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# Evolution of Luminous Red Galaxies based on SDSS data

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**Abstract**
We compared the broadband colors of different simulated galaxies with $\sim 10^5$ luminous red galaxies from the Sloan Digital Sky Survey to obtain constraints for the possible star formation histories of this type of galaxies. The simulation was done using the GALAXEV evolutionary stellar population synthesis code. Our results are consistent with these objects having solar metallicities, having formed 11 Gyr before present and evolving passively, without significant star formation since then.
**Keywords:** *Galaxies: evolution*

## 1 Introduction

The Sloan Digital Sky Survey (York et al., 2000) contains a large set of luminous, red galaxies. Their study can be important for a number of scientific goals. The evolution of these systems is a probe of galaxy formation theories. They are strongly correlated with clusters, making them an ideal tool for detecting and studying clusters. Finally, they are among the most luminous galaxies of the Universe, and sample large cosmological volumes, interesting for the study of large scale structure.

## 2 The data

The SDSS is a photometric and spectroscopic survey using a 2.5-m telescope, mapping $\pi$ steradians of the sky. It has as of yet photographed 180 million objects using five broadband filters – $u$, $g$, $r$, $i$, $z$ (Fukugita et al., 1996) – and took spectra of some of them, including 560 000 galaxies. Eisenstein et al. (2001) selected a sample of luminous red galaxies (LRGs) on the basis of color and magnitude to yield a sample of luminous intrinsically red galaxies. We used a sample of LRGs from the latest SDSS data (Adelman-McCarthy et al., 2006), using the same color cuts, that is *Cut I* for $z \lesssim 0.4$:

$$r_{\mathrm{Petro}} < 13.1 + c_{\parallel}/0.3 \tag{1}$$

$$r_{\mathrm{Petro}} < 19.2 \tag{2}$$

$$|c_{\perp}| < 0.2 \tag{3}$$

$$\mu_{r,Petro} < 24.2 \mathrm{mag\ arcsec}^{-2} \tag{4}$$

$$r_{\mathrm{PSF}} - r_{model} > 0.3, \tag{5}$$

where (1) and (2) are luminosity tresholds, (3) selects the galaxy locus, (4) constrains the surface brightness and (5) is for star-galaxy separation, and

$$\mu_{r,Petro} = r_{Petro} + 2.5 \log_{10}(2\pi R_{50}^2)$$
$$c_{\perp} = (r - i) - (g - r)/4 - 0.18$$
$$c_{\parallel} = 0.7(g - r) + 1.2((r - i) - 0.18).$$

Similarly the sample can be extended with an other color selection for $z \gtrsim 0.4$, *Cut II*:

$$r_{\mathrm{Petro}} < 19.5$$
$$c_{\perp} > 0.45 - (g - r)/6$$
$$g - r > 1.30 + 0.25(r - i)$$
$$\mu_{50} < 24.2 \mathrm{mag\ arcsec}^{-2}$$
$$r_{\mathrm{PSF}} - r_{\mathrm{model}} > 0.5.$$

These selections, after rejecting some outliers, leave us with 120 000 LRGs, with redshifts $0 < z < 0.6$. However, since they are based on color cuts, and we're about to derive conclusions precisely from the colors of these objects, it seems approproate to create a control sample with a different method. For not too far galaxies we can select a sample of early type galaxies using morphological and spectral criteria according to Bernardi et al. (2003):

- $C = r_{90}/r_{50} > 2.5$ in $i$ (concentration index) [1]
- $L_{DeV} > 1.03 L_{Exp}$ (de Vaucouleurs fit vs. exponential fit likelihood)
- eClass $< -0.1$ (PCA classification typical of early type galaxies)
- zWarning $= 0$ (good spectroscopy)
- S/N $> 10$ (good signal-to-noise spectroscopy)

This sample extends out only to about $z \sim 0.3$ if we want to have reliable quality. The colors of these objects evolves with redshift, both because of that redshifting results in the filters sampling a different portion of the spectra and because of the evolution of the objects with time. Comparing the median colors in $g - r$, $r - i$ and $i - z$ as functions of redshift for the two sample shows that they agree fairly well. Figure 1 shows the two samples compared in $r - i$.

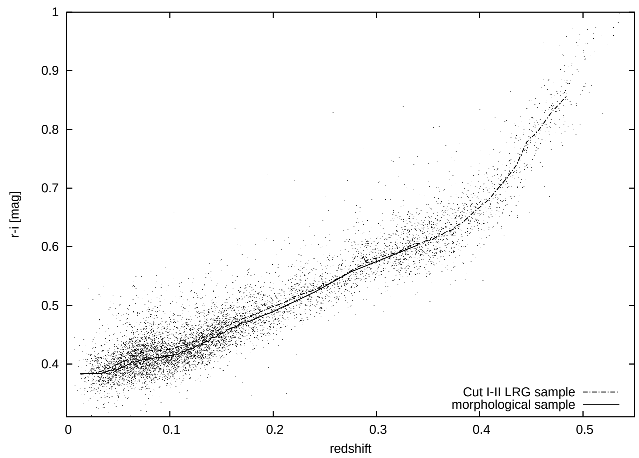


**Figure 1**: *Comparison of the two kind of samples' median colors ($r - i$ in this case) as a function of redshift. Dots are a random subsample of the individual objects.*

[1]According to Strateva et al. (2001), $C > 2.6$ are mostly early type systems.

# 3 Stellar population synthesis

In order to derive physical properties from the evolution of broadband colors of the sample, we compared them to the colors of simulated galaxies. For this purpose we used the GALAXEV stellar population synthesis code (Bruzual & Charlot, 2003). This is a semiempirical simulation based on the Geneva and Padova stellar evolutionary tracks, which allows one to compute the spectral evolution of single or multiple stellar populations, in wide ranges of metallicity and age. Dust content may also be varied, and different star formation histories can be chosen, apart from the "single burst" model, like exponentially declining star formation rate or multiple bursts.

We examined models with metallicities $0.4Z_{\odot}$, $1Z_{\odot}$, $2.5Z_{\odot}$, ages 7-13 Gyr, constant SFR, exponentially declining SFRs and a single burst model. After generating the spectra, redshift them by $0 < z < 0.5$, apply the SDSS filters, calculate $g-r$, $r-i$ and $i-z$ colors, thus constructing the color-redshift relation for each model. When we redshift an object to $z > 0$, we also place it back in time into the younger Universe, so its age has to be corrected with the light travel time corresponding to that redshift.

After having the curves of the photomtric evolution of the simulated galaxies, to test their agreement with the sample data, we calculated $\chi^2$ between the median of the color-redshift relations of the sample and each model.

## 3.1 Results

The data are best fit with an 11 Gyr old solar metallicity ($Z_{\odot}$) single burst (passively evolving) model. Other metallicities (available in the synthesis code) are inconsistent with the data. Also, any significant star formation in the past 5 Gyr would distort their colors far from what we observe. The dust content should be $\mu < 0.1$ (see Bernardi et al. (2003) for the definition of $\mu$).

However, a few problems should be noted here. The metallicity can only be varied in large steps, which prevents a better fit. Even worse is that we face the well known age-metallicity degeneration. Thirdly, the spectral synthesis is never perfect – actually, we could create better fits by adding some peaks to the model spectra "by hand".

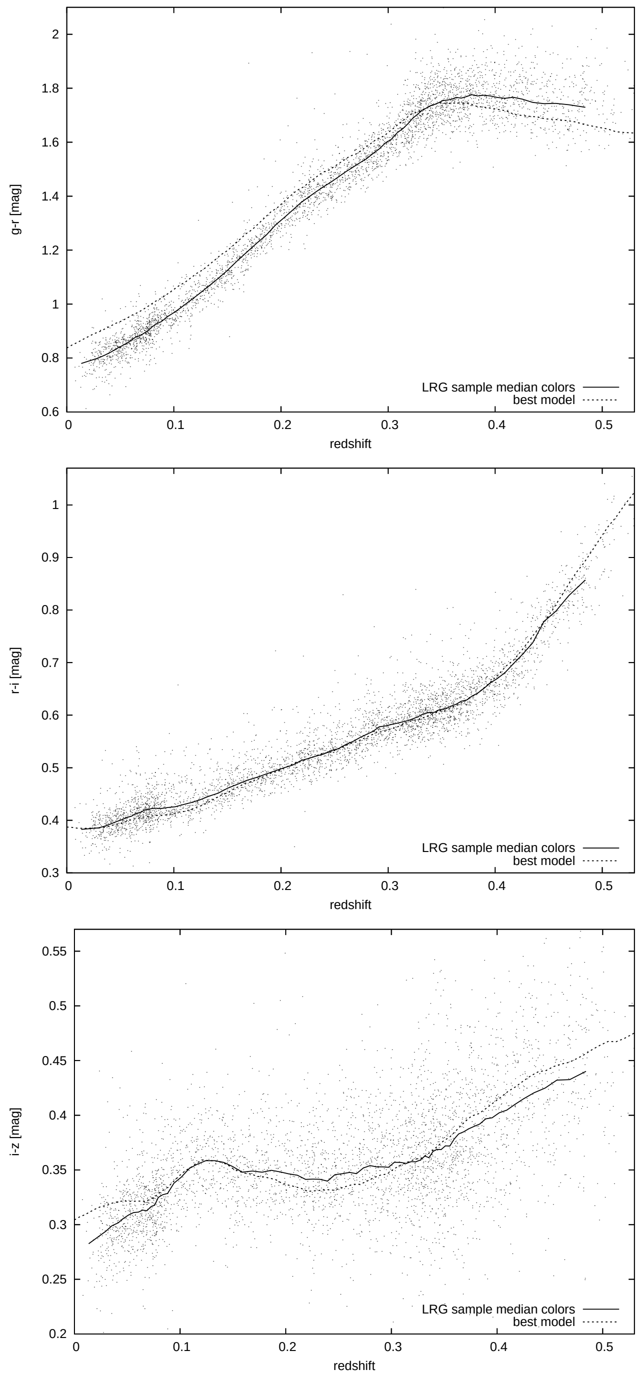


**Figure 2**: *Colors versus redshift, best fitting model copared to the LRG sample*

# 4 Distribution of physical properties

At a given redshift, the objects of our sample have significantly different colors, as opposed to what would be expected from a perfectly homogenous group of galaxies. This scatter of colors, which turns out to be gaussian, is clearly partly the result of instrumental errors, but it may also be caused by the difference between their physical properties such as age or metallicity. Since the SDSS database contains an estimation of the magnitude errors, we can test this scatter of colors in our sample against that of a simulated set of objects. In the simulated set, each object had identical physical properties, and they were spersed in redshift to have the same distribution as our sample data. Then we applied a random gaussian error to their photometric magnitudes, where the parameter of the gaussian was derived from the SDSS photometric errors in the database. The *color* errors are calculated from:

$$\delta(m_i - m_j)^2 = (\delta m_i)^2 + (\delta m_j)^2 - 2C_{ij}, \tag{6}$$

where $m_i$ and $m_j$ are the $i$th and $j$th magnitudes that define the color, and $C_{ij}$ is the covariance matrix of the magnitudes, should such a correlation exist (otherwise zero).

Figure 3 shows the scatter of colors as a function of redshift. The observational errors clearly don't explain fully the observed scatter.

Therefore we changed the simulation, and introduced a scatter in the input parameters of the simulation (while keeping adding the observational errors). We varied the amount of the scatter to find the best fit to the data.

## 4.1 Results

Figure 4 shows the observed scatters and the best fitting simulation. The observed scatter constrains the possible scatter of the formation ages of the LRG sample objects, to less than $\pm 1.5$ Gyr. Unfortunately the value of metallicity can only be changed in discrete and large steps, so we couldn't repeat the same test for metallicities. But even if we could, there's a caveat here. We presumed that the physical parameters are independent. However, this doesn't necessarily be true – see "age-metallicity conspiracy", Worthey et al. (1995). If we can't account for the correlation term between them, we might misjudje the ranges of these parameters.

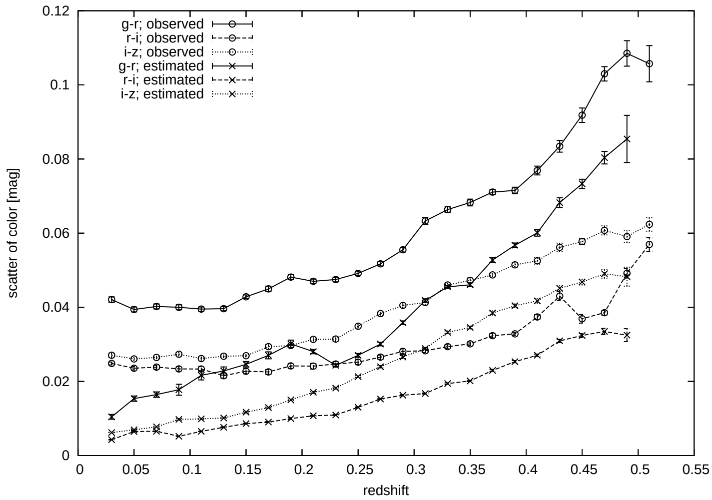


**Figure 3**: *The three pair of functions ($g-r$, solid; $r-i$, dashed; $i-z$, dotted) would ideally run together (pairwise), if the source of the observed scatter of colors (circles) was the photometric error (xs)*

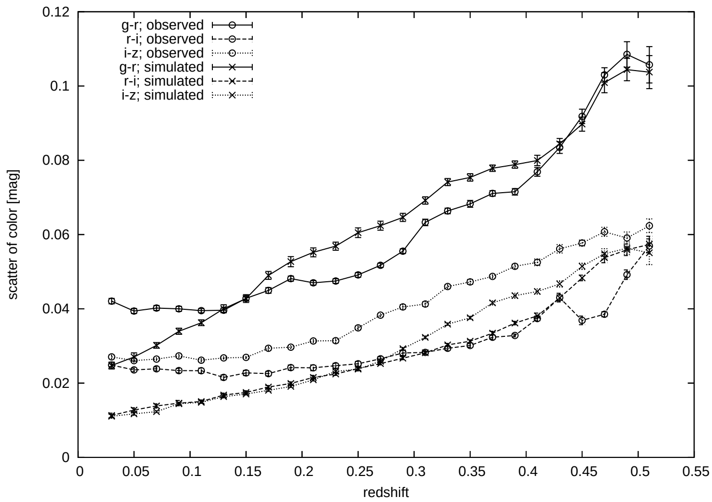


**Figure 4**: *Same as Figure 3, except that the ages of the simulated objects are also varied (before applying photometric errors).*

# 5 Summary

We showed that the LRGs in the SDSS data show broadband colors that are consistent with an 11 Gyr old, passively evolving population, having solar metallicity. The distribution of their physical properties are also limited by the observations.

According to (Scranton et al., 2005), the photometric errors in the SDSS may have to be revised. They found the magnitude errors to be slightly underestimated, while also measuring the correlation of the different color bands (which is not zero), which term (see equation (6)) can now be used to calculate proper color errors. Although their measurements don't extend to bright enough objects to be used with our samples right now, they point to the possibility that later a much tighter constraint may be given to the distribution of the physical properties.

The age-metallicity-dust degeneration can possibly be resolved either by calculating metallicity indices from the spectra, or other indices calculated from broader bandpasses of the spectra, such as in Kauffmann et al. (2003).

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