Exploring the formation and evolution of massive ellipticals with Extremely Red Objects

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Abstract. Extremely Red Objects (EROs) provide the important possibility to shed light on the formation and evolution of the present-day massive ellipticals. On one hand, they allow to select $z > 1$ old passively evolving spheroidals and to compare their abundance with the predictions of galaxy formation scenarios. On the other hand, they provide the possibility to find dust obscured starbursts, a fraction of which may trace the formation of proto-ellipticals at $z > 2$. In this paper, the most recent results on EROs are reviewed and the main implications discussed.

1 Introduction

A fraction of the galaxies selected in the near-infrared show very red colors (e.g. $R - K > 5$). The first cases were serendipitously discovered by [1], and even more extreme cases were found by [2]. Such galaxies are known as Extremely Red Objects (EROs), and the most recent surveys demonstrated that they form a substantial field population [3,4] ($\sim 0.5$ EROs arcmin$^{-2}$ for $R - K > 5$ and $K < 19$), whereas EROs are often found in excess around high-$z$ radio-loud AGN [5,6]. Because of the “age – dust” degeneracy, the red colors are consistent with EROs being $z > 1$ old passively evolving ellipticals as well as star-forming galaxies and AGN strongly reddened by dust extinction. Because of their faintness, the observation of EROs is very challenging (sometimes unfeasible) even with 10m-class telescopes. However, recent spectroscopy demonstrated that ellipticals and starbursts are indeed present in the ERO population [7,8,9,10,11]. The key question is then to derive the relative fractions of both galaxy types in order to exploit the stringent clues that EROs can place on the formation and evolution of elliptical galaxies and on the abundance of dust obscured systems at high-$z$.

2 EROs as old ellipticals

The question on the origin of the present-day massive spheroidals is one of the most debated issues of structure formation and galaxy evolution [12]. The fundamental question is to understand if ellipticals formed at early cosmological epochs (e.g. $z > 2 - 3$) through a relatively short episode of intense star formation followed by a passive evolution to nowadays, or if they built up through the merging of pre-existing disk galaxies taking place mostly at $z < 1$, thus making massive spheroidals at $z > 1$ rare objects [3,14].
A direct way to test such galaxy formation scenarios is then to search for massive field ellipticals at $z > 1$ and to compare their number with the above model predictions. Since near-IR light is a good tracer of the galaxy stellar mass \cite{13} (e.g. $10^{11} M_\odot$ correspond to $18 < K < 20$ for $1 < z < 2$ \cite{16}), ERO surveys are capable to select massive passively evolving elliptical candidates. For instance, a color of $R-K > 5.3$ is expected for $z > 1$, $z_f > 2$, $H_0=50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.1 - 1.0$, $Z = Z_\odot$, Salpeter IMF (from Bruzual & Charlot 1997 models). Searches based on this approach gave very discrepant results and claimed either a strong deficit or a constant comoving density of $z > 1$ ellipticals \cite{17,18,19,20,21,22,23,24,25}. Since such results were based on small field surveys (typically 1-60 arcmin$^2$), wide field searches for EROs have been recently made in order to overcome the possible effects of the field-to-field variations.

In one of the widest field survey to date \cite{1}, 700 arcmin$^2$ were observed to $K < 19$, covering a sky area about ten times larger than the previous surveys and providing a complete sample of about 400 EROs with $R-K > 5$. The main results of such a survey were the detection of strong angular clustering of EROs (an order of magnitude larger than that of field galaxies), and the solid estimate of their surface density. Such results were recently confirmed by \cite{27}. The observed clustering can easily explain the previous discrepant results as due to strong “cosmic variance” effects, and it suggests that most EROs with $K < 19$ are ellipticals rather than dust reddened starbursts (see \cite{1} for more details). If this is the case, the spatial correlation length $r_0$ of $z \sim 0.9 - 1.5$ ellipticals is in the range of 6-$10h^{-1}$ Mpc comoving \cite{26,27}.

Concerning the comparison with galaxy evolution scenarios, even in a conservative case where 70% of EROs are ellipticals, their observed surface density is in good agreement with the predictions of passive evolution (Fig. 1), suggesting that most field ellipticals were fully assembled at least by $z = 2.5$ \cite{28}. This result does not imply that the formation of massive spheroids occurred necessarily through an old fashioned “monolithic collapse” \cite{29}, but it simply constrains the epoch when the formation took place, and it implies that, if ellipticals formed through merging, this occurred mostly at $z > 2.5$.

Follow-up observations are needed to verify that most EROs are ellipticals. Despite the observational difficulties due to their faintness, the 10-m class telescopes are spectroscopically confirming that a substantial fraction of EROs are $z > 1$ passively evolving ellipticals with old ages ($\sim 1 - 4 \text{ Gyr}$) consistent with being formed at remote cosmological epochs \cite{31,32}. The preliminary results of the $K20$ survey \cite{32} show that emission lines were detected in only $\sim 20\%$ of the EROs with $K < 20$ and $R-K > 5$ observed so far, whereas the remaining fraction is made by spectroscopically identified ellipticals at $z > 1$ and by unidentified objects with no emission lines which could be either ellipticals at higher $z$ or dusty star-forming galaxies at $z > 1.4$ (i.e. with emission lines falling out of the observed optical spectral range). In addition to spectroscopy, recent HST imaging showed that most EROs
Fig. 1. The filled symbols show the observed surface density of EROs with $R-K > 5.3$ (corresponding to select passively evolving ellipticals at $z > 1$, see text) derived from the wide field surveys of [3,4]. The error bars take into account the non-poissonian fluctuations due to the strong angular clustering discovered by [4]. The curves show the predicted densities in case of pure luminosity evolution (PLE) for different formation redshifts adopting the Marzke et al. (1994) local luminosity function of ellipticals and the Bruzual & Charlot (1997) spectral synthesis models with Salpeter IMF and solar metallicity (see [28] for more details). The starred symbols show the observed density in case 70% of EROs are passively evolving elliptical galaxies. The good agreement between the observed and the predicted surface densities suggests that PLE models cannot be discarded and that most ellipticals formed at $z > 2.5$. 

PLE, $\tau = 0.1$ Gyr

- $z_f = 1.9$
- $z_f = 2$
- $z_f = 2.5$
- $z_f = 3$
- $z_f = 10$
have morphologies and surface brightness profiles characteristic of dynamically relaxed spheroidals, whereas only 15-30% have irregular or disk-like morphologies [33,34] (see also [35]).

3 EROs as dusty starbursts and proto-ellipticals

The possibility that EROs were dust reddened starbursts with high far-IR luminosity was first explored by [36] who detected submm and mm continuum emission from HR10 (z = 1.44; [4]) and showed that such a galaxy is an ultraluminous infrared galaxy (ULIG; $L_{FIR} > 10^{12} L_\odot$). Strong CO emission was then detected by [17] implying a hydrogen molecular gas mass of $\sim 10^{11} M_\odot$. Such results demonstrated that a fraction of EROs are dust obscured ULIGs with star formation rates (SFRs) >> 100 M_\odot yr^{-1} (see also [38]).

Besides HR10, other EROs have been detected in the submm, and all of them displayed properties consistent with being ULIGs at even higher redshifts ($z_{\text{estimated}} \sim 2 - 5$) and with extreme SFRs up to $\sim 1000 M_\odot yr^{-1}$ [39,40,41,42]. Preliminary SCUBA results suggest that EROs with significant submm emission may be segregated among the objects with the most extreme colors [43] (e.g. $I - K > 6$, $R - K > 7$). Although preliminary, this seems in broad agreement with the HST results showing that EROs with irregular/merging-like morphologies (i.e. consistent with being dusty starbursts) have the tendency to have the reddest colors [33]. If confirmed, this would allow to disentangle dusty EROs from ellipticals on the basis of their colors.

If a fraction of massive ellipticals formed at early cosmological epochs through a short-lived starburst phenomenon, such a phase may have occurred in a dusty environment where the UV light from OB stars is absorbed by the dust grains and re-emitted in the rest-frame far-infrared, making them weak in the observed-frame optical and bright in the submillimeter ([4] and references therein). It is then intriguing to speculate whether the dusty EROs which have properties consistent with being ULIGs at $z > 2$ represent proto-ellipticals seen during their formation episode. A circumstantial evidence in favour of this comes from the similarity between the estimated comoving density of submm-selected galaxies with $S_{850\mu m} > 10$ mJy (which often have ERO counterparts) and that of present-day ellipticals with $L \geq 4L^*$ [42].

4 Conclusions and future work

The most recent results suggest that $z \sim 1 - 1.5$ ellipticals are probably the dominant population among the EROs selected at $K \sim 18-20$, whereas a minor, although significant, fraction is made by dust enshrouded ULIGs over a wide range of redshifts ($1 < z < 5$). Multiwavelength observations of complete samples are needed to establish the relative fractions of the galaxies forming the ERO population in order to constrain the evolution of massive
Extremely Red Objects and of their clustering, and to investigate the link between EROs and obscured AGN suggested by recent X-ray observations.

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