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LETTER

Letter to the Editor

EROs and the formation epoch of field ellipticals

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Abstract. A comparison is presented between the observed surface density of extremely red objects (EROs) and the densities of red high-z elliptical galaxies predicted by Pure Luminosity Evolution (PLE) and by some CDM hierarchical models. The analysis is based on the widest field survey for EROs available to date (covering in total ∼850 arcmin^2), and it takes into account the effects of ERO clustering. Good agreement is found between the observed surface densities of EROs and those predicted by PLE models for ellipticals selected using the same color and luminosity thresholds. Since there is evidence that the bulk of EROs are passively evolving ellipticals, this result implies that most field ellipticals were fully assembled at least by $z \sim 2.5$. Existing hierarchical models predict instead a surface density of red ellipticals that is much smaller than that of the EROs.

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

1. Introduction

The formation of elliptical galaxies remains one of the most controversial issues of galaxy evolution and structure formation. While there is now wide consensus that the bulk of stars in ellipticals formed at very high redshifts (see e.g. Renzini 1998 and the introduction of Schade et al. 1999 for recent reviews), opinions diverge as to the epoch at which ellipticals have been assembled to their present size and mass. In semianalytical simulations of hierarchical Cold Dark Matter (CDM) cosmologies (e.g. Kauffmann 1996; Baugh, Cole & Frenk 1996; Baugh et al. 1998) massive ellipticals form at relatively low redshift ($z < 1$) through the merging of spiral galaxies.

Empirical support for this scenario has been claimed from an alleged deficit of old ellipticals at $z \sim 1$ compared to pure luminosity evolution (PLE) models (Kauffmann, Charlot & White 1996, Zepf 1997, Franceschini et al. 1998, Barger et al. 1999, Menanteau et al. 1999, Treu & Stiavelli 1999). However, others found evidence for a constant comoving density of ellipticals up to $z \sim 2$ (Totani & Yoshii 1997, Benitez et al. 1999, Broadhurst & Bowens 2000, Schade et al. 1999; Scodeggio & Silva 2000), which would instead favor an early assembly of ellipticals, no matter whether in clusters or in the field. One obvious way to solve the issue is to search for putative high-z ellipticals over much larger fields than in previous studies. Passively evolving ellipticals in the redshift range $1 \lesssim z \lesssim 2$ are in fact characterized by very red colors ($R - K_{\rm s} \gtrsim 5 - 6$), which qualify them as extremely red objects (ERO).

In a recent study based on the largest survey for EROs to date, Daddi et al. (2000) reported the discovery of strong EROs angular clustering. This finding suggest that the origin of such discrepant results were definitively in the small fields covered by previous studies (ranging from ~ 1 to ~ 60 arcmin^2), which are likely to be affected by field-to-field variations in the number of intercepted large scale structures, hence in the number of red, color selected galaxies. Moreover, the strong clustering argues for the bulk of EROs being made by elliptical (Daddi et al. 2000) rather than starburst galaxies, that can have very red $R - K_{\rm s}$ colors as well (e.g. Cimatti et al. 1998). This agrees with independent indications that ellipticals are at least a fraction of $\sim$ 70% among EROs (Moriondo et al. 2000, Stiavelli & Treu 2000, Cimatti et al. 1999). Under this assumption, the surface density of EROs can therefore set strong constraints to models for the formation and evolution of elliptical galaxies.

In this Letter we present the results of the comparison between the observed surface density of EROs and the densities predicted by PLE and hierarchical models for the evolution of the elliptical galaxy population. Such a comparison is based on the results of our wide-field survey for EROs (Daddi et al. 2000) and on the Thompson et al. (1999) survey, covering a total area of about 850 arcmin^2 resulting in the selection of a total sample of several hundreds of EROs. In addition, the measurements of the angular clustering allow us to quantify for the first time the uncertainties on the surface density of EROs due to cosmic variance. For these reasons, our study represents a significant improvement respect to previous attempts. For example, the widest field analysis most recently done was based only on 16 EROs selected from an area of 60 arcmin^2 (Barger et al. 1999).

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2. Predicting the surface density of high-z ellipticals

The surface density of EROs (μ, in objects arcmin^{-2}) redder that a color threshold T, in a survey with limiting magnitude $K_{\rm LIM}$ is calculated as:

$$\mu = \int_0^\infty dz_{\rm f} \int_{z_{\rm a}(z_{\rm f},T)}^{z_{\rm b}(z_{\rm f},T)} dz \int_{-\infty}^{M_{\rm UP}} dM \; LF(M,z,z_{\rm f}) \frac{dV(z)}{dz} F(z_{\rm f})$$

where $F(z_{\rm f})$ describes the formation redshift distribution (for a single redshift of formation $z_{\rm f} = z_0$, $F(z_{\rm f}) = \delta(z_{\rm f} - z_0)$), $z_{\rm a}$ and $z_{\rm b}$ give the redshift range where the galaxy is redder than the threshold T (derived from the modeled $R - K_{\rm s}$ color vs. z), $M_{\rm UP}$ is the absolute $K_{\rm s}$ magnitude of the faintest galaxy detectable in the survey at a given z (calculated from $K_{\rm LIM}$ via the luminosity distance and the K–correction), $V(z)$ is the comoving volume intercepted by 1 arcmin^2 and LF is the luminosity function where $M^\star$ evolves consistently with z.

The following ingredients are required in order to compute μ in a PLE scenario: a spectral synthesis model, an IMF, a metallicity, a star formation history (i.e. how the initial burst is characterized and how the star formation rate evolves with time), a formation redshift $z_{\rm f}$, a local LF for elliptical galaxies, a dust reddening and, finally, a set of cosmological parameters. Our calculations are based on the Bruzual & Charlot (1997) spectral synthesis models with the Salpeter IMF, solar metallicity and no dust reddening. Following Barger et al. (1999), the Marzke et al. (1994) pure elliptical LF was used, transforming the magnitudes from the B to the K-band assuming $B - K = 4.43$ as the color of local ellipticals (Huang et al. 1998). The results discussed in the next sections do not significantly change by using instead a K–band LF (e.g., Loveday 2000; Szokoly et al. 1998; Gardner et al. 1997; Glazebrook et al. 1995; Mobasher et al. 1993), or the R–band LF (Lin et al. 1996) adopting $R - K \sim 2.7$ for local ellipticals and a fraction of ellipticals in those samples of 25–30% of the total population of galaxies. We adopt $\Omega_0 = 0.3, \Lambda = 0.7$, and $h_{100} = 0.7$, for which the present age of the universe is ~ 14 Gyr. A wide range of formation redshifts was considered, from $z_{\rm f} = 1$ to $z_{\rm f} = 30$. The star formation rate is assumed to decline exponentially following the beginning of a burst at $z = z_{\rm f}$, with a timescale $\tau = 0.1$ and 0.3 Gyr.

3. Comparison with the observations

The database consists of the Daddi et al. (2000) and of the Thompson et al. (1999) surveys. The first one is the widest survey for EROs so far and is made of a single mosaic centered at $\alpha = 14^{\rm h}49^{\rm m}29^{\rm s}$ and $\delta = 09^o00'00''$ (J2000); it is based on $K_{\rm s}$ and R band imaging and it is complete to $K_{\rm s} = 18.8$ over the whole area of 701 arcmin^2 and to $K_{\rm s} = 19.2$ over 447.5 arcmin^2. The latter survey is smaller (154 arcmin^2 centered at $\alpha = 16^{\rm h}24^{\rm m}33^{\rm s}$ and $\delta = 55^o43'59''$ (J2000)) but, being complete to $K' \sim 20$, it has been used to extend the magnitude range to deeper values, providing sufficient statistics.

EROs were selected using the color thresholds $R - Ks > 5.3$ and $R - Ks > 6$, which correspond to passively evolving ellipticals at $z \gtrsim 1$ and $z \gtrsim 1.3$, respectively (Daddi et al. 2000). An $L = L_*$ elliptical evolved at $z = 1$ and $z = 1.3$ would have $K_{\rm s} \sim 18.5$ and $K_{\rm s} \sim 19.2$, respectively, thus our samples consist of bright $L \approx L_*$ objects. Fig. 1 shows the resulting surface densities of EROs. After taking into account the different filters used, the Thompson et al. survey yields a surface density of EROs of 0.42 and 0.8 arcmin^{-2} for the $R - K_{\rm s} > 5.3$ samples with $K_{\rm s} < 19.2$ and $K_{\rm s} < 19.6$ respectively, and 0.4 arcmin^{-2} for the $R - K_{\rm s} > 6$ sample with $K_{\rm s} < 19.8$.

The use of such large surveys is of crucial importance to carry out a reliable comparison. In fact Daddi et al. (2000) showed that, as EROs are strongly clustered and large voids are present in their distribution on the sky, small field surveys can easily lead to wrong determinations of the ERO surface density and the probability of an underestimate is much larger than that of an overestimate. As an example of this effect, in the small (43 arcmin^2) Chandra/AXAF Deep Field South the surface density of EROs with $R - K_{\rm s} > 5$ and $K < 19$, derived by Scodeggio & Silva (2000), is a factor of 5 smaller than the one derived in the 700 arcmin^2 survey by Daddi et al. (2000), with the same color and magnitudes thresholds.

Given the clustering effect, error bars in the surface density of EROs are larger than the mere Poisson statistics for the number of objects. The extreme of error bars shown in Fig. 1 are obtained by solving for $\overline{n}$ the equation $(\overline{n} - N)^2 = \overline{n}(1 + AC\overline{n})$, where $\overline{n}$ and N are respectively the expected average and the observed number of ellipticals in the field, A is the clustering amplitude and C is a factor depending on the geometry (see Daddi et al. 2000 for more details). A direct measure of A for the EROs with $R - K_{\rm s} > 6$ is not available given the relatively small number of objects in the survey. We therefore used an extrapolation of the relation between A and $R - K_{\rm s}$ obtained by Daddi et al. (2000) for $3.0 \leq R - K_{\rm s} \leq 5.7$ and $K_{\rm s} < 19.2$. In order to estimate the clustering amplitude for the EROs with $K_{\rm s} > 19.2$ taken from the Thompson et al. survey, as it was suggested that A decreases with $K_{\rm s}$ (Daddi et al. 2000), we conservatively used the $K_{\rm s} \sim 19$ value, lowered by a factor of 2. Fig. 1 (panels a-b) shows the comparison between the PLE model predictions and the observed surface density of EROs.

- $R - K_{\rm s} > 5.3$: this color threshold corresponds to the selection of $z > 1$ passively evolving ellipticals, and the plots show good agreement, for the models with high formation redshift, between observed and predicted surface densities, i.e., the density of EROs is consistent with the expectation of PLE of local ellipticals. Models in which ellipticals formed at $z_{\rm f} < 2.5$ ($\tau = 0.1$ Gyr) or at $z_{\rm f} < 3$ ($\tau = 0.3$ Gyr) are ruled out because they strongly underpredict the density of EROs. The results do not significantly change if one assumes that a fraction up to 30% of the EROs with $R - K_{\rm s} > 5.3$ are dusty starburst galaxies, low mass stars, or brown dwarfs (the observed densities shown in Fig. 1 would decrease only by 0.15 dex).
- $R - K_{\rm s} > 6$: this color threshold corresponds to $z > 1.3$ passively evolving ellipticals. Only the models with $z_{\rm f} > 2.5$ ($\tau = 0.1$ Gyr) or with $z_{\rm f} > 3$ ($\tau = 0.3$ Gyr) succeed in reproducing the observed surface densities of EROs, also for this redder threshold. Fig. 1 shows that the densities predicted by the models with the highest $z_{\rm f}$ are generally higher than the

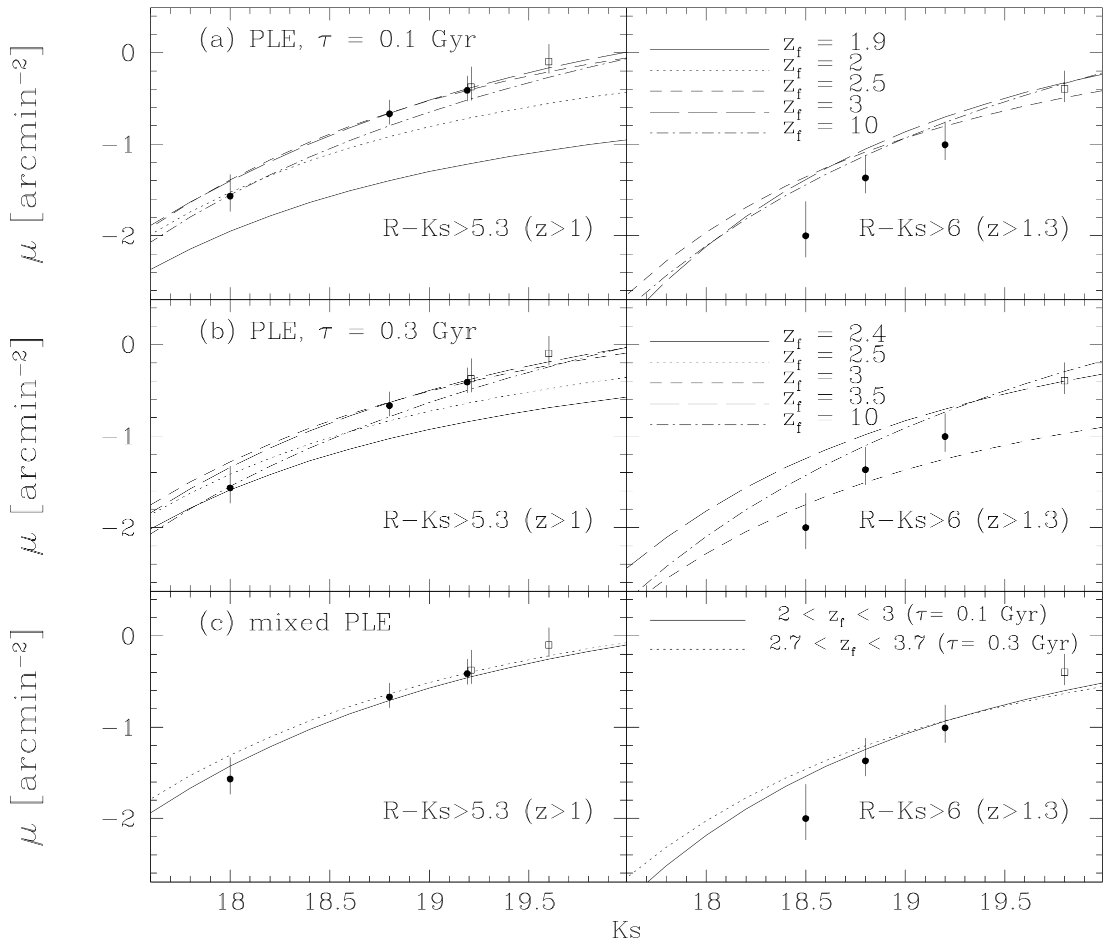

Fig. 1a–c. The three panels show the observed surface densities of EROs as derived from Daddi et al. (2000) and Thompson et al. (1999) surveys (filled circles and empty squares respectively). The curves show the predictions of the surface density of ellipticals with colors redder than $R-K_s=5.3$ (left) and than $R-K_s=6$ (right). Panel **a**: case of passively evolving stellar populations formed with $\tau=0.1$ Gyr, at $z_f=1.9, 2, 2.5, 3, 10$. Panel **b**: case of passively evolving stellar populations formed with $\tau=0.3$ Gyr, at $z_f=2.4, 2.5, 3, 3.5, 10$. Panel **c**: Predictions in the case ellipticals form at $2<z_f<3$ (for $\tau=0.1$ Gyr) and at $2.7<z_f<3.7$ (for $\tau=0.3$ Gyr). The comparison of the observations with the models is described in the text.

observed ones, but only at $\sim 1\sigma$ significance level. Our data do not allow us to conclude whether this is a real deficit of the reddest ellipticals, or if it is due to the poorer statistics with respect to the $R-K_s>5.3$ sample (typically ~ 40 objects with $R-K_s>6$ vs. ~ 200 with $R-K_s>5.3$).

Assuming that this deficit of $R-K_s>6$ ellipticals is real, this would imply that the formation redshift must be close to $z_f\sim 2.5$ (for $\tau=0.1$ Gyr) or $z_f\sim 3$ (for $\tau=0.3$ Gyr). To check this point we also tested a model where ellipticals formed with a constant rate per unit z in the range of $2<z<3$ ($\tau=0.1$ Gyr), or $2.7<z<3.7$ ($\tau=0.3$ Gyr). Fig. 1 (panel c) shows that this "mixed PLE" scenario provides a good agreement with the observations of the $R-K_s>6$ EROs.

These results do not significantly change in case of an open universe ($\Omega=0.1$, $\Lambda=0$, $h_{100}=0.7$) or for a flat universe ($\Omega=1$, $\Lambda=0$, $h_{100}=0.7$).

Existing semiempirical models of hierarchical galaxy formation imply a specific surface density of EROs to various limiting magnitudes. However, no such numbers have been explicitly calculated so far, which makes less straightforward the comparison with the observed number of EROs. According to Kauffmann et al. (1999, Fig. 9 and 10; see also Kauffmann & Charlot 1998b), in their τCDM model the number of massive ellipticals (stellar mass greater than $10^{11}M_\odot$) decreases by a factor of 3 by $z=1$ and by a factor of ~ 15 by $z=2$. Such massive ellipticals are brighter than $K=19$ for $1<z<1.5$ (Kauffmann & Charlot 1998a). Hence this specific realization greatly underpredicts the numbers of EROs compared to the empirical values. The comparison is less clear-cut in the case of the ΛCDM model model of Kauffmann et al. (1999), where the number of massive ellipticals decreases by only $\sim 30\%$ by $z=1$ and by a factor of ~ 3 by $z=2$. However, only a fraction of such *ellipticals* would qualify as EROs, given that in the adopted nomenclature they form by merging gas-rich spirals, with the gas being instantly converted into stars. Therefore, most such $1<z<1.5$ 'ellipticals' contain a significant fraction of young stars, likely to make them bluer than the color threshold for EROs.

4. Conclusions

A robust surface density of EROs has been obtained from a field that is at least ten times larger than in previous determinations, thus greatly reducing the influence of the strong field-to-field variations (cosmic variance), that we estimate given the known clustering properties of EROs (Daddi et al. 2000). This observed surface density of EROs is in fine agreement with the density of $z > 1$ ellipticals with the same color and luminosity thresholds as predicted by a PLE model in which the bulk of field ellipticals were already fully assembled at least by $z = 2.5$, and evolved passively thereafter. The agreement with the predictions of the PLE models remains good even if some 30% of EROs are not elliptical galaxies (e.g. dusty starburst galaxies). This result argues for much of the merging being already completed by $z \gtrsim 2$, in such a way to make elliptical galaxy formation mimicking the old monolithic collapse models.

A more thorough comparison with current realizations of hierarchical models of galaxy formation is hampered by the lack of published predictions for the surface density of EROs. In these models the number density of massive elliptical galaxies drops rapidly with redshift. It does so catastrophically in a τCDM model (Kauffmann & Charlot 1998b), which therefore can be readily excluded, unless only a very small fraction of EROs is made of passively evolving ellipticals. However, this would be in contradiction with the reported strong clustering properties of EROs (Daddi et al. 2000). Less dramatic is the comparison with a ΛCDM model, in which the number of ellipticals drops more gently with redshift. Nevertheless, we argue that also this model can hardly account for the observed number of EROs unless merging does *not* result in significant star formation, which is not the case in existing realizations. Future semianalytical models including specific predictions concerning the number densities of EROs would offer an interesting opportunity, as a comparison with the observed densities is expected to provide a stringent test for such models.

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References

Baugh C.M., Cole S., & Frenk C.S., 1996, MNRAS, 283, 1361
Baugh C.M., Cole S., Frenk C.S., Lacey C.G., 1998, ApJ, 498, 504
Barger A.J., Cowie L.L., Trentham N., Fulton E., Hu E.M., Songaila A., Hall D., 1999, AJ, 117, 102
Benitez N., Broadhurst T.J., Bouwens R.J., Silk J., Rosati P., 1999, ApJ, 515, L65
Broadhurst T.J., & Bowens R.J., 2000, ApJ, 530, 53
Cimatti A., Andreani P., Röttgering H., Tilanus R., 1998, Nature, 392, 895
Cimatti A., Daddi E., di Serego Alighieri S., et al., 1999, A&A, 352, L45
Daddi E., Cimatti A., Pozzetti L., Hoekstra H., Röttgering H.J.A., Renzini A., Zamorani G., Mannucci F., 2000, A&A in press, (astro-ph/0005581)
Franceschini A., Silva L., Fasano G., Granato L., Bressan A., Arnouts S., Danese L., 1998, ApJ, 506, 600
Gardner J.P., Sharples R.M., Frenk C.S. & Carrasco B.E., 1997, ApJL, 480, 99
Glazebrook K., Peacock J.A., Miller L. & Collins C.A., 1995, MNRAS, 275, 169
Huang J., Cowie L.L., & Luppino G.A., 1998, ApJ, 496, 31
Kauffmann G., 1996, MNRAS, 281, 487
Kauffmann G., Charlot S., 1998a, MNRAS, 297, L23
Kauffmann G., Charlot S., White S.D.M., 1996, MNRAS, 283, 117
Kauffmann G., Charlot S., 1998b, proceedings of the Xth Rencontres de Blois, "The Birth of Galaxies" (astro-ph/9810031)
Kauffmann G., Colberg J.M., Diaferio A., White S.D.M., 1999, MNRAS, 307, 529
Lin H., Kirshner R., Shectman S.A., Landy S.D., Oemler A., Tucker D.L., Schechter P.L., 1996, ApJ 464, 60
Loveday J., 2000, MNRAS, 312, 557
Marzke R.O., Geller M.J., Huchra J.P., Corwin H.G. Jr., 1994, AJ, 108, 437
Menanteau F., Ellis R.S., Abraham R.G., Barger A.J., Cowie L.L., 1999, MNRAS, 309, 208
Mobasher B., Sharples R.M. & Ellis R.S., 1993, MNRAS, 263, 560
Moriondo G., Cimatti A. & Daddi E., 2000, A&A in press
Schade D., et al., 1999, ApJ, 525, 31
Renzini A., 1998, in "When and How do Bulges Form and Evolve?", ed. by C.M. Carollo, H.C. Ferguson & R.F.G. Wyse (Cambridge University Press)
Scodeggio M., Silva D., 2000, A&A, in press (astro-ph/0004228)
Stiavelli M., Treu T., 2000, proceedings of the conference "Galaxy Disks and Disk Galaxies", ASP conference series, Funes and Corsini eds
Szokoly G.P., Subbarao M.U., Connolly A.J. & Mobasher B., 1998, ApJ 492, 452
Thompson D., et al., 1999, ApJ, 523, 100
Totani T., Yoshii J., 1997, ApJ, 501, L177
Treu T., Stiavelli M., 1999, ApJ, 524, L27
Zepf S.E., 1997, Nature, 390, 377