A few cluster candidates are present in our survey. These possible clusters include galaxies with $R - K_s \leq 4.5$, and are therefore expected to be at $z \lesssim 0.6$. A detailed analysis of the cluster candidates will be given in a forthcoming paper. For the purpose of the present work, we tested that the measured clustering amplitudes are stable in case of removal of the galaxies of the most evident cluster from the sample. However, the presence of such clusters could explain the observed deviations from the fitted $w(\theta) = A \theta^{-\delta}$ power laws for the three brightest samples, as most of the candidate clusters happen to be in the shallower area.

The derived clustering amplitudes are presented in Table 4. The amplitude errors are obtained from the fit assuming eq. 7. No correction for the stellar contamination was applied. In Fig. 7 the clustering amplitudes that we detect in our samples are compared with the published measurements. The data are shown together with the PLE models of clustering evolution from Roche et al. (1998, 1999) to which we refer for the details on how these were computed. Our measurements are in agreement with the models and the previous estimates of Roche et al. (1999), except the point with $K_s = 18.0$ which is anyway the most uncertain one.

As a check it was verified that the correlations of the stellar sample are consistent with zero within the measured errors, at all the scales. This is a confirmation that the stars are homogeneously distributed on the field (as it should be) and the seeing variation across the area did not cause a detectable bias in our classification.

Table 4. Clustering amplitudes for the $K$–selected sample

| $K_s$ limit | area | Galaxies | $A[10^{-3}]$ | $\delta$ | $C$ |
|------------|------|----------|--------------|---------|-----|
| 18.0       | 701  | 1131     | 1.3±0.5      | 0.8     | 4.55 |
| 18.5       | 701  | 1890     | 1.6±0.3      | 0.8     | 4.55 |
| 18.8       | 701  | 2503     | 1.5±0.2      | 0.8     | 4.55 |
| 19.2       | 447.5| 2222     | 1.6±0.2      | 0.8     | 5.16 |

5.3. The clustering of the extremely red objects

The large sample of EROs derived from our survey allowed us for the first time to estimate their clustering properties. Even a simple visual inspection of the sky distribution of
Table 5. Clustering amplitudes for the Extremely Red Objects

| $K_s$ limit | area arcmin$^2$ | $R - Ks \geq 5$ sample Galaxies | $R - Ks \geq 5.3$ sample Galaxies | $\delta$ | C |
|-------------|-----------------|---------------------------------|----------------------------------|--------|---|
| 18.0        | 701             | 58 | 24±10 | – | – | 0.8 | 4.55 |
| 18.25       | 701             | 106 | 25±5  | – | – | 0.8 | 4.55 |
| 18.5        | 701             | 158 | 22±3  | – | – | 0.8 | 4.55 |
| 18.8        | 701             | 279 | 14±2  | 150 | 14±3.4 | 0.8 | 4.55 |
| 19.2        | 447.5           | 281 | 13±1.5 | 173 | 12±2.3 | 0.8 | 5.16 |

Fig. 8. The sky positions of the objects with $Ks \leq 18.8$ and $R - Ks \geq 5$ in our survey. The region enclosed in dashed line is the deeper region. The colors of the objects inside the circle are showed in Fig. 11.

Fig. 9. The observed bias–corrected two-point correlations for the sample of EROs (with $R - Ks \geq 5$) in our survey. As in Fig. 8, the error in each bin is a factor of two larger than the poissonian one. Because of the small number of objects included, some bins for the two brightest samples, at small angular separation, were not populated. The correspondent upper limits would be in agreement with the measured amplitudes.

The objects with $R - Ks \geq 5$ (see Fig. 8) shows that the EROs have a very inhomogeneous distribution.

The results of the quantitative analysis of the clustering are shown in Fig. 8, where the observed bias–corrected angular correlations $w(\theta)$ of the objects with $R - Ks \geq 5$ is displayed. A strong clustering is indeed present at all the scales that could be measured, and its amplitudes (Tab. 5) are about an order of magnitude higher than the ones of the field population at the same $Ks$ limits. The correlations are well fitted by a $\delta = 0.8$ power law. No attempt was made to correct the amplitudes for the stellar contamination (see Section 5.1), and we stress that such corrections would increase them. Adopting the errors derived from the fits, our detections are significant at $\gtrsim 8\sigma$ level for the samples with $R - Ks \geq 5$ and $Ks \leq 18.5$ or $R - Ks \geq 5$ and $Ks \leq 19.2$.

There is a trend of decreasing amplitude of clustering for fainter EROs: the $Ks \leq 19.2$ EROs are less clustered than the ones with $Ks \leq 18.5$ and the difference is at 2.7$\sigma$, based on the derived errors. In part, this could be an effect of the stellar contamination that increases towards the limit of our survey (see Section 2.5). In fact, from
Fig. 10. The measured correlation amplitude for the samples with $R - K_s$ redder than a fixed threshold, in function of the threshold itself. This was obtained with the $K_s \leq 18.8$ sample. The horizontal lines show the $\pm 1\sigma$ range for the clustering of the whole population of field galaxies at this level. The fitted power law (dashed line) is $log A = 0.43(R - K_s) - 4.04$.

Defining redder thresholds drastically reduces the number of EROs and it is not possible to estimate with sufficient accuracy how the amplitudes change for objects with even redder $R - K_s$ colors. We only could verify that the sample of EROs with $R - K_s \geq 5.3$ has clustering amplitudes consistent with those of the $R - K_s \geq 5$ samples (see Tab. 3). To measure the clustering of the $R - K_s \geq 6$ EROs, an area at least 10 times larger than ours (i.e. $\sim 2$ square degrees) at $K = 19$ would be needed, assuming that their clustering amplitudes are similar to those of the EROs with $R - K_s \geq 5$.

Finally, it was studied if and how the clustering amplitude changes as a function of $R - K_s$ for the $K_s \leq 18.8$ sample (see Fig. 10). A clear increase of $A$ with $R - K_s$ is present for colors $R - K_s \geq 3.5$, while the $R - K_s \geq 3$ sample has an amplitude that is consistent with that of the whole sample of field galaxies. The variation of $A$ can be described with a power law in the range of $3 \leq R - K_s \leq 5.7$. Previous efforts to disentangle the clustering properties of the red and blue populations in faint $K$-selected samples probably failed because the ERO population was not sufficiently sampled. For instance, Kummel & Wagner (2000) did not find significant differences in the clustering of objects with color bluer or redder than $R - K_s = 3.49$ for their $K < 17$ sample. This is not surprising since at $K < 17$ the ERO population is almost absent (see Tab. 3 and Fig. 3).

To check for the stability of these results, possible systematics that could produce a bias in our work were analyzed. For example, as EROs are the tail of objects in the $R - K_s$ color distribution, systematic variations of the photometric zeropoints across the area could have the effect of creating artificial ERO overdensities and voids. To exclude this possibility it was verified that the blue tail of the $R - K_s$ distribution is homogeneously spread across our survey, with a very low clustering amplitude. In case of zeropoints variations these should have the same effect in both the tails of the color distribution. Moreover, to test the reality of the large void of EROs detected in the bottom part of our survey (see Fig. 5), the $R - K_s$ color distribution of the galaxies inside and outside such large void were compared by means of a Kolmogorov-Smirnov test, selecting only the galaxies with $R - K_s \leq 4$ in both region. The probability that the two distributions are extracted from the same population is 43%. All these tests strongly showed that the inhomogeneous ERO distribution is a real effect.

6. Main implications

6.1. On the nature of EROs

The strong clustering signal that we find to increase with the $R - K_s$ threshold and to reach very high values for the EROs is potentially capable to give insight about the problem of the nature of these objects.

The main possible source of objects that may contribute to the ERO population, as discussed in the introduction, are old passively evolving $z \sim 1$ ellipticals, dust-reddened starburst galaxies and, in case of unresolved objects, low-mass-stars or brown dwarfs. Being our field at high galactic latitude ($b \sim 57^\circ$), stars are expected to have no clustering, and to be homogeneously distributed, and for sure not to give the strong clustering signal detected. About the starburst galaxies, it must be noted that in such galaxies the red colors are mainly driven by the amount of dust extinction and not by the redshift, as in the case of ellipticals (see Fig. 13), and therefore a wide redshift distribution is expected which dilutes their intrinsic clustering. Moreover it is known that the IRAS–selected galaxies (which are typically star–forming galaxies) have very low intrinsic clustering (e.g. Fisher et al. 1994). We must therefore reasonably conclude that the observed signal is due to the clustering of high redshift ellipticals. This is also suggested by studies of the local universe which have shown that early-type galaxies are much more clustered than late-type galaxies (e.g. Guzzo et al. 1997, Willmer et
In the last years a few examples of massive clusters at $z \geq 1$ present in our field. From those data the average number of massive clusters expected in our field in the range $0.9 < z < 2$ is $\sim 0.12$ (for $\Omega_0 = 1$).

Moreover, the detection of the ERO positive correlation, following a $\delta = 0.8$ power law on all the scales from 10$'$$'$ to 15$'$$'$ (corresponding to $\sim 8$ comoving Mpc at $z \sim 1$) suggests that the clustering signal does not come from a few possible clusters detected in our field, but rather from the whole large scale structure traced by the elliptical galaxies.

### 6.2. Fluctuations of the ERO number density

Our results on the clustering of EROs have important consequences on the problem of estimating the density of high-$z$ ellipticals (see Section 1).

The existence of an ERO angular correlation with $\delta = 0.8$ and with a high amplitude implies strong surface density variations around the mean value that are actually observed, even for large areas. In presence of a correlation with amplitude $A$, the rms fluctuations of the counts around the mean value $X$ is (see for example Roche et al. 1999):

$$\sigma^2_{\text{true}} = X \left(1 + XAC\right)$$

The factor $C$ is the same as in eq. 5 and, by applying eq. 8 for several areas, it was found that it can be approximated as:

$$C = 58 \text{ Area}^{-0.4}$$

if the area is expressed in arcmin$^2$ and $\delta = 0.8$. The validity of such approximation has been tested for square regions and for areas not larger than the ones of our survey. With eq. 8 and 9 the expected variations of the ERO number counts can be calculated, once their clustering amplitude is known.

To verify the consistency of this picture, we derived the distribution of the number of EROs (with $R - K_s \geq 5$ and $K_s \leq 18.8$, i.e. those in Fig. 8) that can be recovered in our area by sampling it with a field of view of 5$'$$'$×5$'$$'$, which is the typical field of view of a near-infrared imager such as SOFI. In Fig. 12 the observed frequencies of the number of EROs recovered in this counts-in-cell analysis is plotted. As the mean number of EROs expected is about 10, the poissonian fluctuations would have $\sigma_{\text{poisson}} \sim 3.2$, while fluctuations with $\sigma = 5.4$ are actually observed. Applying eq. 8 the measured clustering amplitude $A = 0.013$ implies $\sigma = 5.55$, in optimal agreement with the measured $\sigma$ value.

We also note that the distribution of the numbers of EROs in Fig. 12 is very broad, ranging from $N = 0$ to $N = 30$. In 29% of the cases, the number of EROs recovered is $N \leq 5$, which implies a surface density half of the real one. Only in 19% of the fields the observed number

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**Fig. 11.** Color magnitude diagram of all the objects with $K_s \leq 18.8$ in the region inside the circle of Fig. 8.
would have been \( N \geq 15 \). This means that the distribution is not symmetric, and that, on average, it is more probable to underestimate the real surface density of these objects. This is a clear property of the sky distribution that we observe, as the voids seem to extend on a very large fraction of the surveyed area. In this respect, it should be noted here that all previous estimates of the number density of high-\( z \) ellipticals were based on surveys made with small fields of view, typically ranging from 1 arcmin\(^2\) in the case of the NICMOS HDF-S (Benitez et al. 1999) to 60 arcmin\(^2\) in the case of Barger et al. (2000).

Our results show how strong the effects of the field-to-field variations are in the observation and the estimate of the sky surface density of EROs. In particular, as discussed in the next section, this result has important implications on the problem of the high-\( z \) ellipticals.

### 6.3. Implications for the evolution of elliptical galaxies

The selection of galaxies with colors \( R - Ks > 5 \) can be used to search for elliptical galaxies at \( z > 0.9 \) (see Fig. 13), and to study their evolution by comparing their observed surface densities with those expected from the PLE or hierarchical models of massive galaxy evolution. In this respect, very discrepant results have been obtained so far, making the formation of spheroids one of the most controversial problems of galaxy evolution (see the Introduction).

Our results on the ERO clustering clearly show that for such a comparison to be reliable, both a wide field survey (resulting in a large number of EROs) and a consistent estimate of their surface density fluctuations are necessary before reaching solid conclusions on the evolution of elliptical galaxies.

In this section, a preliminary comparison is presented between the sky density of EROs observed in our survey and the predictions of an extreme PLE model similar to that used by Zepf (1997). In this model, ellipticals formed at \( z_f = 5 \) and their star formation rate (SFR) is characterized by an exponentially decaying burst with \( SFR \propto \exp(t/\tau) \), with \( \tau = 0.1 \) Gyr. Adopting the Markze et al. (1994) local luminosity function of ellipticals, and the Bruzual & Charlot (1997) models with solar metallicity and Salpeter IMF, the expected surface densities of passively evolving ellipticals with \( R - Ks \geq 6 \) was calculated for different limiting \( Ks \) magnitudes.

Fig. 14 shows the comparison between the expected densities and the densities of EROs with \( R - Ks \geq 6 \) (such color threshold consistently selects passively evolving galaxies at \( z \gtrsim 1.3 \)). Each data point shows three different error bars, which are actually the region of confidence in the poissonian case (at 1\( \sigma \)) and in the true case (at 1\( \sigma \) and 2\( \sigma \)). Such confidence regions have been estimated, following the prescriptions of eq. 8, by finding the
range of values for the true average counts $X$ for which the observed $N$ would represent a deviation of the required number of $\sigma$ from the real density. In other words such ranges are defined from the two solution of the equation:

$$\alpha^2 = \frac{(X - N)^2}{X (1 + XAC)} \quad \text{(10)}$$

where $\alpha$ is the number of $\sigma$ considered. The same equation is also appropriate for deriving the confidence at which a certain observed number density can be rejected given a model. The amplitude used for the $R-Ks \geq 6$ EROs are those derived for the $R-Ks \geq 5$ EROs, which is a conservative assumption as the amplitudes of redder samples should be higher, as suggested by Fig. [1].

Fig. [4] shows that the observed EROs densities are lower than the PLE predictions. However, for the most deviant point, the PLE models can be rejected at only the $2.5\sigma$ and $2.3\sigma$ level for $\Omega_0 = 1$ and $\Omega_0 = 0.1$ respectively. Note that the different points plotted in that figure are not statistically independent both because they are partially obtained with the same objects (they are cumulative values) and because they are relative to the same field (this means that if there is an under-density in the field, i.e. we are looking through a void, this will be reflected to all magnitude levels).

It should be recalled here that the observed ERO densities plotted in Figure 14 are an overestimate of the true density of the ellipticals because of the contamination by dusty starbursts (see Cimatti et al. 1998, 1999; Dey et al. 1999; Smail et al. 1999) and by field low-mass stars. The fraction of dusty starbursts in complete ERO samples is not known yet, as discussed in the introduction, but our results show that they should not be the dominant population. For instance, assuming that the fraction of dusty starbursts and low-mass stars is 20% and 10% of the ERO population respectively, this would decrease the observed densities plotted in Fig. [3] accordingly, but it would also increase by a factor of 2 the clustering amplitudes of the high-$z$ ellipticals (see Section [5.3]), and hence the error bars related to those points. In that case, we find that the PLE models could not be rejected neither at the $2\sigma$ confidence level.

It is relevant to mention that the predictions of the PLE models depend very strongly on many parameters that have to be adopted a priori such as $H_0$, $\Omega_0$, the local LF of ellipticals (uncertain by a factor of 2), the redshift of formation $z_f$, the history of star formation, the metallicity, the IMF, the spectral synthesis models. For instance, even just a decrease of $z_f$, or a small residual star formation (Menanteau et al. 98, Jimenez et al. 99), would relax the predictions making them more consistent with our data. We therefore conclude that it seems premature to reject even extreme PLE models at a high level of statistical significance.

Besides the PLE models, our results can be preliminary compared with some aspects of the hierarchical models of galaxy formation. First of all, our findings could qualitatively fit into the predictions of such models, where high-$z$ ellipticals should be very clustered (Kauffmann et al. 1999) because they are expected to be linked to the most massive dark matter haloes which are strongly clustered at high-$z$. The indication (marginally significant at $\sim 2\sigma$ level) of a decrease of the clustering amplitude of the EROs with the $Ks$ magnitude (see Section [5.4]), which mainly depends on the redshift, but also on the mass of the galaxy, could also fit well in this framework because smaller objects should be connected to smaller dark matter haloes which are expected to be less correlated. Of course, we are aware that at this level these predictions are only qualitatively confirmed, and that the derivation of the 3D correlation should be obtained, by means of the Limber equation. This will be done in Paper II. On the other hand, our results seem to conflict with the predictions made by Kauffmann & Charlot (1998) on the fraction of $K$-selected galaxies with $K \leq 19$. In fact, the fraction of galaxies observed to have color $R-Ks \geq 5.3$ (which corresponds to the selection of $z > 1$ ellipticals) is about 7% of the total in our survey (see Tab. [3]), that is larger than the fraction of $z > 1$ galaxies with $K \leq 19$ expected in the Kauffmann & Charlot (1998) hierarchical model, which is about 2–3%. This evidence support the finding of Eisenhardt et al. (1998).

In general, in $K$-selected samples of $z > 1$ galaxies, the fraction of ellipticals is expected to be large, both in PLE
and hierarchical models, and our results therefore imply significant cosmic variance also for these kind of studies, which must be taken into account.

A more detailed analysis and comparison of our results with the predictions of the PLE and hierarchical models is beyond the purpose of this work and it will be presented in our next paper.

7. Summary

We presented the observational results of a survey made in the $K_s$ and $R$ bands aimed at selecting a large and complete sample of EROs. The main results of this work are:

- We have observed 701 arcmin$^2$ at a 85% completeness level of $K_s = 18.8$, of which 447.5 arcmin$^2$ are complete to $K_s = 19.2$, and with a $R$-band coverage as deep as $R \geq 26.2$ at the 3$\sigma$ level.
- The observed galaxy counts are derived over the largest area so far published in the range of $18 \leq K_s \leq 19.2$. Such counts are briefly compared to the models and to other published data.
- The median $R - K_s$ color of field galaxies increases by 0.5 mags from $K_s = 16.5$ to $K_s = 18$, and it remains constant to $K_s = 19.2$.
- A sample of 422 EROs has been selected. The ERO counts and surface densities have been derived for several color thresholds and $K_s$ limiting magnitudes. In particular, we find $0.042 \pm 0.008$ (poissonian) EROs arcmin$^{-2}$ with $K_s \leq 18.8$ and $R - K_s \geq 6$. Our ERO sample is the largest published to date and it is characterized by an area larger of about four times than previous surveys.
- The surface density of EROs with $R - K_s \geq 7$ has been estimated for the first time to be of the order of $\sim 0.01$ arcmin$^{-2}$ at $K_s \sim 19$.
- The clustering of field galaxies was estimated to be $A(1\degree) \sim 0.0015$ at $18.5 \leq K_s \leq 19.2$, in agreement with previous published data.
- For the first time, we detected the clustering of EROs, which resulted to be $A(1\degree) \sim 0.02$ for the objects with $R - K_s \geq 5$, in the range $18.5 \leq K_s \leq 19.2$.
- The clustering amplitude of the galaxies as a function of the $R - K_s$ color threshold was measured, finding that it increases with the relation $\log A \propto 0.43(R - K_s)$, for $3 \leq R - K_s \leq 5.7$ at $K_s \leq 18.8$.
- The strong clustering of EROs is shown to be a direct evidence that a large fraction of these objects are indeed high-$z$ ellipticals. Our result is therefore the first detection of the large scale structure traced by the elliptical galaxies at $z \sim 1$.
- The ERO clustering explains the conflicting results obtained so far on the density of high-$z$ ellipticals in terms of strong field-to-field variations affecting the surveys based on small fields of view (e.g. $5 \times 5$ arcmin).
- Taking into account the clustering of EROs, even the predictions of extreme PLE models for the comoving density of high-$z$ ellipticals cannot be rejected at more than 2$\sigma$ significance level.

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