The Morphology of Extremely Red Objects

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Abstract. We briefly discuss our survey of Extremely Red Objects (EROs) with HST/NICMOS and deep ground-based images and summarize its results. We use the high-resolution NICMOS images to sub-divide EROs into morphological classes, tentatively arguing that about 60% of EROs (18 out of 30) are early-type galaxies. About 20% (6 out of 30 objects) appear to be flattened disk systems. Another 10% (3 out of 30) have an irregular morphology. Thus, combining disk and irregular systems, our data are compatible with 30% of EROs being dusty starbursts. A small fraction (3 out of 30) appear point-like even on the HST images and could therefore be either compact high redshift galaxies or stars in the Milky Way halo.

1. Introduction

The advent of high quality near-infrared detectors has allowed a veritable breakthrough in the study of extremely red objects (hereafter EROs), i.e., galaxies characterized by $R - K$ colors of 5 or redder. Clearly, a natural interpretation of their red colors is that EROs are elliptical galaxies with relatively old stellar populations at a redshift between 1 and 2. This has been confirmed by Spinrad et al. (1997) for the ERO with regular morphology LBDS 53W091. However, Graham & Dey (1996) have shown that another ERO, HR10, actually has a spectrum with emission lines. Cimatti et al. (1998) definitely confirmed the dusty nature of HR10. Clearly, on the basis of colors alone it is not possible to discriminate between a dusty starburst or an old stellar population at $z > 1$. On the other hand, spectroscopy of a large sample of EROs is, unfortunately, prohibitive even with 8-meter class telescope (e.g., Cimatti et al. 2000).

One important difference between LBDS 53W091 and HR 10 is their morphology. At HST resolution, the former appears regular while the latter has an irregular morphology. This has led us to adopt as a working hypothesis the assumption that morphology with HST can help identify the nature of EROs. Therefore, we have carried out a survey of EROs in fields where HST/NICMOS images were available. In Section 2, we describe our survey and some basic results. Section 3 is devoted to a discussion of morphologies. Section 4 sums up.
Figure 1. We plot the observed luminosity function of candidate high-redshift elliptical galaxies (HiZECs) at $z \geq 1$ (hexagons) and $z \geq 1.5$ (triangles) as a function of observed magnitude in the F160W filter. The data are compared to the luminosity function obtained for local early-type galaxies formed as a single burst of star formation (solid line for $z \geq 1.5$, dashed line for $z \geq 1.0$). The left panels and the right panels refer to different cosmologies. Each panel lists the formation redshift ($z_f$) and the fraction of early-type galaxies required to fit the data.

2. An ERO survey with HST/NICMOS

We have carried out a survey of EROs over an area of 13.74 arcmin$^2$ using HST/NICMOS F160W images, for a total of 23 fields. We have complemented the near-IR data with either WFPC2 F606W images or ground-based R-band images (see Treu & Stiavelli 1999, hereafter TS99, for more details). We built a number of Bruzual & Charlot (1993, and 1996 unpublished) models to assess the range of colors displayed by a variety of star formation histories. We focussed on two star formation histories that may be relevant for high-redshift elliptical galaxies: i) a stellar population 1 Gyr old at any given redshift, and ii) a stellar population formed as a single burst at $z=10$. EROs were selected according to two color criteria determined on the basis of these models. The first, broader, criterion is aimed at selecting elliptical galaxy candidates at $z \geq 1$ and defines our basic ERO sample. Its color criteria are $R-H_{160} > 3.2$ and $V_{606}-H_{160} > 3.8$ (here and in the following we will use magnitudes in the AB system.) The second criterion selects candidate elliptical galaxies at $z \geq 1.5$ and corresponds to $R-H_{160} > 4.0$ and $V_{606}-H_{160} > 4.5$.

We have identified a total of 30 EROs. The completeness of our data set was verified by carrying out a large set of Montecarlo simulations showing that at the faintest level we are still more than 90 per cent complete. The luminosity
function that we derive extends down to $H_{160} = 24.5$ (only for a fraction of the field, see TS99 for a detailed list of the area covered at each depth.) At this depth we detect $\sim 3 \pm 1$ EROs arcmin$^{-2}$.

Each ERO was morphologically classified by visual inspection independently by the two authors. In general there was a good agreement between the two independent classifications by the authors but in four cases there was a discrepancy. These cases were looked in more detail until a common classification could be agreed upon. The final breakdown of morphologies are given in Table 1. Those objects classified as early-type galaxies (E/S0) were then used to derive a luminosity function to be compared with the one observed at low redshift under the assumption of passive evolution. The number density of regular EROs in our survey at the limit of $H_{160} = 24.5$ is $\simeq 2 \pm 0.5$ arcmin$^{-2}$. The derived luminosity function is compared to the observed one in Figure 1. The number of red galaxies that we find requires the early formation of at least some early-type galaxies. However, our data do not support the formation at high-redshift of all early-type galaxies, i.e. we see a deficit of red galaxies. Each panel in the figure indicates the fraction of early-type that could have formed at the given redshift. This fraction ranges from 15 to 66 per cent depending on cosmology and formation redshift (TS99). This discrepancy could be interpreted in a number of ways:

i) all ellipticals are already in place at high redshift but we are only seeing those that have not been polluted by younger populations. In fact, only a very modest fraction of young stars would be sufficient to make an elliptical appear bluer than our selection criteria;

ii) only some of the early-type galaxies were in place at $z \geq 2$. As an example, lenticular galaxies could have formed later while giant ellipticals were already present at $z = 2$;

iii) our error bars are underestimated due to the clustering of EROs seen, e.g. by Daddi et al. (2000), and our results are thus compatible with all early-type galaxies forming at high redshift.

Clearly it is difficult at this stage to determine which of these alternatives (or their combinations) is correct. However, our data strongly suggest that at least some elliptical galaxies were already in place at relatively high redshift.

3. Morphologies

In the course of our morphological analysis we have binned EROs in four classes: i) E/S0, characterized by regular morphology, ii) disk, characterized by high apparent flattening, iii) irregular, and iv) point-like. The point-like objects could be red stars in the Milky Way halo, small elliptical galaxies, or compact regions embedded in low surface brightness objects. The number of point-like objects that we detect (3) is well within the limits expected for brown dwarfs in the Galactic halo (e.g. Flynn et al. 1996).

In the analysis of the luminosity function of early-type galaxies we have included only those objects belonging to the E/S0 category. Clearly there could be a contamination introduced by face-on disk EROs. However, the E/S0 EROs tend to be characterized by a $R^{1/4}$ light profile (e.g. Stiavelli et al. 1999); this is in contrast to the low redshift luminous disk galaxies none of which has an
4. Discussion and Conclusions

Our results suggest that some early-type galaxies were in place at high redshift. We detect a deficit of red objects which may imply either that some early-type galaxies formed later, or that observational effects or interactions intervene to make the colors bluer and thus cause some early-type galaxies to drop from the E/S0 ERO sample.

We find a number density of about 0.5 arcmin$^{-2}$ (at $H_{160} = 24.5$) of EROs that appear to be as flattened as a disk. They could be massive disks already in place at $z > 1$. We expect these objects as well as the irregular EROs to be characterized by a dusty starburst spectrum.

The major limitation of our study is the relatively small area of the survey especially in light of the large field-to-field fluctuations discovered by Daddi et al. (2000) for the bright-end of the ERO distribution. For this reason, we are planning to increase the area of our survey by a factor four in the near future.

References

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