CLASSIFICATION OF EXTREMELY RED OBJECTS IN THE COSMOS FIELD

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Received 2008 October 16; accepted 2009 July 20; published 2009 August 21

ABSTRACT

We present a study of the classification of $z \sim 1$ extremely red objects (EROs), using a combination of Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS), Spitzer Infrared Array Camera (IRAC), and ground-based images of the COSMOS field. Our sample includes $\sim 5300$ EROs with $i - K_s \geq 2.45$ (AB, equivalently $I - K_s = 4$ in Vega) and $K_s \leq 21.1$ (AB). For EROs in our sample, we compute, using the ACS F814W images, their concentration, asymmetry, as well as their Gini coefficient and the second moment of the brightest $20\%$ of their light. Using those morphology parameters and the Spitzer IRAC $[3.6] - [8.0]$ color, the spectral energy distribution (SED) fitting method, we classify EROs into two classes: old galaxies (OGs) and young, dusty starburst galaxies (DGs). We found that the fraction of OGs and DGs in our sample is similar, about $48\%$ of EROs in our sample are OGs, and $52\%$ of them are DGs. To reduce the redundancy of these three different classification methods, we performed a principal component analysis on the measurements of EROs, and find that morphology parameters and SEDs are efficient in segregating OGs and DGs. The $[3.6] - [8.0]$ color, which depends on reddening, redshift, and photometric accuracy, is difficult to separate EROs around the discriminating line between starburst and elliptical. We investigate the dependence of the fraction of EROs on their observational properties, and the results suggest that DGs become increasingly important at fainter magnitudes, redder colors, and higher redshifts. The clustering of the entire EROs, DGs, and OGs was estimated by calculating their correlation function, and we find that the clustering of EROs is much stronger than that of full $K$-limited samples of galaxies; the clustering amplitude of OGs is a factor of $\sim 2$ larger than that of DGs.

Key words: cosmology: observations – galaxies: evolution – galaxies: fundamental parameters – galaxies: high-redshift – galaxies: photometry

Online-only material: color figures

1. INTRODUCTION

Understanding when and how the most massive galaxies in the universe formed is one of the most outstanding problems in cosmology and galaxy formation (Conselice et al. 2007). At $z < 1$, the most recent results seem now to agree in indicating that the majority of massive galaxies were already in place at $z \approx 0.7-0.8$, with a number density consistent with the one at $z = 0$ (Yamada et al. 2005; Cimatti et al. 2006; Bundy et al. 2007). However, despite the remarkable success in finding and studying massive galaxies over a wide range of cosmic time, the global picture is far from being clear, especially for massive galaxies at redshift $z > 1$ (Cimatti et al. 2008).

Deep imaging and spectroscopic surveys in the optical and near-infrared indicate that most of the massive galaxies at $z > 1$ are extremely red objects (hereafter EROs, such as Cimatti et al. 2004; Glazebrook et al. 2004; Conselice et al. 2008). Therefore, EROs are largely the test bed for galaxy models, and understanding their properties is an important test of the physics behind galaxy formation, EROs, which are defined as objects having red optical-to-infrared colors, such as $I - K \geq 4$ or $R - K \geq 5$ in the Vega-based magnitude system, were first discovered by deep near-infrared surveys by Elston et al. (1988). Since then many authors have detected EROs in near-infrared surveys (McCarthy et al. 1992; Thompson et al. 1999; Smith et al. 2002; Kong et al. 2006). Such very red colors can be produced by high-redshift ($z \gtrsim 1$) old elliptical galaxies (hereafter OGs) with intrinsically red spectral energy distributions (SEDs), and can also be produced by dusty starburst galaxies whose UV luminosities are strongly absorbed by large amounts of internal dust (hereafter DGs; Hu & Ridgway 1994; Graham & Dey 1996; Smith et al. 2008).

EROs continue to attract considerable interest. On the one hand, the research in the literature suggests that they may well be the high-redshift counterparts and progenitors of local massive E and S0 galaxies. These two classes of EROs may represent different phases in the formation and evolution of high-redshift massive elliptical galaxies. The number densities of OGs provide the strongest constraints on models of galaxy evolution (Gonzalez-Perez et al. 2008). On the other hand, DGs could be related to the ultraluminous IR galaxies producing the bulk of the total energy in the universe since the recombination era (Elbaz & Cesarsky 2003). The properties of EROs, specifically the fraction of OGs and DGs, are therefore a crucial test of galaxy formation theories, and will improve our ability to make complete measurements of the star formation history of the universe (Cimatti et al. 2004; Glazebrook et al. 2004; Renzini 2006). Many groups are currently investigating the fractions of these two ERO populations using a variety of observational approaches (such as Moriondo et al. 2000; Stiavelli & Treu 2001; Mannucci et al. 2002; Smail et al. 2002; Cimatti et al. 2003; Yan & Thompson 2003; Giavalisco et al. 2004; McCarthy 2004; Moustakas et al. 2004; Sawicki et al. 2005; Doherty et al. 2005; Simpson et al. 2006; Conselice et al. 2008; Fang et al. 2009), but the fraction of OGs and DGs from different survey is different, even the same classified method was used. Therefore, their
reliable classification and study, in particular the relative fraction of different ERO types, can provide crucial constraints on the evolution of massive, starburst, dusty, and/or ultraluminous infrared galaxies known to exist at higher redshift, e.g., BzK galaxies, distant red galaxies, and submillimeter and IR-luminous Lyman break galaxies.

Since EROS are rare and clustered, wide-field surveys are essential for studies of the statistical properties of EROs (Daddi et al., 2000; Roche et al., 2002; Kong et al., 2006). Therefore, one possibility of the difference among previous works is that the ERO samples are small. The Cosmic Evolution Survey (COSMOS), the largest contiguous survey ever with Hubble Space Telescope (HST), provides for the first time a combined data set capable of simultaneously exploring large-scale structure and detailed galaxy properties (luminosity, size, color, morphology, nuclear activity) out to a redshift approaching \( z = 1.5 \).

The deep, panoramic multicolor data from Canada–France–Hawaii Telescope (CFHT)-*u*, *i*, Subaru Suprime-Cam *B*, *g*, *V*, *r*, *i*, and *z*, Cerro Tololo Inter-American Observatory (CTIO)/KPNO-Ks (hereafter K), Spitzer Infrared Array Camera (IRAC; 3.6, 4.5, 5.8, 8.0 \( \mu \)m), and the superb resolution HST data enable us to classify the EROS into OGs and DGs by different methods, such as the \([3.6] - [8.0] \) infrared color (Wilson et al., 2007), the multi-wavelength SED fitting method, the morphological parameters of Gini coefficient (G), the second-order moment of the brightest 20% of the galaxy’s flux (\( \mu_{20} \)), concentration index (C), and rotational asymmetry (A). Considering the limited ERO sample in the previous papers, we will use those different methods to classify ~5300 EROS over the COSMOS field in this paper. The structure of this paper is as follows. We describe the COSMOS survey in Section 2. The ERO sample is constructed in Section 3. Classification of EROS, using the spectral type, infrared color, morphological parameter, and the principal component analysis (PCA) method, is performed in Section 4. In Section 5, we compare the properties of OGs and DGs. A summary is given in Section 6. Throughout this paper, we assume a standard cosmological model with \( \Omega_M = 0.3 \), \( \Omega_{\Lambda} = 0.7 \), and \( h = H_0 \) (km s\(^{-1}\) Mpc\(^{-1}\))/100 = 0.71.

2. THE COSMOS SURVEY

The COSMOS project is centered upon a complete survey in the F814W band (central wavelength at 8332 Å, with width 2510 Å) using the Advanced Camera for Surveys (ACS) on board HST of an area of 2 deg\(^2\) (Scoville et al., 2007a). The COSMOS field is equatorial to ensure coverage by all astronomical facilities (centered at J2000.0 \( \alpha = 10^h00^m28^s, \delta = +02^\circ12^\prime21^\prime.0 \)), which was chosen to be devoid of bright X-ray, UV, and radio sources. An overview of the COSMOS project is given in Scoville et al. (2007b).

With an ACS field of view of 202 arcsec on a side, this required a mosaic of 575 tiles, corresponding to one orbit each, split into four exposures of 507 s dithered in a four-point line pattern. The final images have absolute astrometric accuracy of better than 0.1 arcsec. A version with 0.05 arcsec pixels was used to measure the morphology of galaxies in the structure. More details and a full description of the ACS data processing are provided in Koekemoer et al. (2007).

Ground-based follow-up observations have been performed using the CFHT Megacam (\( u^* \) and \( i^* \)), Subaru Suprime-Cam (\( B, g^*, V, r^*, i^*, \) and \( z^* \)), Kitt Peak Flamingos (\( K \) band), and CTIO (also \( K \) band) telescopes, providing deep coverage, with typical limiting magnitudes of 27 (\( AB, 3\sigma \)), of the field from the \( u^* \) to \( z^* \) bands, as well as shallower imaging in the \( K = 21.6 \) (AB).

Details of the ground-based observations and data reduction are presented in Çakap et al. (2007a) and Taniguchi et al. (2007). A multi-wavelength photometric catalog (Çakap et al. 2007a) was generated using SExtractor (Bertin &Arnouts, 1996), with the \( i^* \) band as the selection wavelength.

In additional, a deep infrared imaging survey for the COSMOS field (S-COSMOS) was carried out with the Spitzer Space Telescope (Werner et al., 2004). 166 hours of observations with the Spitzer IRAC camera (Fazio et al., 2004) have been dedicated to cover the entire 2 deg\(^2\) COSMOS field. The field has been observed simultaneously in the four IRAC channels—3.6, 4.5, 5.8, and 8.0 \( \mu \)m. 54 hours of observations with the Multiband Imaging Photometer for Spitzer (MIPS) camera (Rieke et al., 2004) have been dedicated to cover the entire 2 deg\(^2\) COSMOS field with a shallow survey (16 hr) at 24, 70, 160 \( \mu \)m, and a small “test” area (0.16 deg\(^2\)) with very deep observations (38 hr) at 24, 70, 160 \( \mu \)m in the Cycle 2. More details and a full description of the Spitzer data processing are provided in Sanders et al. (2007).

3. EROS SELECTION

Compared to optical, the near-infrared selection (in particular in the \( K \) band) offers several advantages, including the relative insensitivity of the \( k \)-corrections to the galaxy type even at high redshift, the less severe dust extinction effects, the weaker dependence on the instantaneous star formation activity, and a tighter correlation with the stellar mass of the galaxies. Therefore, the studies of faint galaxy samples selected in the near-infrared have long been recognized as ideal tools to study the process of mass assembly at high redshift (Broadhurst et al., 1992; Kauffmann & Charlot, 1998; Cimatti et al., 2002; Bundy et al., 2006). Therefore, we selected objects in the COSMOS survey using the \( K \)-band limiting magnitude.

The limiting magnitude (in \( AB \)) of the \( K \)-band image was defined as the brightness corresponding to 5\( \sigma \) on a 3\( '' \) diameter aperture for an isolated point source by Capak et al. (2007a), the value is \( K = 21.6 \) (AB). The edges of the \( K \)-band image have low signal-to-noise value, therefore, the area, as discussed in this paper, was reduced from the COSMOS 2 deg\(^2\) to 1.82 deg\(^2\). 3234,836 objects were detected and included in the Capak et al.’s ALL catalog (\( v20060103 \)), and 2797,708 of them are in the 1.82 deg\(^2\) area (Capak et al., 2007a). We selected objects to \( K_{\text{Vega}} < 19.2 \) (\( K \)-band total magnitude, ~21.1 in \( AB \)), over a total sky area of 1.82 deg\(^2\). The total magnitudes were defined as the brightest between the Kron automatic aperture magnitudes and the corrected aperture magnitude. The aperture corrections were estimated from the difference between the Kron automatic aperture magnitudes and the 3\( '' \) aperture magnitudes. Simulations of point sources show that in all the area the completeness is well above 90% at this \( K \)-band level.

Therefore, we selected objects to \( K_{\text{Vega}} < 19.2 \), over a total sky area of 1.82 deg\(^2\), and 34,391 objects are included in our final catalog. Stellar objects are isolated with the color criterion \( (z - K)_{\text{AB}} < 0.3(B - z)_{\text{AB}} - 0.5 \) (Daddi et al., 2004), same as in Kong et al. (2006). 626 objects were classified as stars, and the number of the final galaxy sample is 33,765. Figure 1 shows a comparison of \( K \)-band number counts in the COSMOS survey with a compilation of literature counts. The red-, green-, and blue-filled squares correspond to the counts of field galaxies in the COSMOS (this paper), Daddi-F, and Deep3a-F (Kong et al., 2006), respectively. As shown in the figure, our counts are in good agreement with those of previous surveys.
Figure 1. K-band differential number counts for field galaxies and EROs in COSMOS, compared with a compilation of results taken from various sources. The filled squares correspond to field galaxies, and triangles correspond to EROs. Red, green, and blue color correspond to the counts of galaxies and EROs in the COSMOS (this paper), Daddi-F and Deep3a-F (Kong et al. 2006), respectively. The error bars of EROs indicate the Poissonian uncertainties. (A color version of this figure is available in the online journal.)

Figure 2(a) shows \( i - K \) (\( i \) is the Subaru Suprime-Cam \( i^+ \) filter) model color of several representative galaxies against redshift. Model SEDs are adopted from the Kodama & Arimoto’s (1997; KA97) population synthesis library. Ordinary late-type galaxies never reach red color, while both early-type galaxies and reddened late-type galaxies cross the \( i - K = 2.45 \) line when seen beyond \( z \approx 0.8 \). Therefore, in this paper we define EROs as objects whose \( i - K \) color is equal to or redder than 2.45 in AB, which is similar to \( I - K = 4.0 \) in Vega. Figure 2(b) plots \( i - K \) as a function of the \( K_{\text{Vega}} \) magnitude for all galaxies in our sample. The horizontal line denotes our boundary for the ERO selection. There are 5264 objects which satisfy the ERO threshold, \( i - K \geq 2.45 \), down to \( K_{\text{Vega}} = 19.2 \) mag. We refer to these objects as the ERO sample.

The K-band differential number counts of the EROS in the COSMOS field (red triangles) are shown in Figure 1, together with those in Deep3a-F (blue triangles) and Daddi-F (green triangles; Kong et al. 2006). From this figure, we found that the counts of COSMOS match very well with those of Deep3a-F and Daddi-F. It can be explained easily, since the areas of those three fields are large (from 320 arcmin\(^2\) to 1.82 deg\(^2\)), the field-to-field variation in the number counts is very small. Another feature seen in previous surveys, which we also see, is a turnover in the slope of the counts at \( K_{\text{Vega}} = 18.5 \), being steeper at bright magnitudes and flattening out toward faint magnitudes. As we saw in Figure 2(b), and will see in Figure 3(b), \( i - K \) color cut can effectively remove the \( z < 0.8 \) foreground from galaxy surveys. The steep slope of the counts at relatively bright magnitudes reflects the exponential cutoff of the galaxy luminosity function. Unlike the full K-selected counts, the red color-selected objects span a fairly narrow redshift range, and thus the shape of the counts closely reflects the shape of the luminosity function, i.e., most of the EROS are luminous galaxies.

Then we match our ERO sample with the S-COSMOS data (Sanders et al. 2007). The catalog of S-COSMOS IRAC GO2 Delivery (v27May2007) includes photometry in the four IRAC channels for all those sources that have a measured flux in IRAC Channel 1 (3.6 \( \mu \)m above 1 \( \mu \)Jy), 345,512 objects were included. We match the 5264 EROS in our sample with the S-COSMOS IRAC catalog, using a 2.5" radius around the Subaru \( i^+\)-band position, and 5255 EROS have IRAC counterparts, nine EROS have not IRAC counterparts. We also match our ERO sample with the S-COSMOS MIPS-Ge GO2 Delivery (v27May2007), and found 325 of them have counterparts in the MIPS 24 \( \mu \)m catalog.

4. CLASSIFICATION OF EROS

Since EROS can be divided into two broad classes, passively evolving OGs and DGs, the populations should be differentiated before we attempt to analyze their properties. In this section, we shall classify our EROS into two classes, using three different methods: SED fitting, infrared color, and morphology. In the

Figure 2. (a) Model \( i - K \) color as a function of redshift. Representative model galaxy SEDs are taken from Kodama & Arimoto’s (1997; KA97) population synthesis models: a late-type galaxy with \( A_V = 0.0 \) (triangles), an early-type galaxy with \( A_V = 0.0 \) (stars), and a late-type galaxy with \( A_V = 2.05 \) (squares). (b) \( i - K \) plotted against \( K \) for all galaxies in the \( K\)-limited sample. Red circles denote EROs. The horizontal dashed line corresponds to the color threshold (\( i - K = 2.45 \) in AB) for selecting EROS in this paper.

(A color version of this figure is available in the online journal.)
last subsection, we also perform the PCA method to our EROs sample, and discuss the differences.

4.1. Classification Based on SED Fitting

An SED fitting technique based on an updated version of the HyperZ code (Bolzonella et al. 2000) is used to classify our ERO sample into different type, dusty and evolved using their multi-waveband photometric properties. This technique has been used in many previous works, such as Smail et al. (2002), Miyazaki et al. (2003), Georgakakis et al. (2006), and Fang et al. (2009).

We use a stellar population synthesis model by KA97 to make template SEDs. KA97 include the chemical evolution of gas and stellar populations, and have been successfully used to obtain photometric redshifts of high- and low-redshift galaxies (Kodama et al. 1999; Furusawa et al. 2000). The template SEDs consist of the spectra of pure disks, pure bulges, and composites made by interpolating the two as shown in Table 1. Pure disk SEDs correspond to young or active star-forming galaxies, and pure bulge SEDs correspond to elliptical galaxies. Model parameters for the bulge galaxies are calibrated to reproduce the average color of elliptical galaxies in clusters of galaxies, and for the disk galaxies, which are close to the values estimated for the disk of our Galaxy.

The intermediate SED types were made by combining a disk component and a bulge component with the same age, but with different star formation histories. The ratio of the bulge luminosity to the total luminosity in the B band, which we define as \( f_{\text{bul}} \), is changed from 0.1 to 0.99, as shown in the second line of Table 1. \( N_{\text{age}} \) is the number of the template SED age, 33 different ages from 0.01 Gyr to 15 Gyr for pure disk templates, and 15 different ages from 1 Gyr to 15 Gyr for others. In total, our basic template set consists of \( 15 \times 12 + 33 = 213 \) SEDs. More details about the templates can be found in Furusawa et al. (2000).

The SED derived from the observed magnitudes of each object is compared to each template spectrum (redshift from 0.0 to 6.5 with step 0.05; \( A_V \) from 0.0 to 6.0 with step 0.05; Calzetti et al.’s internal reddening law, Calzetti et al. 2000) in turn. The weighted mean redshift, computed in the confidence intervals at 99% around the main solution, from HyperZ, was calculated for each object. For all 5264 EROs in our sample, 5255 of them have four IRAC channel magnitudes, the 13 band magnitudes, including CFHT-\( u^* \) and \( i^* \), Subaru-\( B_g \), \( g^* \), \( V_i \), \( r^* \), \( i^* \), and \( z^* \), near-infrared K band, and IRAC 3.6, 4.5, 5.8, and 8.0 \( \mu m \) bands, were used to calculate photometric redshift and classify EROs. Nine of them have not IRAC counterparts, only optical and near-infrared K-band data were used for calculations.

Thirty-eight EROs in our sample have spectroscopic redshifts (0.71 < \( z < 1.30 \)) from zCOSMOS (Lilly et al. 2007). In Figure 3(a), we show a comparison of the photometric redshift from our SED fitting method with the spectroscopic redshift for those EROs; the range of spectrometric redshifts does not extend to lower or higher redshift. In additional, we plot the photometric redshift from Mobasher et al. (2007) in this figure as well, which were calculated with optical and near-infrared bands, and E/S0, Sab, Sc, Im, and two starburst templates (Ilbert et al. 2009) gave the photometric redshift of \( i^* < 26 \) galaxies in the COSMOS field with 30 band images, but we do not get the data yet). The filled and open circles show objects where the photometric redshift are taken from our method and from Mobasher et al. (2007), respectively. From this figure, we found that our photometric redshifts fit the spectroscopic redshifts well, with an average \( \delta z/(1 + z_{\text{spec}}) = 0.02 \). Photometric redshifts of EROs from Mobasher et al. (2007) were systematic overestimated, with an average \( \delta z/(1 + z_{\text{spec}}) = 0.06 \). The main reason for this difference is that the IRAC four band data were not used in Mobasher et al. (2007). In addition, the templates used in this work are different from those of Mobasher et al. (2007), where four normal galaxy templates (E, Sbc, Sed,

![Figure 3](image-url)
and Im) from Coleman et al. (1980) and two starburst templates (SB2 and SB3) from Kinney et al. (1996) were used.

We plot the photometric redshift histogram of EROs in our sample in Figure 3(b). The average redshift and the peak of the redshift distribution of EROs in our sample are at $z_{\text{phot}} \sim 1.1$, only less than 5% of them have $z_{\text{phot}} < 0.8$. The photometric redshift distribution supports that the color criteria $i-K \geq 2.45$ is valid for culling galaxies at $z \gtrsim 0.8$, and that the redshift estimates by the spectrum fitting method are reasonable. We have checked the effect from templates, with a set of synthetic templates obtained using the GALAXEV03 code (Bruzual & Charlot 2003), and found similar results from those different templates.

Given as an example, we show SED of two EROs in our sample, with the best-fitting template from KA97 as shown in Figure 4(a). Some outputs from HyperZ, such as photometric redshift, the number of the spectral type (see the last line of Table 1), age, and dust extinction in the V band, for each EROs are also shown. The top panel of Figure 4(a) shows an ERO, which SED can be fitted with a late-type template, the age of stellar population is young (0.02 Gyr), and the dust extinction is high ($A_V = 3.6$), so it is a DG with redshift $z = 1.27$. The bottom panel of Figure 4(a) shows another EROs, which SED can be fitted with an early-type template, the age of stellar population is old (3 Gyr), and the dust extinction is low ($A_V = 0.4$), it is an OG with redshift $z = 0.92$.

In Figure 4(b), we show the number of the spectral type (SpT) distribution for our ERO sample, we found that most of the EROs can be fitted well by the templates with SpT $\leq 3$ (disk-dominant galaxies, DGs) or with SpT $\geq 8$ (bulge-dominant galaxies, OGs). Only 5% of EROs in our sample are well fitted with intermediate templates (SpT from 4 to 7), because the number is small, they have very limited effect to ERO’s classification. Based on these analysis, we classify EROs as DGs, if the SpT of the best-fitting template less than 6.5 ($SpT < 6.5$, the ratio of the bulge luminosity to the total luminosity in the B band less than 50%), the others were classified as OGs. Out of the 5264 EROs in our sample, 2505 ($\sim 48\%$) are classified as OGs, while 2759 ($\sim 52\%$) are classified as DGs. Therefore, based on the SED fitting classification method, we concluded that the fraction of OGs and DGs in the COSMOS field is similar.

Figure 4(c) shows the distribution of dust extinction in the V band ($A_V$) for EROs in our sample. EROs with a large SpT (bulge-dominant galaxies) are found to have small $A_V$ values, which is fully consistent with the properties of passively evolving ellipticals with small amounts of dust. DGs with SpT $\leq 2$ are found to have $A_V \sim 1.5$–4.5, with a median value of $\sim 3.1$. This corresponds to $E(B-V) \sim 0.77$ (Calzetti’s extinction law was adopted). The $A_V$ distribution of our DGs is in good agreement with that of Cimatti et al.’s (2002). They have found that the average spectrum of DGs for which they made spectroscopy is fitted by a local starburst galaxy with $E(B-V) \sim 0.8$. They have also found that the global shape of the continuum and the average $R-K$ color of their DGs can be reproduced by synthetic spectra of star-forming galaxies with $0.6 < E(B-V) < 1.1$. (A color version of this figure is available in the online journal.)
4.2. Classification Based on $[3.6] - [8.0]$ Color

Since the COSMOS survey does not release the $J$-band data yet, so we cannot classify EROs into OGs and DGs based on their locations in the $J - K$ versus $R - K$ plane (Pozzetti & Mannucci 2000). However, in the rest-frame near-infrared, old stellar populations show a turnover at wavelengths longer than the rest-frame 1.6 $\mu$m “bump,” while dusty starburst populations show emission from small hot dust grains, therefore, the near- and mid-infrared data from Spitzer can be used to help us distinguish among different ERO populations. Wilson et al. (2007) introduced a new method, based on IRAC $[3.6] - [8.0]$ color, and classified EROs as OGs, DGs, or active galactic nuclei (AGNs). They found that OGs are expected to have the bluest colors ($[3.6] - [8.0] \sim -1.0$), DGs are expected to have intermediate colors ($[3.6] - [8.0] \sim -0.5$), and AGNs are expected to have the reddest colors ($[3.6] - [8.0] \sim 1.0$). $[3.6] - [8.0] < -0.75$ was used to classify EROs as OGs, $-0.75 < [3.6] - [8.0] < 0.0$ was used to classify EROs as DGs, and galaxies with $[3.6] - [8.0] > 0.0$ were used to classify EROs as AGNs.

Strong, rest-frame 6–12 $\mu$m polycyclic aromatic hydrocarbon (PAH) and very small dust grains features redshift into the 24 $\mu$m band at $z \sim 1–2$, DGs are clearly distinguished from OGs at mid-infrared (Yan et al. 2004; Stern et al. 2006). Because the very deep MIPS observation for the whole COSMOS field is not yet finished, Figure 5(a) shows the 325 EROs in our sample, which were detected on the shallow MIPS 24 $\mu$m images (Sanders et al. 2007). They are bright DGs, so can be detected on the shallow MIPS 24 $\mu$m image. From this figure, we found that most of them have $[3.6] - [8.0] > -0.95$, the color $[3.6] - [8.0] = -0.75$ from Wilson et al. (2007) is too red to be used to classify OGs and DGs. This can be confirmed with Figure 1 (the evolution track of early-type template) and Figure 2 (EROs with MIPS 24 $\mu$m detection) of Wilson et al. (2007) as well. Therefore, we will use $[3.6] - [8.0] = -0.95$ as the color criterion to classify EROs as OGs and DGs in this paper.

We have a total of 5264 EROs in our sample, 5255 of them are detected at 3.6 $\mu$m, but only 4761 of them with fluxes brighter than the $3\sigma$ flux limit of 1 $\mu$Jy at both 3.6 and 8.0 $\mu$m band images. We will apply the $[3.6] - [8.0] = -0.95$ color criterion to classify these 4761 EROs in our sample. Figure 5(b) shows the distribution of EROs in the $[3.6] - [8.0]$ versus the $i - [3.6]$ plane. Two thousand one hundred and seventy-six of them (45%) have $[3.6] - [8.0] < -0.95$, which can be classified as OGs; 2494 of them (51%) have $-0.95 < [3.6] - [8.0] < 0.0$, which can be classified as DGs, and 4% of them with $[3.6] - [8.0] > 0.0$ are AGNs. The fraction of AGN among the ERO population here is similar to that in Brusa et al. (2005). Using an 80 ks XMM-Newton observation of a sample of near-infrared-selected EROs ($K_{\text{ Vega}} \lesssim 19.2$; Daddi et al. 2000), the authors found that the fraction of AGN EROs within near-infrared-selected ERO samples is $\sim$3.5%.

In Section 4.1, we have classified EROs as OGs and DGs, based on the SED fitting method. EROs with SpT $< 6.5$ are DGs, and with SpT $> 6.5$ are OGs. We colored the symbols with the SpT of EROs in Figure 5(b), red indicates OGs with SpT $> 6.5$, and blue indicates DGs with SpT $< 6.5$. We found that most of the EROs with SpT $> 6.5$ sit on the area with $[3.6] - [8.0] < -0.95$; however, EROs with SpT $< 6.5$ sit on the area with $[3.6] - [8.0] > -0.95$. To show this point more clearly, we plot in Figure 5(c) the $[3.6] - [8.0]$ distribution of EROs in our sample, from SpT = 1 (pure disk) to SpT = 13 (pure bulge), which were classified by the SED fitting method. We found that, in general, EROs with
small SpT number (DGs) have red $[3.6] - [8.0]$ color (most of them $> -0.95$), and with large SpT number (OGs) have blue $[3.6] - [8.0]$ color. However, the $[3.6] - [8.0]$ distribution shows that there is a significant overlap among EROs with different SpT. As we shall discuss in Section 4.4, the $[3.6] - [8.0]$ color cut cannot separate EROs very well, which depends on reddening, redshift, and photometric accuracy.

4.3. Classification Based on Morphology

As different morphologies are expected in the case of OGs (early type) or DGs (late type), *HST* imaging can be used to classify EROs. Visual morphological classification on nearby galaxies has had a significant impact on our understanding of galaxy formation, environment, and evolution. However, it is widely acknowledged that visual classification is an inherently uncertain and subjective process. In the high-redshift regime, the visual classification of galaxy morphology is further complicated by limited resolution (even with *HST*). Another method is to describe a galaxy parametrically, by modeling the distribution of light as projected into the plane of the sky with a prescribed analytic function, but they assume that the galaxy is well described by a smooth, symmetric profile—an assumption that breaks down for irregular, tidally disturbed, and merging galaxies (Peng et al. 2002; Simard et al. 2002; Balcells et al. 2003).

Nonparametric measures of galaxy morphology, such as Gini coefficient (the relative distribution of the galaxy pixel flux values, or $G$), $M_{20}$ (the second-order moment of the brightest 20% of the galaxy’s flux), $C$ (concentration index), and $A$ (asymmetry), do not assume a particular analytic function for the galaxy’s light distribution and therefore can be applied to irregulars, as well as standard Hubble-type galaxies (Gini 1912; Abraham et al. 1996, 2003; Bershady et al. 2000; Conselice 2003; Lotz et al. 2004). To classify EROs as OGs or DGs, we have measured these nonparametric quantification ($G$, $M_{20}$, $C$, and $A$) of galaxy structure for 4455 EROs in our sample with the *HST* ACS F814W images. Specific details of these measurements can be found in Abraham et al. (2007). For the other 809 EROs, we cannot measure these nonparametric quantifications for them, since they are located at the edge of our study area, and have no *HST*/ACS observation, or the signal-to-noise of *HST*/ACS images is low.

Figure 6 illustrates the relationship between the Gini coefficient and the central concentration for EROs in our sample. The big squares represent the median values of $G$ at different $C$ bins. The solid line in Figure 6 corresponds to a slope of unity and a $y$-axis intercept of 0.13 (i.e., a given galaxy has a slightly greater value of $G$ than $C$). The dashed lines show a ±10% offset relative to the solid line. EROs in our sample span a broad range of morphologies, from pure disk systems at low $C$ to highly centrally concentrated elliptical galaxies at high $C$. Although there is clearly a very strong correlation between $G$ and $C$, but the $C$-$G$ relation of EROs exhibits large scatter, objects with low central concentration (late-type galaxies) exhibit greater scatter. The reason for the scatter is that measurements of central concentration have been based on simple aperture photometry, therefore rely on two key assumptions. First, the measurements depend on an assumed symmetry in the galaxies. The second assumption is that galaxy images have a well-defined center. Inspection of the images of high-redshift galaxies shows that neither of these assumptions is likely to be fulfilled when studying galaxies in the distant universe (Abraham et al. 2003; Lotz et al. 2004). Therefore, we will not use concentration index as a classification parameter for EROs in this paper.

Capak et al. (2007b) have compared the morphology classification for ~2000 F814W < 22.5 mag galaxies, by rotational asymmetry and Gini coefficient, and by visual morphologies. They found that both log $G = -0.35$ and log $A = 5.5$ log $G + 0.825$ can be used to classify early-type galaxies and late-type galaxies using only the *HST*/ACS F814W images. Figure 7(a) shows the distribution of EROs in the log $G$ versus log $A$ (asymmetry index) plane. As in Capak et al. (2007b), the dashed line is defined as log $A = 2.353$ log $G + 0.335$, used to separate irregular and spiral galaxies; the solid line is defined as log $A = 5.5$ log $G + 0.825$, used to separate spiral and early-type galaxies; and the dot-dashed line is defined as log $G = -0.35$, used to separate early-type and late-type galaxies. The classifications by the SED fitting method are indicated with different colors in this figure, OGs (with SpT > 6.5, early-type) are shown as red, and DGs (with SpT < 6.5, late type) are shown as blue. From this figure, we found that the distribution of EROs in the log $A$ versus log $G$ diagram is in good agreement with classifications based on visual method, most of the EROs with SpT > 6.5 have log $G > -0.35$ or log $A < 5.5$ log $G + 0.825$. If we chose a cut at log $G = -0.35$ as the dividing line between early- and late-type galaxies, the fractions of OGs (early type) and DGs (late type) are 48% and 52%, respectively. If we chose a cut at log $A = 5.5$ log $G + 0.825$ as the dividing line between early- and late-type galaxies, the fractions of OGs (early type) and DGs (late type) are 47% and 53%, respectively.

In Figure 7(b), we show the Gini coefficient and $M_{20}$ of EROs. The distribution of EROs is very similar to that of local galaxies in Lotz et al. (2004), with OGs showing high $G$ and low $M_{20}$ values, and DGs with lower $G$ and higher $M_{20}$ values. Most of the OGs have $M_{20} < 8.0$ log $G + 1.1$. If we use this line as the selection limits for early- and late-type galaxies, we found 47% of EROs are classified as OGs and 53% of them are DGs.
4.4. Classification Based on Principal Component Analysis

The agreement among these different methods is found to be satisfactory. Among the EROs with \( K_{\text{vega}} < 19.2 \) mag, \( \sim 52\% \) of the EROs classified as DGs, and \( \sim 48\% \) of them classified as OGs. However, when we consider some EROs in our sample, they may be classified as OGs by one method, but be classified as DGs by the other methods. To check the efficiency of these different methods, and classify all EROs in our sample definitely, we therefore performed a PCA using the measurements of SpT, \( [3.6] - [8.0] \), \( G \), \( A \), and \( M_{20} \) as basic variables.

PCA is mathematically defined as an orthogonal linear transformation that transforms the data to a new coordinate system such that the greatest variance by any projection of the data comes to lie on the first coordinate (called the first principal component, \( PC_1 \)), the second greatest variance on the second coordinate (\( PC_2 \)), and so on (Kong & Cheng 2001; Scarlata et al. 2007). The principal components (PCs) are a linear combination of the original variables and define a new coordinate system obtained by rigid rotation of the original space. All variables are standardized before performing the analysis by subtracting their median value and normalizing them with their standard deviation \( \sigma \). The five variables considered in this paper are defined as:

\[
x_1 = (d_5 - \overline{d_5})/\sigma_{d_5},
\]

\[
x_2 = (d_5 - \overline{d_5})/\sigma_{d_5},
\]

\[
x_3 = (d_5 - \overline{d_5})/\sigma_{d_5},
\]

\[
x_4 = (d_{GA} - \overline{d_{GA}})/\sigma_{d_GA},
\]

\[
x_5 = (d_{GM} - \overline{d_{GM}})/\sigma_{d_{GM}},
\]

where \( d_{GA} \) is the perpendicular distance from each point in the \( G \) versus \( A \) diagram to the line \( \log G = 5.5 \log R + 0.825 \), which was used to separate OGs and DGs in Section 4.3; \( d_{GM} \) is the perpendicular distance from each point in the \( G \) versus \( M_{20} \) diagram to the line \( M_{20} = 8.0 \log G + 1.1 \), which was used to separate OGs and DGs in Section 4.3.

There are 5264 EROs in our sample, and all of them have SpT parameters, but only 4761 of them have \([3.6] - [8.0]\) values (with fluxes brighter than the 3\( \sigma \) flux limit of 1 \( \mu \)Jy at both 3.6 and 8.0 \( \mu \)m band), and 4455 of them have nonparametric quantification (\( G, A, \) and \( M_{20} \)) of galaxy morphology. Therefore, only 4028 EROs in our sample have all SpT, \([3.6] - [8.0]\), \( G, A, \) and \( M_{20} \) measurements, we apply the PCA method on these EROs, and the results are presented in Table 2. The first row gives the eigenvalue (i.e., variance) of the data along the direction of the corresponding PC. The second row shows the fraction of the variance that is explained by each of the PCs, i.e., the fraction of the “power” that is contained in each PC; the third row lists the cumulative fraction of the variance. In the last five rows of the table, each column lists the weights assigned to each input variable, in the linear combination that gives the direction of the specific PC. Some distinct characters can be found from this table. First, the first two PCs account for \( \sim 82\% \) of the total variance, the other PCs can be ignored. Therefore, to classify EROs, we will use the first two PCs only. Second, for \( PC_1 (PC_1 = 0.34 x_1 - 0.26 x_2 + 0.54 x_3 - 0.54 x_4 - 0.49 x_5) \), the absolute weights of \( x_1, x_4, \) and \( x_5 \) are large; on the other hand, for \( PC_2 (PC_2 = -0.56 x_1 + 0.71 x_2 + 0.28 x_3 - 0.23 x_4 - 0.22 x_5) \), the absolute weights of \( x_1, x_2, \) and \( x_5 \) are large. Therefore, \( PC_1 \) is dominated by \( d_G, d_{GA}, \) and \( d_{GM} \), and \( PC_2 \) is dominated by \( d_5 \) and \( d_1 \).

Figure 8 shows the EROs in our sample on \( PC_1 \) versus \( PC_2 \) diagram, colored with different parameters. In Figure 8(a), EROs with SpT > 6.5 are shown as red color, but with SpT < 6.5 are shown as blue color. In Figure 8(b), EROs with \([3.6] - [8.0] < -0.95 \) are shown as red, with \(-0.95 < [3.6] - [8.0] < 0.00 \) are shown as blue, and with \([3.6] - [8.0] > 0.00 \) are shown as green. Because \( PC_2 \) is dominated by \( d_5 (x_1) \) and \( d_1 (x_2) \), and OGs have \( d_5 > 0 \) and \( d_1 < 0 \), so OGs have a small \( PC_2 \) value, but DGs have a large \( PC_2 \) value. From Figure 8(a), we found that EROs with SpT > 6.5 and SpT < 6.5 can be separated by the dashed line \( PC_2 = 0.5 \times PC_1 \). In Figure 8(b), we found a similar sequence as in Figure 8(a); AGNs stay at the upper-left area, OGs stay at the lower-right area, and DGs stay at the middle area. The other character which can be found in Figure 8(b) is that OGs and DGs are mixed in the separation area. Therefore \([3.6] - [8.0] \) can be used to classify EROs if...
Figure 8. Plot of PC1 vs. PC2 for EROs in our sample. (a) EROs are colored with SpT, SpT > 6.5 (OGs) are red, DGs are blue. (b) [3.6] – [8.0] < −0.95, [3.6] – [8.0] > 0.0, and −0.95 < [3.6] – [8.0] < 0.0 are colored as red, green, and blue, respectively. (c) log $G$ > −0.35 (OGs) are plotted as red and DGs as blue. (d) EROs are colored with the best-separated line from panel (a) and panel (c).
(A color version of this figure is available in the online journal.)

Table 2
Results of the PCA Method, Including the Eigenvalue, Fraction of Eigenvalue, and Weights of Each Input Variable

| Variable | PC1  | PC2  | PC3  | PC4  | PC5  |
|----------|------|------|------|------|------|
| Eigenvalue$^a$ | 2.97 | 1.11 | 0.55 | 0.34 | 0.03 |
| Proportion$^b$ | 59.42 | 22.14 | 10.94 | 6.81 | 0.69 |
| Cumulative$^c$ | 59.42 | 81.56 | 92.50 | 99.31 | 100.00 |
| $d_G(x_1)$ | 0.34 | −0.56 | 0.75 | −0.09 | 0.03 |
| $d_G(x_2)$ | −0.26 | 0.71 | 0.64 | −0.07 | −0.02 |
| $d_G(x_3)$ | 0.54 | 0.28 | −0.10 | −0.33 | 0.72 |
| $d_G(x_4)$ | −0.54 | −0.23 | 0.10 | 0.41 | 0.69 |
| $d_G(x_5)$ | −0.49 | −0.22 | −0.05 | −0.84 | 0.05 |

Notes.

$^a$ The eigenvalue of the data along the direction of the corresponding PC.

$^b$ The fraction of the variance that is contained in each PC.

$^c$ The cumulative fraction of the variance.

Those infrared photometry are measured accuracy; however, in practice the required photometric precision is often difficult to obtain. A clear classification of EROs, which lies within 0.1 mag of the dividing line, is difficult. In addition, the [3.6] – [8.0] color also depends on reddening and redshift of galaxy.

In Figure 8(c), EROs with log $G$ > −0.35 were plotted as red points, and with log $G$ < −0.35 as blue points. The distributions are similar if we plot EROs with $d_{GA} < 0$ or $d_{GM} < 0$ as red, and with $d_{GA} > 0$ or $d_{GM} > 0$ as blue. PC1 is dominated by $G$, $A$, and $M_{30}$. Comparing with DGs, OGs have larger $d_G$ (weight value is 0.54, positive; see Table 2 for detail), smaller $d_{GA}$ (−0.54, negative) and $d_{GM}$ (−0.49, negative), so the PC1 of OGs are larger than those of DGs. EROs with log $G$ > −0.35 and log $G$ < −0.35 can be separated by the dot-dashed line as PC1 = 0.30. Using the dashed line in Figure 8(a) and the dot-dashed line in Figure 8(c), we divide PC1 versus PC2 diagram into four different regions, and plot EROs with different colors in Figure 8(d). Forty-three percent of EROs with PC2 > 0.5PC1 and PC1 < 0.30 are classified as DGs (blue points), they have late-type SEDs and small concentrations. Thirty-six percent of EROs in our sample with PC2 < 0.5PC1 and PC1 > 0.30 are classified as OGs (red points), they have early-type SEDs and high concentrations. Eleven percent of them have PC2 > 0.5PC1 and PC1 > 0.30 (black points), so they have late-type SEDs, but elliptical type morphologies. This kind of EROs has been reported by Cotter et al. (2005). Using near-infrared spectroscopy, ground-based optical and near-infrared imaging, and HST imaging, Cotter et al. found vigorous star formation in a bulge-dominated ERO at $z = 1.34$. The other EROs (10%) have PC2 < 0.5PC1, but PC1 < 0.30 (green points). These EROs have late-type morphologies, but have early-type SEDs (SpT > 6.5, but SpT for most of them are less than 8, well fitted with intermediate templates), probably many of them are late-type galaxies, but have large underlying bulges, and so their SEDs may naturally be dominated by underlying old stellar populations. Stockton et al. (2006) have found those kinds of EROs in two quasar fields at $z ∼ 1.4$; SEDs and rest-frame near-UV spectra of them show that they are strongly dominated by old stellar populations; radial surface brightness profiles from adaptive
optics images of these galaxies are best fitted by profiles close to exponentials.

5. RESULTS AND DISCUSSION

In this section, we briefly discuss the properties of OGs and DGs found in our data, including redshift distributions, number counts, and clustering of these two types EROs.

5.1. Redshift Distributions

Figure 9 shows the redshift distribution of DGs (in panel (a)) and OGs (in panel (b)) in our sample, as the solid lines, which were classified by the SED fitting method. The redshift distribution of DGs in our sample has a median value $z \sim 1.12$ (this value depends on the magnitude limit of the observational survey, here for $K_{Vega} = 19.2$) and $\sigma = 0.23$, with a tail toward higher redshift. The redshift distribution of OGs in our sample has a median value $z \sim 1.05$ and $\sigma = 0.13$. The peak of the redshift distribution of OGs in our sample is less than that of the DGs. It is worth noting that our OGs have a narrow redshift distribution, the sigma value of which is $\sigma = 0.13$. Unlike the distribution of DGs, only few OGs have redshift higher than 1.4, the majority of OGs are located at $0.8 < z < 1.4$. The dotted lines in Figure 9 show the redshift distribution of our OGs and DGs, which were classified by the PCA method. We found that the redshift distributions from these two kinds of classification methods are similar; OGs in our sample have small median value and a small sigma value.

5.2. Number Counts

Number–magnitude relations, commonly called number counts, provide a statistical probe of both the space distribution of galaxies and its evolution. For this reason, we derived $K$-band differential number counts for DGs and OGs, classified by the SED fitting method, in the COSMOS field, and plotted them in Figure 10(a). Also shown are the number counts for all EROs in our sample, same as the symbols (triangles with solid line) in Figure 1 for comparison. To check how the color criterion influences the number counts of DGs and OGs, Figure 10(b) shows the number counts of EROs defined by color cut $(i - K)_{AB} \geq 2.55$. The gray solid line with triangles in Figure 10(b) represents EROs defined by color cut $(i - K)_{AB} \geq 2.45$.

The open circles with the dashed line in Figure 10 show the number counts for DGs ($SpT < 6.5$), the filled circles with the dot-dashed line show the number counts of OGs ($SpT > 6.5$) in the COSMOS. We find that the relative fractions of EROs strongly depend on the $K$-band limited magnitudes, and the fraction of DGs in the COSMOS field increases very steeply toward fainter magnitudes: 35% at $K_{Vega} = 17.5$ mag, 39% at $K_{Vega} = 18.0$, 46% at $K_{Vega} = 18.5$, and 52% at $K_{Vega} = 19.2$. For OGs, the slope of the number counts is variable, being steeper at bright magnitudes and flattening out toward faint magnitudes. A break in the counts is present at $K_{Vega} \sim 18.5$, very similar to the break in the number counts for the entire EROs sample. The counts of DGs have roughly the same slope at all $K$-band magnitudes. These results are due to the narrow redshift range of OGs, but the much wider redshift distribution of DGs, as shown in Figure 9. From Figures 10(a) and (b), we find that the color criterion has little or no influence on the number counts of DGs and OGs.

5.3. Color versus Photometric Redshift

Figure 11 shows the $(i - K)_{AB}$ color as a function of photometric redshift for the EROs in the COSMOS field. The red and blue points correspond to OGs and DGs, which are classified by the SED fitting method. Variety of color criteria were used to define EROs, for example $R - K \geq 5, 5.3, 5.9, 6$. To check how the color criterion influences the fraction of EROs, we use $(i - K)_{AB} \geq 2.45, 2.95$, and 3.45 for EROs’ selection (dashed horizontal lines in Figure 11). As described in Section 3, we used $(i - K)_{AB} \geq 2.45$ to select the entire EROs sample in this paper, and found $\sim 52\%$ of them were classified as DGs, and $\sim 48\%$ of them as OGs. If we use $(i - K)_{AB} \geq 2.95$ as the color criterion, the fraction of DGs is 53%. However, if we use $(i - K)_{AB} \geq 3.45$, we found the fraction of DGs increases to 61%.

Figure 11 shows that the distribution of OGs/DGs is very inhomogeneous in the color versus photometric redshift diagram. As described in Section 5.1, DGs have a higher redshift tail, and OGs have a narrow redshift distribution. For EROs with $z_{\text{phot}} > 1.2$, $\sim 73\%$ of them are DGs. To compute the expected $(i - K)_{AB}$ versus redshift of different kinds of dust-free passively evolving galaxies (pure bulge) and dusty starburst galaxies (pure disk), we used the KA97 model. The filled- and open-triangles represent passively evolving galaxies with ages of 5 Gyr and 13 Gyr, and the filled- and open-squares represent dusty starburst and pure bulge galaxies, respectively.
K-band differential galaxy number counts for OGs and DGs, compared with the entire EROs sample as in Figure 1. The solid curves with triangles show the number counts for EROs in the COSMOS, and the filled circles and open circles show the number counts for OGs and DGs, respectively. (a) EROs defined by color cut \((i - K)_{\text{AB}} \geq 2.45\); (b) EROs defined by color cut \((i - K)_{\text{AB}} \geq 2.55\). The error bars indicate the Poissonian uncertainties.

(A color version of this figure is available in the online journal.)

Color vs. photometric redshift distribution for EROs in the COSMOS. Red circles correspond to OGs, and blue circles correspond to DGs. Symbol size is keyed to the \(K\)-band magnitude. The four solid lines indicated predictions by passive evolution and dusty starburst models.

(A color version of this figure is available in the online journal.)

represent dusty \((A_V = 2.05)\) starburst galaxies with ages of 1 Gyr and 5 Gyr, respectively. From the tracks of stellar population synthesis model, we found that the dust-free passively evolving galaxies have a narrow redshift range, EROs with \(z > 1.2\) and \((i - K)_{\text{AB}} < 3.2\) are found to be located outside the region of pure bulge galaxies. On the other hand, the expected color for starburst galaxies has a wide range of redshifts.

5.4. Clustering of the EROs

Measuring the clustering of galaxies provides an additional tool for studying the evolution of galaxies and the formation of structures (Kong et al. 2006; Heinis et al. 2007; McCracken et al. 2007). We estimate the clustering properties of the entire EROs, OGs, and DGs (classified by the SED fitting method), using the estimator defined by Landy & Szalay (1993). In our analysis a fixed slope \(\delta = 0.8\) was assumed for the two-point correlation function, \(w(\theta) = A \times \theta^{-\delta}\).

In the left panel of Figure 12, the bias-corrected two-point correlation functions \(w(\theta)\) of the entire EROs, OGs, and DGs are shown as squares, triangles, and circles, respectively. The dashed line shows the power-law correlation function given by a least-square fit to the measured correlations. The derived clustering amplitudes (where \(A\) is the amplitude of the true angular correlation at 1°) are presented in Columns 2–4 of Table 3, and shown in the right panel of Figure 12 as dashed lines. Furthermore, by using the Limber’s equation (Limber 1954) and the photometric redshift distributions of the entire EROs, OGs, and DGs, we also derived their comoving correlation lengths from the angular clustering amplitudes, at the same \(K\)-band limits. The spatial correlation lengths \(r_0\) for the entire EROs, OGs, and DGs are listed in Columns 5–7 of Table 3.

We find significant clustering for limiting \(K\)-band magnitudes between 18.5 and 19.2 (Figure 12 and Table 3). The clustering amplitudes for our ERO sample are consistent with other previous studies (such as Firth et al. 2002; Georgakakis et al. 2005; Kong et al. 2006), and are much greater than the amplitudes which have been measured for the field population at the same \(K\)-band limits (e.g., Kong et al 2006). The amplitudes shown in Figure 12 suggest a trend of decreasing strength of the clustering for fainter EROs (was also found by Brown et al. 2005), OGs, and DGs. In addition, there appears to be a difference between the clustering properties of the OGs and DGs; the amplitudes and correlation lengths of the clustering of DGs are found to be much lower than those of OGs, a significant overdensity, by a factor of \(\sim 2\), of those OGs clustering amplitudes compare to DGs in the COSMOS field was found.

In the right panel of Figure 12, the solid lines show the angular clustering amplitudes of the entire EROs, OGs, and DGs, which were classified by the PCA method. Since the cover area of \(HST\) image is smaller than that of ground-based images, only 4028/5264 EROs in our sample have all \(SpT, [3.6] - [8.0], G, A,\) and \(M_20\) measurements, so the entire ERO sample here is different from that in the previous. We calculated the clustering properties of the 4028 EROs, DGs, and OGs, in the same manner as for the 5264 EROs. The clustering properties of EROs, OGs, and DGs, by these two classified method, are very similar.
Table 3  
Clustering Amplitudes $A (10^{-3})$ of $w(\theta)$ at $1^{\circ}$ and Spatial Correlation Lengths $r_0$ in $h^{-1}$ Mpc for the Entire EROs, OGs, and DGs Samples in the COSMOS

| $K$ Limit | Classified by the SED Fitting Method |  |  |  |  |
|-----------|--------------------------------------|--|--|--|--|
|           | EROs ($A$) | OGs ($A$) | DGs ($A$) | EROs ($r_0$) | OGs ($r_0$) | DGs ($r_0$) |
| 18.0      | 12.5 ± 0.7 | 17.7 ± 0.8 | 10.2 ± 4.4 | 13.6 ± 0.4 | 14.7 ± 0.3 | 13.0 ± 3.1 |
| 18.5      | 7.8 ± 0.2  | 15.1 ± 0.2 | 6.3 ± 1.3  | 10.5 ± 0.2 | 12.6 ± 0.1 | 10.7 ± 1.1 |
| 18.8      | 6.6 ± 0.1  | 10.4 ± 0.2 | 4.1 ± 0.9  | 9.6 ± 0.1  | 10.2 ± 0.1 | 8.4 ± 1.0  |
| 19.2      | 4.8 ± 0.1  | 8.1 ± 0.1  | 3.3 ± 0.5  | 8.0 ± 0.1  | 8.9 ± 0.1  | 7.5 ± 0.6  |

|  | Classified by the PCA method |  |  |  |  |
|  | EROs ($A$) | OGs ($A$) | DGs ($A$) | EROs ($r_0$) | OGs ($r_0$) | DGs ($r_0$) |
|  | 11.1 ± 1.1 | 16.0 ± 1.6 | 10.6 ± 8.2 | 12.7 ± 0.7 | 14.4 ± 0.7 | 12.6 ± 5.5 |
|  | 7.1 ± 0.3  | 13.1 ± 0.5 | 5.7 ± 2.7  | 10.0 ± 0.3 | 11.1 ± 0.2 | 10.4 ± 2.5 |
|  | 6.0 ± 0.2  | 9.5 ± 0.5  | 4.4 ± 1.9  | 9.1 ± 0.2  | 9.3 ± 0.3  | 9.0 ± 1.9  |
|  | 4.6 ± 0.2  | 8.0 ± 0.4  | 3.1 ± 1.3  | 7.8 ± 0.2  | 8.4 ± 0.2  | 7.4 ± 1.5  |
In order to study the properties of galaxies at redshift \( z \sim 1 \), we constructed a large sample of EROs from the multiwavelength data (from CFHT-\( u^* \) to IRAC-8.0 \( \mu \)m, with 13 bands) of the COSMOS field. We detected 5264 EROs with \( i - K > 2.45 \) down to \( K_{\text{Vega}} = 19.2 \) in the data.

By fitting template spectra of evolutionary population synthesis model to the multiwavelength data, we classified the EROs by their spectral types and estimated their redshifts. Our photometric redshifts fit the spectroscopic redshifts for a tight \( \Delta z/(1 + z_{\text{spec}}) = 0.02 \). The redshift distribution of EROs has a peak at \( z \sim 1.1 \), with a range from \(-0.8 \) to \(1.5 \).

By our template fitting method, we found that the relative fraction of DGs is \( \sim 52\% \) (SpT < 6.5), \( \sim 48\% \) of the EROs in our sample belong to the OG class (SpT > 6.5). Among the OGs, 28% was fitted by templates with 6.5 < SpT ≤ 10, it suggests that a significant fraction of OGs have a nonnegligible amount of star formation.

Using IRAC color \([3.6] - [8.0] \) = −0.95/0.0, we classified EROs as OGs, DGs, and AGNs, the relative fraction of them is 45%, 51%, and 4%, respectively. These fractions agree with the results of the template fitting method, in general. In addition, we found that lots of EROs lie within 0.1 mag of the dividing line, so a clear classification of EROs as OGs and DGs by the [3.6] − 8.0 color requires very high photometric precision.

Using the HST/ACS F814W images, we measured the concentration (C), asymmetry (A), as well as the Gini coefficient (\( G \)) and the second-order moment of the brightest 20% of their light (\( M_{20} \)) of EROs. As found for nearby galaxies, EROs follow a tight \( G - M_{20} - C - A \) sequence, OGs have high Gini coefficients and concentrations and low second-order moments as a result of their bright and compact bulges, DGs have lower Gini coefficients and concentrations and higher second-order moments. Using the same criteria as nearby galaxy, we classified EROs as OGs and DGs by their morphological parameters; the fractions of OGs and DGs are similar to those of the previous two methods.

To classify EROs in our sample definitely, and reduce the redundancy of these different classification methods, we performed a PCA on the measurements of SpT, [3.6] − [8.0], \( G \), \( A \), and \( M_{20} \). We found that the first two PCs full describe the key aspects of the EROs classification. Using the first PC as the classification criterion, 48.3% EROs in our sample is classified as OGs, and 51.7% as DGs. If the first two PCs were used as the classification criteria, EROs can be separated as: 36% of them are OGs (early-type SED and early-type morphology); 10% of them have late-type morphologies, but early-type SEDs; 11% of them have late-type SEDs, but elliptical type morphologies; 43% of them are DGs (late-type SED and late-type morphology).

Finally, we examined the properties of OGs and DGs in our sample, and found that: DGs have a wide range of redshift, with a peak at \( z \sim 1.12 \) and \( \sigma = 0.23 \), the redshift distribution of OGs in our sample has a median value \( z \sim 1.05 \) and \( \sigma = 0.13 \); the relative fractions of EROs strongly depend on the \( K \)-band limited magnitudes, the fraction of DGs increases very steeply toward fainter magnitudes; the angular clustering amplitude of OGs is a factor of \( \sim 2 \) larger than that of DGs. Moreover, the clustering strength of EROs, OGs, and DGs increases with the \( K \)-band limited magnitude decreases.

We thank an anonymous referee for useful and constructive comments that resulted in a significant improvement of this paper. It is a pleasure to thank S. White and E. Daddi for useful suggestions. We gratefully acknowledge R. Abraham for access to his morphology analysis code and P. Capak for his help on COSMOS data. The HST COSMOS Treasury program was supported through NASA grant HST-GO-09822. The work is supported by the National Natural Science Foundation of China (NSFC, Nos. 10573014, 10633020, and 10873012), the Knowledge Innovation Program of the Chinese Academy of Sciences (No. KJCX2-YW-T05), and National Basic Research Program of China (973 Program; No. 2007CB815404).

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Figure 12. Left panel: observed, bias-corrected two-point correlations of the entire EROs (squares), OGs (triangles), and DGs (circles). The error bars on the direct estimator values are 1σ errors. To make this plot clear, we show the error bars of OGs only. Because of the small number of objects included, some bins were not populated. Right panel: the angular clustering amplitudes of the entire EROs, OGs, and DGs are shown as a function of the \( K \)-band limiting magnitudes of the sample analyzed. The solid and dashed lines represent the sample were classified by the PCA method and the SED fitting method. (A color version of this figure is available in the online journal.)
