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GALAXY EVOLUTION IN DISTANT UNIVERSE

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ABSTRACT

This paper summarizes the recent progress made by our group at Seoul National University on studies of the evolution and formation of distant galaxies. Various research projects are currently underway, which include: (i) the number density of distant early-type galaxies ($z < 1$); (ii) the optical-NIR color gradient of nearby early-type galaxies; (iii) $J - K$-selected Extremely Red Objects (EROs) in field (CDF-S) and the cluster environment; and (iv) the Lyman-break galaxies in the Spitzer First Look Survey (FLS) field. These works will constrain the mass evolution and the star formation history of galaxies in different environments, and the results will serve as useful contraints on galaxy formation models.

Key words : cosmology: observations — galaxies: evolution — galaxies: formation — space telescope

I. INTRODUCTION

According to the currently popular hierarchical galaxy formation models (Kauffmann, White, & Guiderdoni 1993; Baugh, Cole, & Frenk 1996; Somerville, Primack, & Faber 2001), the first galaxies that form from the gravitational collapse of over-density peaks are small, less-massive galaxies. Then, these small galaxies continue to merge through gravitational attraction, creating the bigger, more massive galaxies we see today. This is the generic prediction under cosmological models where the majority of the matter content is in the form of cold dark matter (CDM; Blumenthal et al. 1984; Baron & White 1987). In such a CDM-dominated universe, the small density fluctuation prevails, leading to the creation of the small galaxies in the early universe. While the hierarchical galaxy formation models predict the growth of galaxy mass through mergers, they also predict how the galaxy formation process depends on the environment. The gravitational collapse starts at high redshift in high σ over-density peaks, and such high-σ peaks are usually where clusters of galaxies form. Therefore, the second important prediction of the hierarchical galaxy formation models is that the galaxy formation occurs early in clusters of galaxies, followed by a more recent formation of galaxies in field (less dense environment; e.g., Kauffmann et al. 2004; Benson et al. 2003). In order to test these key predictions of the hierarchical galaxy formation models, we have been undertaking observational studies using objects ranging from nearby early-type galaxies to high redshift Lyman break galaxies. Below, we summarize our current efforts.

II. EARLY-TYPE GALAXIES

(a) Distant Early-Type Galaxies

The number density of early-type galaxies is a very powerful means to test the galaxy formation models. N-body simulations have shown that massive early-type galaxies form via merging of equal-mass, gas-rich galaxies (Toomre & Toomre 1972; Farouki & Shapiro 1981). By incorporating the simulation result, hierarchical galaxy formation models predict that massive early-type galaxies formed relatively recently through major merging. In some models, more than one half of the present day early-type galaxies form at $z < 1$. Using the Deep Extragalactic Evolutionary Probe (DEEP) data, we have studied the number density and the luminosity evolution of early-type galaxies out to $z \lesssim 1$. The DEEP is a project which combines HST images and Keck spectra for galaxy evolution study (Vogt et al. 2005; Koo et al. 1996). The HST image are used to do morphological classification of distant galaxies, and the Keck spectra offers spectroscopic identification of redshifts, as well as kinematic information of each galaxy.

Using the DEEP 1 sample, we have selected 145 early-type galaxies out to $z \sim 1$ from a region of the sky named, "Groth Strip". The Groth strip is made of 27 contiguous HST WFPC2 fields arranged in the shape of a strip, and the total field of view of the Groth Strip is 118 square arcminutes. Morphological classification was done quantitatively. The quantitative morphological classification method uses the B/T (the bulge-to-total light ratio), and the residual parameter R. The B/T parameter quantifies how the light is concentrated in the center, and for the early-type galaxies, the value should be $B/T > 0.4$. The R parameter quantifies how blobby the object is, and the smooth, early-type galaxies have $R \lesssim 0.08$. This selec-

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tion method has been tested extensively on the rescaled local galaxy images, and it has been proved that our method is excellent in selecting early-type galaxies with no disturbed features (Im et al. 2002a). For early-type galaxies without spectroscopic redshift, we have used photometrically estimated redshift which has the accuracy of about 10%.

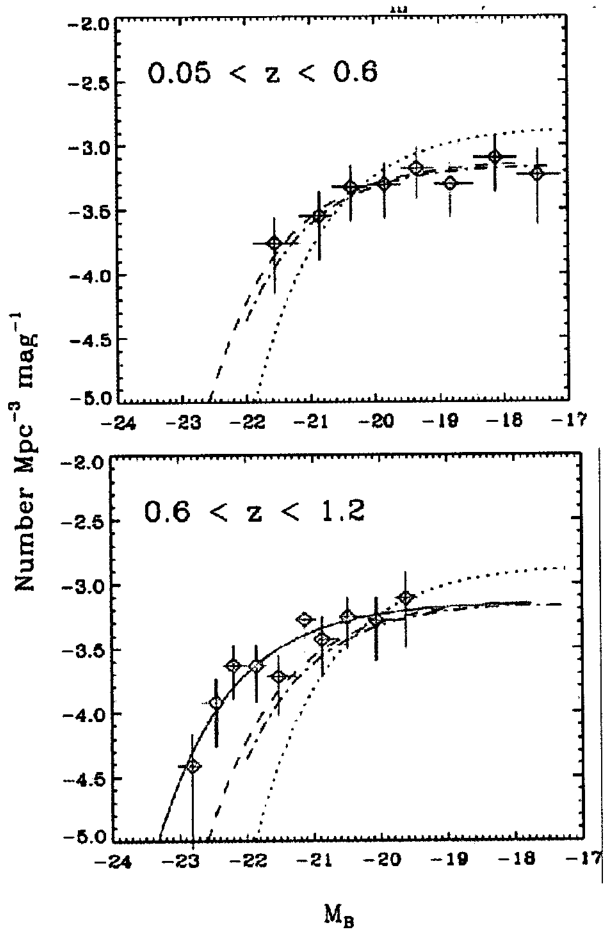

Fig. 1.— Luminosity function of GSS E/S0s at two different redshift intervals. The upper panel shows the LF function at $0.05 < z < 0.6$ (blue points points and the blue dashed line), while the lower panel shows the luminosity function at $0.6 < z < 1.2$ (red points and red solid line). Overplotted in the both figures are the local E/S0 LF's of Marzke et al. (1998; the dotted lines) and Marinoni et al. (1999; dot-dashed lines). In the lower panel, we also plot the best-fit LF of the lower redshift E/S0s with the dashed line. The higher redshift LF is shifted toward the brighter absolute magnitude with respect to the lower redshift LF, indicating the luminosity brightening toward $z \sim 1$. Along the y-axis, the LF does not shift much from low-z to high-z, suggesting that the number density evolution is not strong. The assumed cosmology is $\Omega_m = 0.3$, $\Lambda = 0.7$, and $H_0 = 70 km/sec/Mpc$.

Using this sample, we have constructed the luminosity function of early-type galaxies at low and high redshift. Fig. 1 shows these luminosity functions of the 145 early-type galaxies. To derive the luminosity function, we have assumed the cosmology with $\Omega_m = 0.3$, $\Lambda = 0.7$, and $H_0 = 70\, km\, sec^{-1}\, Mpc^{-1}$. In Fig. 1b, the high-redshift ($0.6 < z < 1.2$) luminosity function (points) is compared with the low redshift luminosity function (dashed line). Compared to the low-redshift luminosity function, the high-redshift luminosity function is shifted toward the brighter magnitude. The horizontal shift of the luminosity function from low redshift to high redshift implies that early-type galaxies are brighter at $z \sim 1$, then at $z \sim 0$, and the amount of the luminosity brightening is about 1.5-2.0 B magnitude. The luminosity brightening corresponds to the formation epoch of stars at $z = 1.5 \sim 2$, if all the stars in the early-type galaxies were born at a single epoch. The vertical shift of the luminosity function from low redshift to high redshift would imply the change in the number density. We measure the number density evolution, parameterized as $(1+z)^m$, to be $m \simeq 0.8 \pm 0.7$, meaning that the number density of early-type galaxies $z \sim 1$ is consistent with, or moderately smaller (by 50%) than the present-day value. Our result shows that the number density evolution of early-type galaxies is not very strong as claimed by a previous study (Kauffmann & Charlot 1996) nor by models (e.g, Baugh et al. 1996). We are currently expanding our sample by studying the HST archival data. We expect to provide a much stronger constraint on the number density evolution from this study.

(b) Nearby Early-Type Galaxies

Having constrained that the formation epoch of the majority field early-type galaxies might be around $z \gtrsim 1$, and that the number of such galaxies have increased moderately since $z = 1$, we are currently investigating the environmental effect on the formation/evolution of early-type galaxies. There are mixed results on the formation epoch of early-type galaxies in different environments. Some studies suggest that early-type galaxies in high density environments do not appear to have formed much earlier than early-type galaxies in low density environments (Bernardi et al. 2003). The difference in the formation ages appears to be not much more than about one Gyr. On the other hand another study suggests a larger difference in the formation epochs ($\Delta t \sim 2$ Gyr; Thomas et al. 2005). These works, however, focus on the difference in mean ages by treating the stellar population in each galaxy as a whole. If the majority of stars in early-type formed early, and the early-type galaxies grew via merging of such old, less-massive systems, such a merging history will not show up in the above analysis. In order to trace the past merging activities, we are studying the optical-NIR color gradient in early-type galaxies in different environments. Colors of the inner parts of early-type galaxies are redder than their outer parts – this is called "color-gradient". The existence of the color gradient can be explained as the following: The initial formation of massive early-types occurs via a merger of two, gas-rich galaxies or a monolithic collapse of protogalactic gas at high redshift. After the merger, the gas will be retained in the central part much longer than in the outer part due to the deeper gravitational potential. Hence, the star formation can occur in multiple epochs at center, enriching the metallicity of stars in the central part. Therefore, early-type galaxies would have the higher metallicity at the center, and the lower metallicity at the outer region. This is called the "metallicity gradient". Since stars with the higher metallicity are redder than those with the lower metallicity, the metallicity gradient translates into the color gradient.

Continuous merging with other galaxies alters this color gradient. Merging with gaseous objects provides additional gas in the central region, triggering a more recent star formation activity. As a support of this picture, some studies have discovered early-type galaxies with bluer cores (Hinkley & Im 2001; Menanteau et al. 2004). Also, merging with other objects mixes up stellar population, and leads to the diffusion of the color-gradient. Therefore, galaxies that have gone through frequent merging activities would have the color-gradient shallower than the color gradient of those that have not. In hierarchical galaxy formation model, merging activity can occur over an extended period in cluster environment, while early-type galaxies in field are relatively younger in its formation history. This reflects on the observed color gradient as a shallow color gradient in early-type galaxies in cluster, and a steep gradient for field early-type galaxies. For this color gradient study, we are using the optical-NIR data of Pahre (1999). Optical-NIR data provides a wide color baseline making it easier to detect subtle difference in color gradients between different objects (e.g., Hinkley & Im 2001). Our preliminary study shows that cluster early-type galaxies have the shallower color gradients than field early-type galaxies. More detailed discussion on this, and the plots showing this preliminary result can be found in Ko & Im (2005) of this proceedings.

III. EXTREMELY RED OBJECTS

Extremely Red Objects (EROs) are objects with very red optical-NIR colors, typically $R - K > 5$mag or $I - K > 4$mag. These color cuts correspond to the colors of passively evolving early-type galaxies at $z > 1$ (e.g., McCarthy, 2004). The ERO study is motivated by the desire to identify red, early-type galaxies at $z > 1$. As described in the previous section, early-type galaxies are now identified out to $z \sim 1$, and the number density of $z < 1$ early-types does not seem to have changed significantly. This motivates the need for a similar study which extends out to $z > 1$. However, such studies have not been performed effectively due to the difficulty of identifying $z > 1$ early-types. One reason for this difficulty of identifying $z > 1$ early-types is that the flux of early-type galaxies drops sharply below the 4000Åbreak (Balmer break + Ca H+K absorption lines). At $z > 1$, the 4000 Åbreak redshifts out of optical wavelengths. Hence, $z > 1$ early-type galaxies are faint in optical, which have been used widely for many galaxy surveys. Another reason is that redshift identification of early-type galaxies relies on absorption features (mainly Ca H+K at $\sim$ 4000 Å), and the features necessary for the redshift identification redshifts out to *NIR* where the spectroscopic observation of faint objects is challenging.

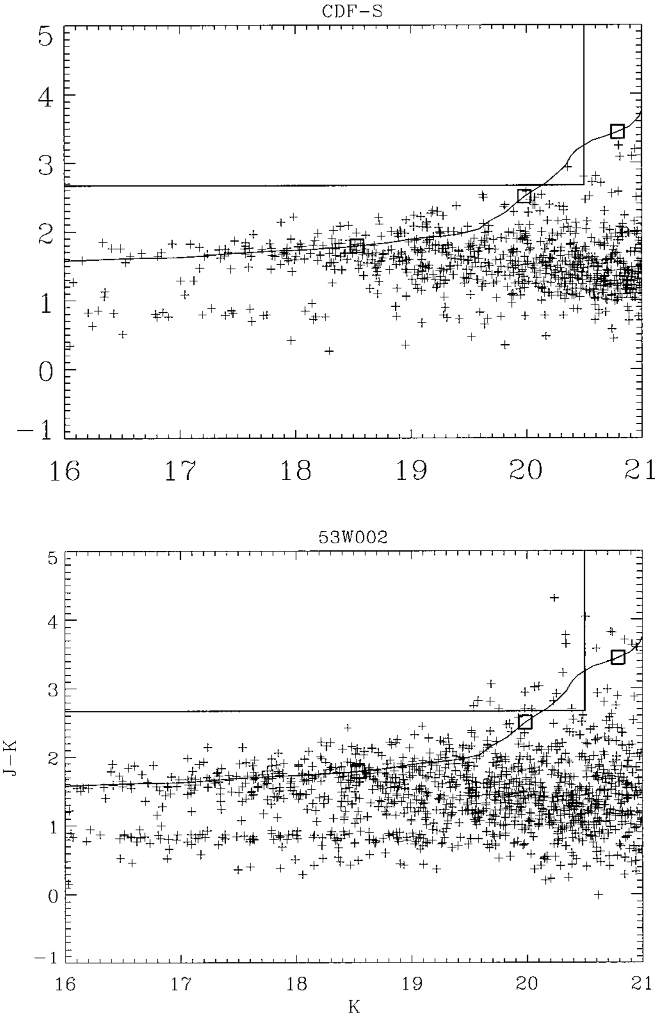

Fig. 2.— K vs J-K diagram of the 53W002 field (left; 64 square arcminutes) compared with the Chandra Deep Field-South (right; 40 square arcminutes). The boxed area in the upper-left corner of each figure is where bright HEROs are found. The line indicates model colors and magnitudes for passively-evolving, early-type galaxies formed at $z = 7$. Large squares on the model lines indicate present redshifts of 1, 2, 3 respectively (from left to right). The horizontal sequence near $J - K = 0.8$ is mostly stars. There are more objects in the 53W002 field because of the difference in the area coverage (×1.5). The 53W002 field also has more stars than the CDF-S since the 53W002 field is located at a somewhat lower galactic latitude ($b = 36$). Even consid-

ering the difference in area, there are far more HEROs in the 53W002 field than in the CDFS field (reproduced from Im et al. 2005, in preparation).

Therefore, instead of building up morphologically classified $z > 1$ early-type galaxies, people have picked up $z > 1$ early-type galaxy candidates using optical-NIR colors. This method is advantageous over the more rigorous approach of using HST and spectroscopic data, since it requires only imaging data (both in optical and NIR, though). The previous ERO studies have concentrated on a sample selected from optical-NIR color cuts which are geared to select red galaxies at $z > 1$, and tried to constrain the formation epoch of early-type galaxies by comparing their number density to model predictions. The results so far are mixed – some claim no significant number density evolution even at $z > 1$ (e.g., Cimatti, A. et al. 2002), while other studies claim a significant evolution (Yan & Thompson 2003). One complication in this kind of study is that red galaxies consist of a variety of objects, such as early-types and dusty-star forming galaxies. Therefore, the ERO number density does not necessarily mean the number density of early-types at $z > 1$. Also, EROs are in general strongly clustered, so field-to-field fluctuation makes it difficult to pin down the exact number density of EROs. In order to extend the ERO study to a higher redshift, we are currently undertaking a study of NIR-color selected EROs. A passively-evolving early-type galaxy at $z > 2$ has $J - K > 2.3$, and $J - K > 2.7$ at $z > 2.4$. The objects with $J - K \gtrsim 2.7$ are called "Hyper Extremely Red Objects" (HEROs; Totani et al., 2001; Im et al. 2002b). We have studied these $J - K$-selected EROs in the GOODS Chandra Deep Field South (CDF-S)data, and in the field called, 53W002. The CDF-S field contains no previously known high redshift overdensity, therefore it is a very good field to study for early-type galaxies at $z > 2$ in field. The CDF-S field also includes deep HST imaging data, so we can use the dataset to investigate the morphological properties of EROs. On the other hand, 53W002 field includes a known galaxy proto-cluster at $z \sim 2.4$, so it is good field to use for studying early-type galaxy formation in cluster environment at high redshift. Fig. 2 shows the K vs J-K (Vega magnitude) of objects in the CDF-S field (upper panel) and the 53W002 field (lower panel). The archived VLT NIR data have been used for the CDF-S field, while our deep, wide-field, Palomar dataset is used for the 53W002 field. The boxed area shows where HEROs are, and it is remarkable that the number of bright HEROs in the 53W002 field far exceeds the number of HEROs in the CDF-S. This confirms that the overdense region at $z \sim 2.4$ in the 53W002 field. Also, the large number of HEROs suggests that massive early-type galaxies existed at $z \sim 2.4$ in cluster region, but not in the field. In order to understand the nature of the EROs in CDF-S in more detail, we are currently studying HST data as well as the Spitzer Space Telescope data. Fig. 3 shows the postage stamp images of the J-K selected EROs in the CDF-S in HST and in VLT NIR data. Note that HST provides enough depth to show the morphology for some of the EROs, while some of the HEROs are barely seen in the HST images. For the EROs which have enough S/N, their morphology show a very irregular nature, nothing like a typical early-type galaxies today. This suggests that $J - K$-selected EROs in the CDF-S are mostly dusty starforming galaxies. For HEROs, the HST data do not have enough S/N to reveal their morphological nature. For HEROs in both the CDF-S and the 53W002 fields, we are constructing the spectral energy distribution which extends out to 8 μm. The 1.6 μm bump, common in old stellar population, redshifts into 6 μm, and should be detectable in the Spitzer data. We find such a feature in some of HEROs, confirming that at least some HEROs are old, massive galaxies. At the same time, we find a number of HEROs which have steeply increasing spectral energy distribution toward the longer wavelength – they are likely to be AGNs at $z \sim 2$, and may also harbor massive host galaxies. The results on the Spitzer observation of the 53W002 field will appear elsewhere (Im et al. 2005, in preparation).

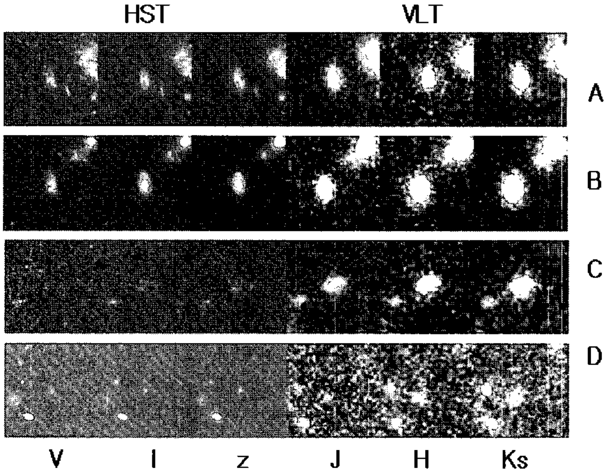

Fig. 3.— The postage stamp images of the J-K-selected Extremely Red Objects.

IV. LYMAN-BREAK GALAXIES

Lyman-break galaxies are galaxies at high redshift, whose Lyman-break (912 Å) redshifts out of the bluest passband used for the photometric observation. Depending on the passband from which the galaxies' light disappear, Lyman-break galaxies are named U-band dropout ($z \sim 3$ galaxies), B-band dropout ($z \sim 4$ galaxies), and so on. This method has been widely used to identify galaxies at $z > 3$, and our understanding on the cosmic star formation history at $z > 3$ relies largely from these Lyman break galaxies (e.g., Steidel et al. 1999; Lowenthal et al. 1997). Most Lyman break galaxies have flat spectra in the rest-frame UV, which means that they are star-forming, young galaxies. One of the intriguing questions on the nature of Lyman-break galaxies is whether they are massive objects or not. Answering such a question is important for understanding the mass evolution history of galaxies which is a critical test of hierarchical galaxy formation models. The optical data of Lyman-break galaxies sample the UV emission. However, the UV emission is highly dependent on the star formation activity, and is not a good measure of stellar mass. It is important to cover the longer wavelength, preferably the rest-frame NIR, and it is not easy to do so from the ground for the Lyman-break galaxies. Another interesting question is how dusty Lyman-break galaxies are. The dust extinction plays a significant role in understanding the cosmic star formation history. The rest-frame UV continuum or optical recombination lines are commonly used for estimating star formation rate. However, the UV or optical light can be easily affected by the extinction. As a consequence, the cosmic SFR estimated from such methods are often underestimated by an unknown amount of dust extinction. The SFR estimate from submm galaxies shows a much higher value than the SFR from the UV-optical studies, therefore the dust extinction is a great concern for the study of the cosmic star formation rate.

In order to study the mass and the dust extinction of Lyman-break galaxies, we have assembled a sample of bright Lyman break galaxies in the Spitzer First Look Survey (FLS). The Spitzer FLS observation offers a very important dataset which covers 3-8 & 24 microns. These wavelengths correspond to the rest-frame NIR and the MIR. The rest-frame NIR data are a good measure of stellar mass of galaxies, while MIR flux can tell us how dusty each object is. In order to support the Spitzer FLS observation, we have taken a deep u- and g-band images using the CFHT Megacam Camera (4hrs exposure each, to the depth of $\sim$ 26.5 AB mag) over a 1x1 square degree area in the central part of the FLS field. Combining this u- and g-band dataset with the existing R-band ground-based ancillary data (Fadda et al. 2004), we have selected Lyman-break galaxies from a g-R vs u-g color-color diagram. The total number of Lyman-break galaxy candidates amounts to 500 at $R_{AB} < 24$ mag. We have matched each Lyman-break galaxy candidate with the IRAC 3-8 micron data as well as with the MIPS 24+70 micron imaging data. Our preliminary study suggests that the bright Lyman break galaxy candidates are indeed quite massive (10^{10} – $10^{11} M_{\odot}$). Also, some of the Lyman-break galaxy candidates are detected in MIPS 24 micron band, thus are found to be dusty in nature. Among these, we identify one of the Lyman-break galaxy candidates as a submm source discussed in Frayer et al. (2004). The Lyman-break galaxy study and the detailed description of the CFHT dataset will appear elsewhere (Shim et al. 2005, in preparation).

V. CONCLUSION

We have studied nearby and distant early-type galaxies, as well as EROs and Lyman-break galaxies, in an attempt to understand the evolution and formation of galaxies and to test the hierarchical galaxy formation models. The findings can be summarized as:

(1) The number density of distant early-type galaxies $z < 1$ seems not so dramatically different from that of nearby early-type galaxies. This excludes extreme merging scenarios for the formation early-type galaxies, and pushes the major formation epoch of early-type galaxies to $z > 1$.

(2) The optical-NIR color gradient of early-type galaxies in different environments show the shallow color gradients for early-types in cluster environment, and the steep color gradients for field early-type galaxies. This seems to suggest that early-type galaxies in cluster environment have gone through more merging events than field early-type galaxies. The result is consistent with the hierarchical merging picture.

(3) $J-K$ selected EROs have been studied in CDF-S and in 53W002. These objects are the likely candidates of red galaxies at $z > 2$. We find that EROs in CDF-S are likely to be dusty, star-forming galaxies, while some of the EROs in 53W002 seem to be evolved, massive galaxies.

(4) We identify bright, Lyman-break galaxy candidates in the Spitzer First Look Survey using u-g-R ground-based data. We find these objects to be massive ($M = 10^{10}$ - 10^{11} $M_{\odot}$), and actively star forming. Some of these Lyman-break galaxies appear to be dusty objects.

Our findings suggest that the major formation epoch of massive galaxies seem at $z = 1 - -3$, and this needs to be explained by hierarchical models. On the other hand, the environmental dependence on galaxy formation seem evident from the study of color-gradient of nearby early-type galaxies, and the distant EROs.

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