Chapter 6

Summary and Outlook

This chapter contains a summary of the results on the abundance and classification of extremely red galaxies, with an optical to near-infrared colour of R-J$\geq$5. We will also discuss, how our results fit in with to the predictions of Cold Dark Matter models of structure formation.
Section 6.3 will summarise the analysis of multi-colour observations, especially in the context of the classification of EROs, defined by a R-K$\geq$5 colour criteria.

6.1 Wide-field Survey for EROs with R-J$\geq$5

We have carried out a wide-area multi-field (79) survey to search for extremely red galaxies, with optical to near-infrared colours redder than R-J$\geq$5. After analysing $\sim$ 4.5 square degree of combined R and J-band data, we have identified 160 such galaxies, yielding a surface density of $(0.97 \pm 0.07)\times 10^{-2}$ arcmin^{-2} to J$\sim$ 20.5. This corresponds to a co-moving volume density of $(4.71 \pm 0.37)\times 10^{-5}$ h_{70} Mpc^{-3}, assuming a redshift interval of 1.4$\leq$z$\leq$3.

The results of stellar synthesis models, suggest that galaxies with extreme red colours (R-J$\geq$5) are evolved ellipticals, whose stars formed at redshifts above z=3. This does not imply that the formation of massive spheroidals occurred necessarily through an old fashioned “monolithic” collapse, but it simply constrains the epoch when the formation took place, and it implies that, if ellipticals formed through merging, this occurred at z>3.
However, if these EROs are preferentially found in clusters, this statement has to be put into perspective. The stars of early-type galaxies could be old, while the early-types themselves have been assembled relatively recently. This agrees well with hierarchical galaxy formation models predicting that massive field ellipticals are several Gyr younger than cluster ellipticals, because galaxy formation is accelerated in dense environments (Kauffmann 1996).
Galaxies dominated by evolved stars are least affected by the details of recent star formation and therefore allow the most reliable measurements of accumulated stellar mass. Consequently, these evolved galaxies are particularly useful in discriminating between galaxy formation scenarios.

Why are extremely red galaxies so effective for constraining different models of galaxy formation and evolution? In the Cold Dark Matter (CDM) model of structure formation, lower mass objects form first, and larger mass objects form hierarchically through mergers and accretion. Therefore, measurements of the number density of massive structures at high redshift put strong constraints on this class of models. These models should be able to produce enough high mass dark matter halos to harbour the observed number of massive galaxies at a given redshift.

Somerville (2004) predicted the cumulative number density of dark matter halos above a given mass, from 10^{11} - 10^{15} $M_{\odot}$, as a function of redshift (Figure 6.1).
Making the assumption that about 15% of the total mass is in the form of baryons, and a few tens of percent of the baryons are in stars, one can easily accommodate the observed number of $10^{11} M_{\odot}$ mass objects, such as sub-mm galaxies (blue starsymbols in Figure 6.1, Chapman et al. 2003) or EROs (open square, Moustakas et al. 2004) within dark matter halos of $10^{13} M_{\odot}$. In comparison, we have added the calculated co-moving volume density for our EROs sample (red dots), having colours redder than R-J$\geq$5. The points are placed in the centre of the assumed redshift interval, $1.4 \leq z \leq 2$ or $1.4 \leq z \leq 3$ (see section 4.3.2).

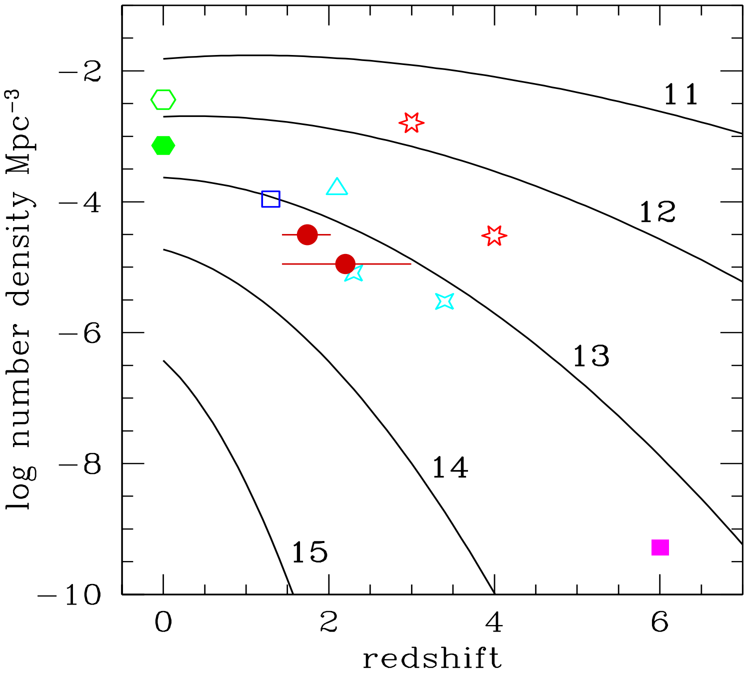

Figure 6.1: Comparison of the cumulative number density of dark matter halos more massive than 10^{11}, 10^{12}, 10^{13}, 10^{14} and 10^{15} $M_{\odot}$ (from top to bottom, as labelled), as function of redshift. The two red dots show the estimated co-moving volume density for EROs with R-J$\geq$5, assuming either a redshift interval of $1.4 \leq z \leq 2$ or $1.4 \leq z \leq 3$. The red lines indicate the assumed redshift range, $1.4 \leq z \leq 2$ and $1.4 \leq z \leq 3$, respectively. The Figure is adopted from (Somerville 2004), containing also the references for the observational results.

The observed co-moving volume density of EROs (R-J$\geq$5) in conjunction with Somerville's (2004) models suggest that these galaxies live in halos of $\approx 10^{13.3}$ $M_{\odot}$. At the present epoch, this co-moving density corresponds to galaxies with a stellar velocity dispersion of $\approx$ 340 km s^{-1} (Sheth et al. 2003). Although the size of the co-moving volume changes by a factor of 2 between the two redshift intervals, it is not the major factor for this conclusion.

The number EROs per field is not sufficient to calculate the angular correlation or cluster amplitudes, as demonstrated for EROs with R-K$\geq$5 by Daddi et al. (2000) and Roche et al. (2002). Nevertheless, the observed apparent inhomogeneous spatial distribution of EROs among our 79 survey fields, suggests them to be good tracers for galaxy clusters.

6.2 Using the R-band galaxy number count - magnitude relation for photometric zero-point calibration

At this point, we should make some remarks about the problems encountered using the number count magnitude relation, calculated by Metcalfe et al. (1991), for calibrating the R-band photometry. Although the relation is not designed for this purpose, it will be interesting to see what causes the sometimes large offsets in R-band magnitudes (on average 0.53^{mag}), based on the Metcalfe result and the calibration with SDSS photometry. As we have demonstrated, this offset is not explained by limited accuracy of the observed number counts, since the offset has always the same direction, meaning the zero-points calculated with the Metcalfe relation are always too faint.

From the tested parameters, only the surface density of galaxies in the magnitude range between $20 \leq \mathrm{R} \leq 23$ seems to be related to the observed magnitude offset. However, using the galaxy surface density to correct the R-band magnitudes introduces additional errors, which can be avoided using the photometry of SDSS sources to calibrate our optical data.

6.3 The ISAAC sample - abundances and classification of R-K$\geq$5 EROs

The first analysis of our data set was used to select a small number of EROs for multi-colour follow-up observations with the near-infrared camera ISAAC at the VLT. The observations include higher resolution imaging in the J_s - and K_s-band, which substituted the J-band observations with OmegaPrime (Calar Alto).

In the 6 observed fields, covering approximately 27.1 deg^2, we found 15 objects with R-K$\geq$5. Considering statistical uncertainties due to the small area, the calculated surface density of (0.55 ± 0.14) arcmin^{-2}, agrees well with the result of Daddi et al.(2000).

Thirteen of these objects were also found in the J-band, allowing their classification as old ellipticals or dusty starbursts, based on the classification scheme of Pozzetti & Mannucci (2000). The separation of these populations in the R-K *vs.* J-K colour plane indicates that three objects are dusty starbursts, while the remaining 10 are ellipticals with an evolved stellar population.

Including statistical errors, this confirms the findings of Cimatti et al. (1999) and Moriondo et al. (2000), that EROs with K<19 are dominated by elliptical galaxies.

6.4 Outlook

Our wide-field survey has provided a number of extremely red galaxies with colours redder than R-J=5. Stellar synthesis models predict these galaxies to be massive galaxies with an evolved stellar population at redshift 1.4 and above. Nevertheless, there are still questions to be addressd:

- Does the spectral energy distribution confirm the nature of our EROs?
- How does the volume density of EROs evolve with redshift?
- Which model of galaxy formation and evolution describes the number count distribution best?
- Do we find these massive galaxies in the centre of a galaxy cluster?

Before we can draw any further conclusions about the abundance of the ERO population, we have to confirm their nature as evolved elliptical galaxies. This would involve either obtaining high signal-to-noise spectra or using the proposed colour-colour classification of Pozzetti & Mannucci (2000), Pierini et al. (2004), or Bergström & Wiklind (2004) (see also chapter 3).

We have seen in Figure 6.1, that the calculated volume density does not support or exclude either one of the two scenarios for the formation of massive galaxies.
In order to test whether or not the 'concordance' ΛCMD model produces enough massive dark matter halos to plausibly host the objects that have been detected, we have to calculate the volume density in smaller redshift intervals.

The example of R-K $\geq$5 selected EROs has shown that the predictions of galaxy evolution models, such as pure luminosity evolution (PLE) or Hierarchical Merging Models (HMM), are not unique. Various authors report consistency with both PLE models (e.g Väisänen and Johansson 2004, Cimatti et al. 2002b) and merging models (Roche et al. 2002). The future will show whether or not our ERO sample can put some constraints on the available parameter space, such as merging fraction, redshift of formation, and co-moving volume density.

In general, redshifts are measured spectroscopically, by comparing the observed wavelength of an emission or absorption line with the rest frame wavelength of this line. However, to obtain spectroscopic redshifts for a significant number of our ERO sample would be very time consuming, although the time factor becomes less important with the increasing availability of multi-object spectrographs. Nevertheless, imaging detectors usually cover a greater area of the sky, i.e. the photometric redshifts of more objects can be measured simultaneously.

First multi-colour observations should concentrate on EROs found in high density areas. If these galaxies are really the most massive ones in a galaxy cluster, than deep follow-up observations should also reveal fainter members of the cluster. Almost constant photometric redshift estimates for the members of a cluster would support this interpretation.