Chapter 1

Introduction

The reddest populations of galaxies are of great interest for the study of galaxy formation and evolution because they show one of the most extreme aspects in the history of galaxy and structure formation. A population called **E**xtremely **R**ed **O**bjects (EROs) has been identified, showing very red optical-to near-infrared (NIR) colours, either because of old populations or severe dust reddening. Both effects are intensified by the intermediate to high redshift of these objects.
The aim of this work is to detect and to classify a sample of very bright, i.e. massive galaxies with extremely red colours, R-J$\geq$5. Although they are usually very faint in the optical, their bright J-band magnitudes will make them suitable candidates for spectroscopic follow-up observations. In addition to theoretical predictions to the nature of these galaxies, we applied a photometric method on multi-colour observations of pre-selected EROs, to separate between the two major ERO populations.

Usually defined by colours with R - K $>$ 5-7 or I - K $>$ 4-6, these galaxies have been widely studied since their discovery by Elston, Rieke & Rieke (1988, 1989). These first detections of EROs were initially presumed to be high-redshift (z$>$6) galaxies in a luminous star-forming phase (Elston et al. 1988). Multi-colour follow-up observations later identified these objects as luminous galaxies at z=0.8, dominated by an old stellar population (Elston et al. 1989).
The detection of two bright (K $\gtrsim$ 18.4) extended objects (HR10 & HR14) with (I-K) colours near 6.5 by Hu and Ridgway (1994) highlighted the difficulty in classifying these galaxies. When first discovered, HR10 and HR14 were interpreted as being ellipticals at z $\sim$ 2.4. Subsequent spectroscopic and morphological observations indicated that HR10 is not a quiescent elliptical galaxy, but rather a bright interacting galaxy at z = 1.44 (Graham and Dey 1996). Additional EROs, both massive old ellipticals and dusty interacting galaxies, were found by various groups (Cowie et al. 1994, Soifer et al. 1999, Thompson et al. 1999, McCracken et al. 2000, Afonso et al. 2001, Cimatti et al. 2002a). These objects appeared in the field of quasars (Liu et al. 2000, Hall et al. 2001, Smith et al. 2002), as counterparts of sub-millimeter galaxies (Smail et al. 1999, Mohan et al. 2002), and in dedicated surveys (Daddi et al. 2002, Cimatti et al. 2002b, Gilbank et al. 2002).

The determination of the nature of EROs and their density is important, since EROs provide valuable clues to structure formation on large scales. For many years the view was held that elliptical galaxies formed the bulk of their stars in a single, explosive burst of star formation at high redshift, after which their stellar population evolved passively (e.g. Tinsley and Gunn 1976). The discovery of a number of old elliptical galaxies at high redshift lends weight to this hypothesis (Dunlop et al. 1996). Furthermore, Ellis et al (1997) found that the scatter in the colour-magnitude relation of elliptical galaxies (also referred to as early-type galaxies) is very small in clusters at z$\sim$0.5, suggesting that the bulk of the star formation occurred at z>3. In the field, however, the situation is more uncertain. Abraham et al. (1999) argue that many early-type field galaxies have experienced a major phase of star formation since z=1.

If most elliptical galaxies formed at very high redshift (z>3), this would be in agreement with the monolithic collapse scenario expected in both the isocurvature cold dark matter (ICDM) (Peebles 1999) or warm dark matter models (Moore et al. 1999). Both predict the assembly of elliptical galaxies at z>3 in single collapse events.

This is in stark contrast with the hierarchical CDM models of galaxy formation, in which typical elliptical galaxies form from the merging of smaller-sized galaxies at lower redshifts (Figure 1.1) (Baugh et al. 1998, Kauffmann 1996).

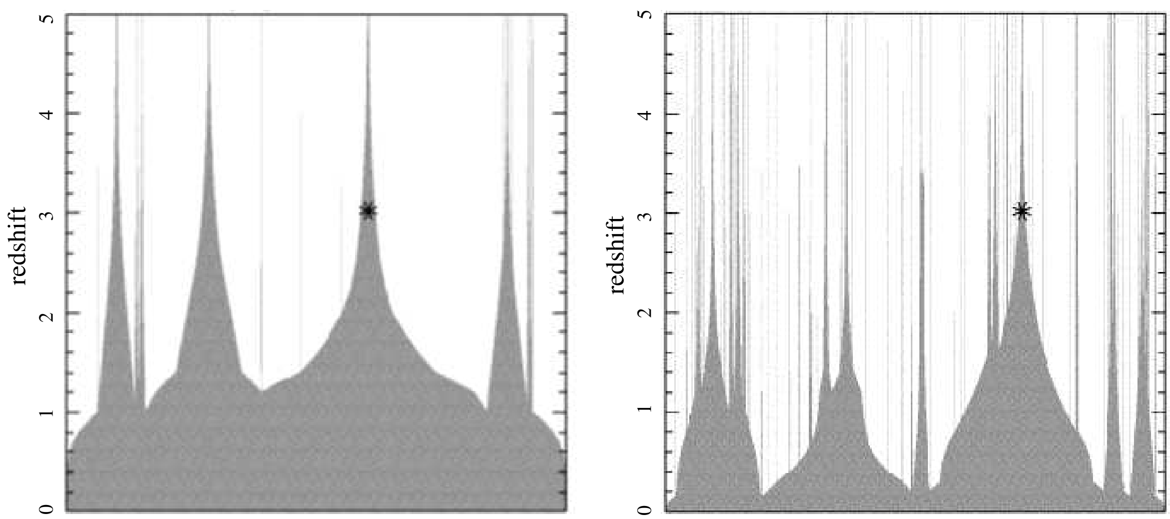

Figure 1.1: The diagrams illustrate the star formation histories for present day ellipticals with high-redshift progenitors. The left panel shows the star formation history for a field galaxy being at the border between being an elliptical or S0 galaxy, the right panel for a cluster elliptical. The actual progenitor is marked by a star. The present day is at the base of each tree; the trees extend back to redshift 5.The width of each branch at any epoch is proportional to the mass in stars in the branch at that redshift. The image was taken from Baugh et al. 1998.

In a pure monolithic scenario, with no merging history but rather pure luminosity evolution, the co-moving volume density of massive galaxies is the same as today (Pozzetti et al. 1996, He and Zhang 1998), while hierarchical formation models (White and Rees 1978, Kauffmann et al. 1993, Somerville et al. 2001) predict a significant decline in the co-moving density

of massive galaxies with increasing redshift.
Observational evidence has been found for both scenarios: several surveys detected a deficit of ellipticals at z >1, supporting the hierarchical merging models (Roche et al. 2002 & 2003, Nagashima et al. 2001, Bell et al. 2004), while others found good agreement between the observed N(z) distribution and the PLE model (Cimatti et al. 2002b, Im et al. 2002).

Like all other structures in the universe, EROs are not evenly distributed but rather show an inhomogeneous spatial distribution. As long as the surveys covered relatively small fields, this could be attributed to low number statistics. However, the results from Daddi et al. (2000) and Roche et al. (2003) show that EROs are strongly clustered, even more so than present-day L $>L^*$ ellipticals, and that the different surface densities of EROs are the result of field-to-field variations, i.e. large-scale structure.
The clusters, filaments and voids of galaxies reflect the initial fluctuations at recombination, plus any further evolution as predicted by 'Hot Dark Matter' (HDM)' or 'Cold Dark Matter' (CDM) models. HDM and the *top-down* scenario predict smooth, weak features in the large scale distribution of galaxies, while CDM and the *bottom-up* scenario predict sharp features with weak connecting filaments.

Strategies to distinguish the different extragalactic ERO types include near-infrared photometric classification (Pozzetti and Mannucci 2000, Mannucci et al. 2002, Pierini et al. 2004), morphological tests (Yan et al. 2000 & 2003, Moriondo et al. 2000), and an increasing number of spectroscopic discriminators (Cimatti et al. 2002a, Smith et al. 2001). Near-infrared spectroscopy of 9 EROs (R-K > 5 and K < 19.0) by Cimatti et al. (1999) showed neither strong emission lines nor continuum breaks. Two of their observed EROs were classified as dusty starburst candidates, because they require strong dust reddening to produce the observed global spectral energy distributions. The remaining $\sim 2/3$ of the total ERO sample, is consistent with being dustless, old, passively evolved, spheroidals at z $\gtrsim 0.8$. A larger sample of 30 EROs with K ≤ 19.2 showed an almost equal distribution between old and star forming galaxies (Cimatti et al. 2002a).

High signal-to-noise spectroscopy is certainly the most useful of the discriminators, providing accurate redshifts and enough spectral information to assign an ERO to one galaxy population. Nevertheless, even with the availability of 8 and 10 m telescopes and the Hubble Space Telescope, the growing number of EROs and their faintness, especially in the optical, make spectroscopic studies on a statistically significant ERO sample difficult. The photometric methods, first introduced by Pozzetti & Mannucci (2000), and later extended by Pierini et al. (2004), are based on the difference in the distribution of modelled ellipticals and dusty starbursts at $1<z<2$ in the I-K (or R-K) versus J-K colour-colour diagram. This separation is mainly due to the fact that passively evolving, old stellar populations at these redshifts have their steep 4000-Å break redshifted between the optical and near-infrared bands, while coeval dusty galaxies show smoother SEDs and therefore redder observed J-K colours, whatever the dust/star configuration.

However, morphological and photometric observations in recent years indicate that the ERO population is perhaps more complex than previously considered (Miyazaki et al. 2003, Yan and Thompson 2003, Moustakas et al. 2004). Yan & Thompson (2003) visually classify both pure bulge or disk galaxies and bulge or disk-dominated galaxies, using HST/WFPC2

F814W and K_s band images of 115 EROs. They find that 30% ±5% of the (F814W-K_s $\geq$ 4) selected sample have morphologies consistent with a pure-bulge dominated galaxy (E/S0), while 64% ±7% of the sample can be described as disks (see Figure 1.2). Similar relative fractions of early and late type galaxies were found among a sample of 275 EROs (R-K$\geq$5), detected in the Great Observatories Origins Deep Survey-South (GOODS-South) (Moustakas et al. 2004).

Optical spectroscopy on a sub-sample of 36 sources (Yan et al. 2004) revealed a more complicated relation between spectral class and morphological appearance. Half of the 22 sources with redshift information were found to have [O_{II}] λ3727 emission, while the remaining 50% are pure absorption-line systems. Both spectral classes have an equal mix of bulge-and disk-dominated galaxies. Hence, there appears to be no direct correspondence of spectral class with the morphological type.
Hard X-ray observations are especially useful for detecting AGNs among the ERO population. A fraction of 10%-30% of hard X-ray sources could be associated with EROs, depending on the limiting fluxes reached in the optical and the X-ray band (Brusa 2003). The fraction of AGN among the optically detected EROs is still unclear, but possibly below 15 %, suggesting that the majority of EROs are not related to active phenomena. A similarly low fraction of EROs have been found in the soft X-ray band, indicating either a low-luminosity AGN or starburst activity (Brusa 2003, Alexander et al. 2002).
EROs, especially the dusty starburst population, contribute significantly to the 850μm background (Wehner et al. 2002), pointing to a connection to sub-millimeter galaxies (SMG). Their near-infrared colours range from J-K=2 for bright sources (K<19) to extremely red (J-K=3) for fainter SMG (Frayer et al. 2004).

Since EROs are rare and clustered, wide field surveys are essential for studies of statistical properties of high-redshift early-type galaxies, such as number density. Furthermore, because EROs are a mixture various galaxy populations, it is necessary to apply a colour criterion which solely selects passive evolved galaxies.
The description of our survey will follow in chapter 2. An introduction to the colour-colour properties of **E**xtremely **R**ed **G**alaxies and the importance of a R-J$\geq$5 colour selection is given in chapter 3. In chapter 4 we present the results of our wide field survey, regarding the surface density and spatial distribution. Chapter 5 presents preliminary results from multicolour observations with the ISAAC instrument.

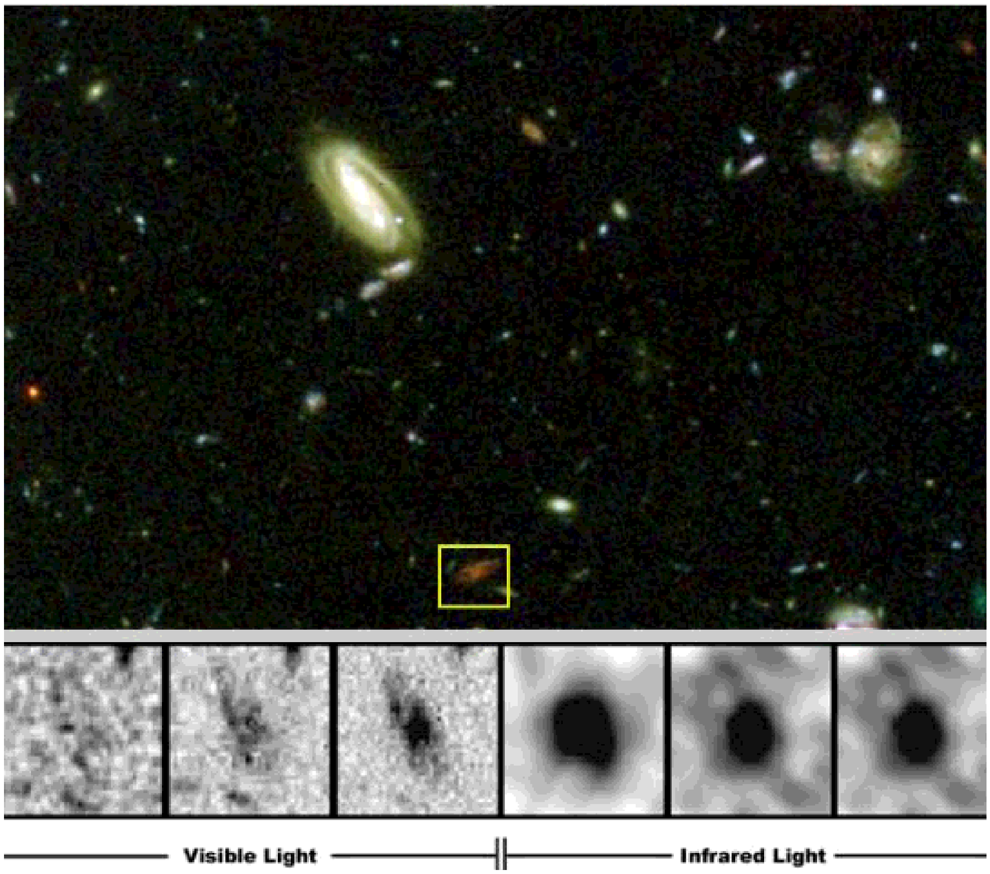

Figure 1.2: This ERO (yellow box) was discovered in the Hercules Deep Field, it might owe its extreme colour to a thick layer of dust which reddens the regions of star formation near the centre.
Credit: J.Colbert, M.Rich, M.Malkan (UCLA), J.Frogel, S.Salim (Ohio State)
HST data from R.Windhorst (ASU), W.Keel (Univ. Alabama).
NASA: Astronomy picture of the day, 17th January 2002