

# Quenching star formation at intermediate redshifts: downsizing of the mass flux density in the green valley

Thiago S. Gonçalves<sup>1</sup>, D. Christopher Martin<sup>2</sup>, Karín Menéndez-Delmestre<sup>1</sup>, Ted K. Wyder<sup>2</sup>, and Anton Koekemoer<sup>3</sup>

<sup>1</sup>Observatório do Valongo, Universidade Federal do Rio de Janeiro, Ladeira Pedro Antonio, 43, Saúde, Rio de Janeiro-RJ, CEP 22240-060  
email: [tsg@astro.ufrj.br](mailto:tsg@astro.ufrj.br)

<sup>2</sup>California Institute of Technology, <sup>3</sup>Space Telescope Science Institute

**Abstract.** The bimodality in galaxy properties has been observed at low and high redshift, with a clear distinction between star-forming galaxies in the blue cloud and passively evolving objects in the red sequence; the absence of galaxies with intermediate properties indicates that the quenching of star formation and subsequent transition between populations must happen rapidly. In this work, we present a study of over 100 transiting galaxies in the so-called “green valley” at intermediate redshifts ( $z \sim 0.8$ ). By using very deep spectroscopy with the DEIMOS instrument at the Keck telescope, we are able to infer the star formation histories of these objects and measure the stellar mass flux density transiting from the blue cloud to the red sequence when the Universe was half its current age. Our results indicate that the process happened more rapidly, affecting more massive galaxies in the past, suggesting a top-down scenario whereby the massive end of the red sequence assembles first. This represents another aspect of downsizing, with the mass flux density moving towards smaller galaxies in recent times.

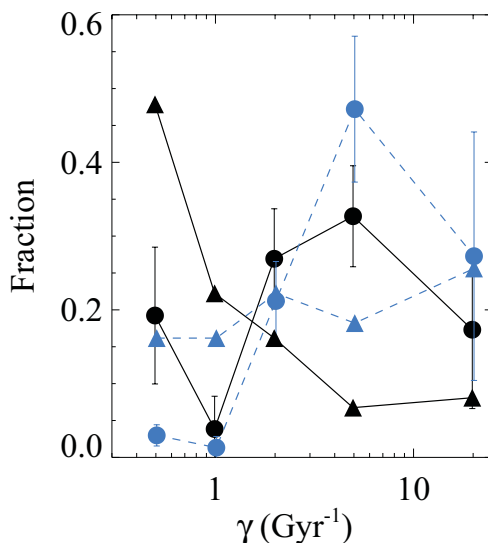
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## 1. Introduction

The distinction between blue star-forming galaxies and red, passively evolving ones has been known for a long time. However, the existing bimodality in the galaxy distribution, with a clear distinction between blue spirals and red spheroids, and its establishment still remain a puzzle. This bimodality in galaxy colors has been observed at low redshifts ( $z \sim 0.1$ ; Wyder *et al.* 2007), but also extends to earlier times, at least out to  $z \sim 1.0$  (Willmer *et al.* 2006). If the color distribution of galaxies can be described as two distinctive peaks, then one can denominate the minimum at intermediate color values the “green valley”. The question then arises: why does such a minimum exist, instead of a homogeneous distribution across the color-magnitude diagram?

The low number density (or number deficit) of galaxies in the green valley indicates that the transition between both groups occurs rapidly. To infer how rapidly galaxies are moving across the green valley, Martin *et al.* (2007) have used spectroscopic features in green valley galaxies to obtain information on their star formation histories. Along with measurements of typical galaxy masses and number densities in the color-magnitude diagram, the authors have been able to determine the mass flux across the green valley at low redshifts ( $z \sim 0.1$ ). We apply here the methods introduced in that work to a sample of galaxies at higher redshift. This will allow us to measure the mass flux in the green valley at intermediate redshifts, and to compare it with results found for galaxies in the low-redshift Universe.



**Figure 1.** Fraction of green valley galaxies as a function of  $\gamma$  bins. Circles represent our sample, while the triangles are the values found at redshift  $z \sim 0.1$ . The blue symbols and dashed lines in both cases are weighted by quenching timescales to correct for the fact that galaxies that are quenching faster are less likely to be observed. We notice an evolution in the fraction of high- $\gamma$  values, in that at higher redshift the timescales for star formation quenching were shorter.

## 2. Observations and Methodology

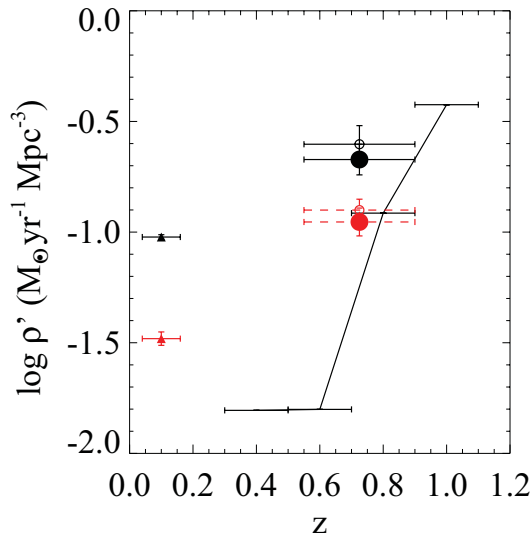
The method to study the mass flux in the green valley is described in detail in Gonçalves *et al.* (2012). In summary, we assume an exponential decline in star formation rates,  $\text{SFR}(t) \equiv \text{SFR}(t=0)e^{-\gamma t}$ . Under that assumption, measurements of the spectral indices corresponding to the 4000Å break ( $D_{4000}$ ) and the equivalent width of a single hydrogen line in absorption ( $H_{\delta,A}$ ), along with comparisons with stellar population synthesis models (Bruzual & Charlot 2003), allow us to infer the quenching timescale associated with the exponent  $\gamma$ .

We have selected a sample of over 100 galaxies from the DEEP2 survey (Newman *et al.* 2012) and CFHTLS with intermediate rest-frame colors ( $3.5 < \text{NUV}-r < 4.5$ ) at redshifts between  $0.55 < z < 0.9$ . In order to accurately measure spectral indices, we have taken the deepest spectra ever obtained of green valley galaxies, with total exposure times up to 9 hours with the DEIMOS instrument on the Keck II telescope.

We have determined luminosity functions of galaxies as a function of color, in order to infer the number density of green valley galaxies as a function of absolute magnitude. We see that (1) green valley and red sequence number densities are smaller than in the local Universe, while number densities are similar for the blue sequence, and (2) all luminosity functions are shifted towards higher luminosities at high redshift.

## 3. Results

We have measured  $D_n(4000)$  and  $H_{\delta,A}$  indices for all green valley galaxies observed. In Figure 1 we compare the quenching timescales we find with the obtained values at  $z = 0.1$ , showing the fraction of galaxies in each  $\gamma$  bin. Since  $\gamma$  correlates with quenching speed, that means galaxies with higher  $\gamma$  values will spend less time in the green valley,



**Figure 2.** Mass flux density in the green valley. Empty circles indicate values measured from stacked spectra. Values at  $z = 0.1$  are shown as triangles. The solid line shows the density growth rate of the red sequence, as determined from Faber *et al.* (2007). Our data points show a clear increase in the mass flux density across the green valley towards earlier times, in agreement with estimates from the growth of the red sequence.

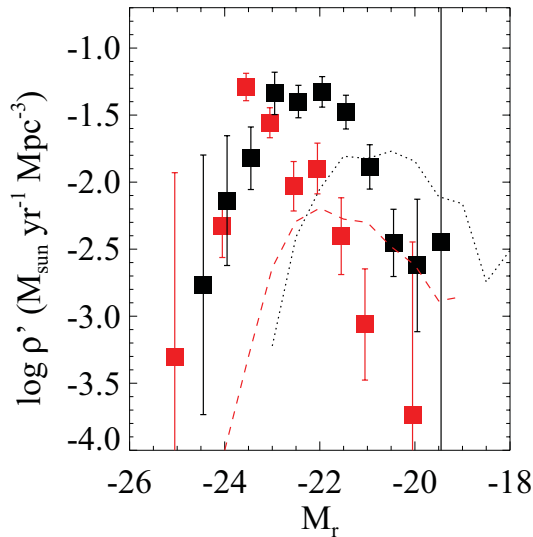
and are less likely to be observed. We show the fractions corrected for this as dashed lines. We represent the data in this work as circles, and the values for low redshift as triangles. The main conclusion we draw from this exercise is that quenching timescales are shorter at higher redshift, since the amount of galaxies with higher  $\gamma$  is increased. In quantitative terms, this represents a factor 2–3 decrease in typical transition timescales.

We determined an average  $\gamma$  in each bin, which in turn corresponds to a period of time required to cross over the color range covered by the green valley. We combine these results with number densities and median galaxy masses for each bin to calculate a mass flux for each given magnitude.

The total mass flux density is the sum of the mass flux through all magnitudes. We show the results in Figure 2. The upper and lower symbols represent values before and after correcting for extinction, respectively. We compare our values to those found at  $z = 0.1$ . Empty circles represent values found for stacked spectra in each magnitude bin. The evolution with redshift from  $z = 0.1$  to 0.8 is evident, with mass flux values at intermediate redshifts being 3 to 5 times higher than those found in the low-redshift Universe. This reflects the significant change occurring in galaxy evolution over cosmic time.

#### 4. Discussion

Our data offers an interesting insight into the problem of red galaxy formation. Comparison with the mass-flux at low-redshift shows that the mass flux occurred at brighter magnitudes at high redshift (Figure 3), indicating the build-up of the most massive end of the red sequence at earlier times, which is in qualitative agreement with the evolution of the luminosity function. This represents a *downsizing* of the green valley evolution, with



**Figure 3.** Mass flux density as a function of  $r$  magnitude. The flux at intermediate redshifts is shown as solid symbols; red squares for the extinction-corrected sample, black squares, no extinction correction. The lines represent the values found for the local Universe; the red dashed line indicates the extinction corrected sample at  $z = 0.1$ . In both cases, the peak at high redshift is shifted towards brighter magnitudes by  $\gtrsim 1$  mag.

the red sequence forming “from the top down”: in the past, more massive star-forming galaxies were being formed and subsequently quenched, forming the more massive red sequence galaxies. At later times, star formation shifts to less massive galaxies; these are then quenched as well, and the fainter end of the red sequence is created.

Since we have calculated the quenching timescales of individual objects, the next logical step is to compare our results with other observable properties in the green valley galaxies, in particular merger signatures and AGN activity. We expect this analysis will help clarify the role of each of these processes in the total quenching of star formation, both at low and at high redshifts.

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