Exploring a new definition of green valley galaxies and its implication

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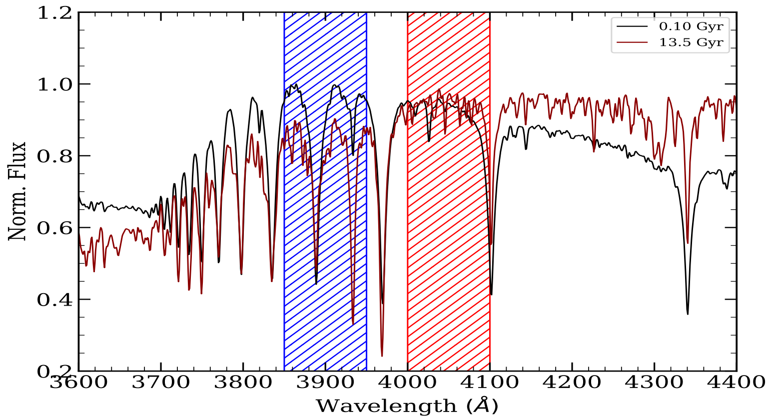
On a plane spanned by a stellar population property and some proxy of mass, galaxies are distributed following a bimodal distribution, defining a red sequence (RS) and a blue cloud (BC). In between these regions resides the transition area termed Green Valley (GV), where we believe most of the quenching processes operate. The traditional method defines the bimodal distribution, thus GV, using colour-magnitude/colour-mass diagrams. However colour is heavily affected by dust, introducing a degeneracy. Any dust correction will be model-dependent and will carry a systematic uncertainty. Thus to avoid the need for dust correction, we use instead a spectral parameter known as the 4000 Å break strength, which is less sensitive to dust. In this instance, without dust correction, we obtain a better separation between BC, GV and RS with less systematic uncertainty. Our study of GV galaxies yields a high fraction of AGN, as well as a transition timescale between 1.0 – 3.5 Gyr correlated with stellar mass. Moreover we find similar properties of the stellar populations between lower GV (lGV) and middle GV (mGV) galaxies than mGV and upper GV (uGV) galaxies, hinting that the transition from BC to GV might be more rapid than that from GV to RS.

Content/Introduction

The availability of large photometric and spectroscopic galaxy surveys has allowed for the discovery of bimodal distribution owing to the existence of two distinct galaxy types; Star forming (SF) and Quiescent (Q) (*Strateva I., et al. 2001*). Galaxies are thought to form in a region dominated by star formation, coined BC, and transition through GV onto a RS, occupied predominantly by Q galaxies, where galaxies tend to reside in after quenching their star formation (*Faber S. M., et al., 2007).* Hence defining the GV in an accurate manner enables a robust study of properties of galaxies during the transition period. From this we are able to study the physical mechanism with which galaxies quench their star formation and the quenching timescale associated with these mechanism for different types of galaxies.

Previous studies have proposed multitude diagnostic diagram, where the key diagrams have adopted to study galaxy evolution in colour-magnitude (*Martin D.C, et al., 2007)* or colour-mass *(Schawinski K., et al., 2014)* diagram. These studies successfully recreate the bimodal distribution associated with galaxy evolution, however the ages derived from these diagrams are heavily degenerate with respect to dust; thus requiring dust correction through various form of modelling *(Cardelli J. A., et al. 1989, Calzetti D., et al., 1994);* hence introducing systematics. Therefore to avoid such systematics, we propose the use of spectral index defined at 4000 Å known as D_n(4000) (*Balogh M. L., et al. 1999)* break, which happens to be more dust resilient, to study the GV and bimodality of galaxy distribution.

Methodology

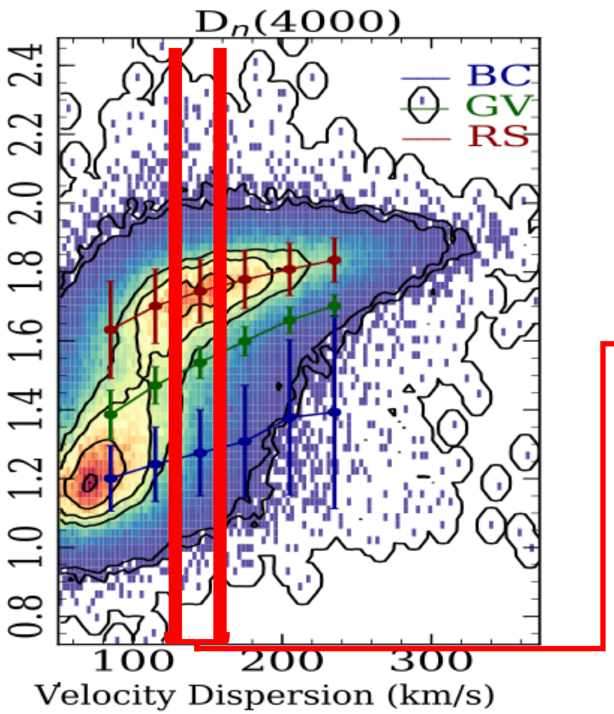


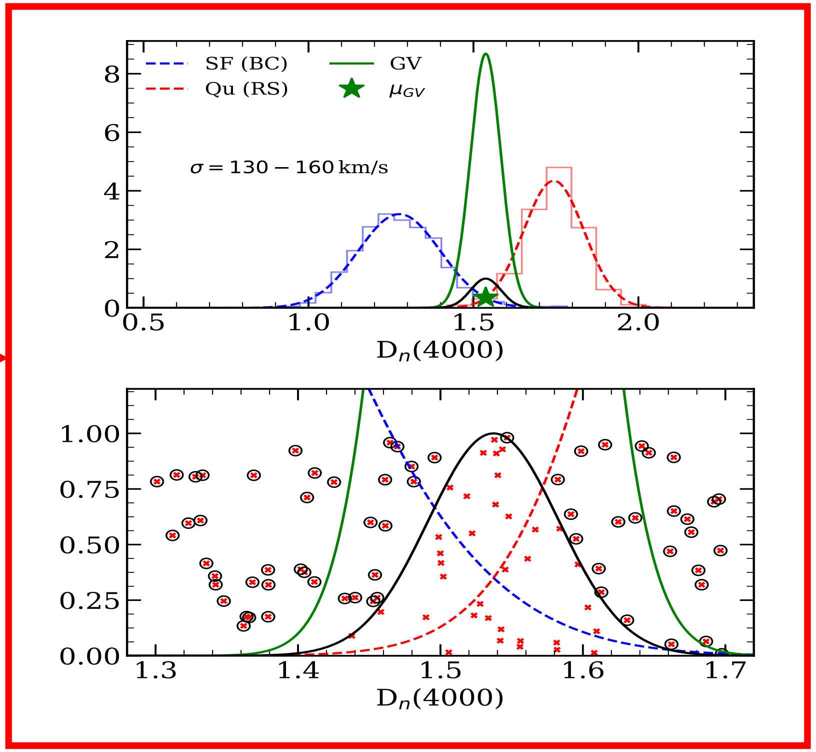
We define BC, GV and RS using the spectral index, $D_n(4000)$ (Top figure) and velocity dispersion or dust-corrected colour and velocity dispersion; for comparison.

Sloan Digital Sky Survey spectra (0.05<z<1) are used for the analysis. The distribution of the sample is shown in the central figure.

We bin the galaxies into 6 different bins:

$\boldsymbol{\sigma = 70-100}$**km/s** , $\boldsymbol{\sigma = 100-130}$**km/s,**
$\boldsymbol{\sigma = 130-160}$**km/s,** $\boldsymbol{\sigma = 160-190}$**km/s,**
$\boldsymbol{\sigma = 190-220}$**km/s,** $\boldsymbol{\sigma = 220-250}$**km/s.**





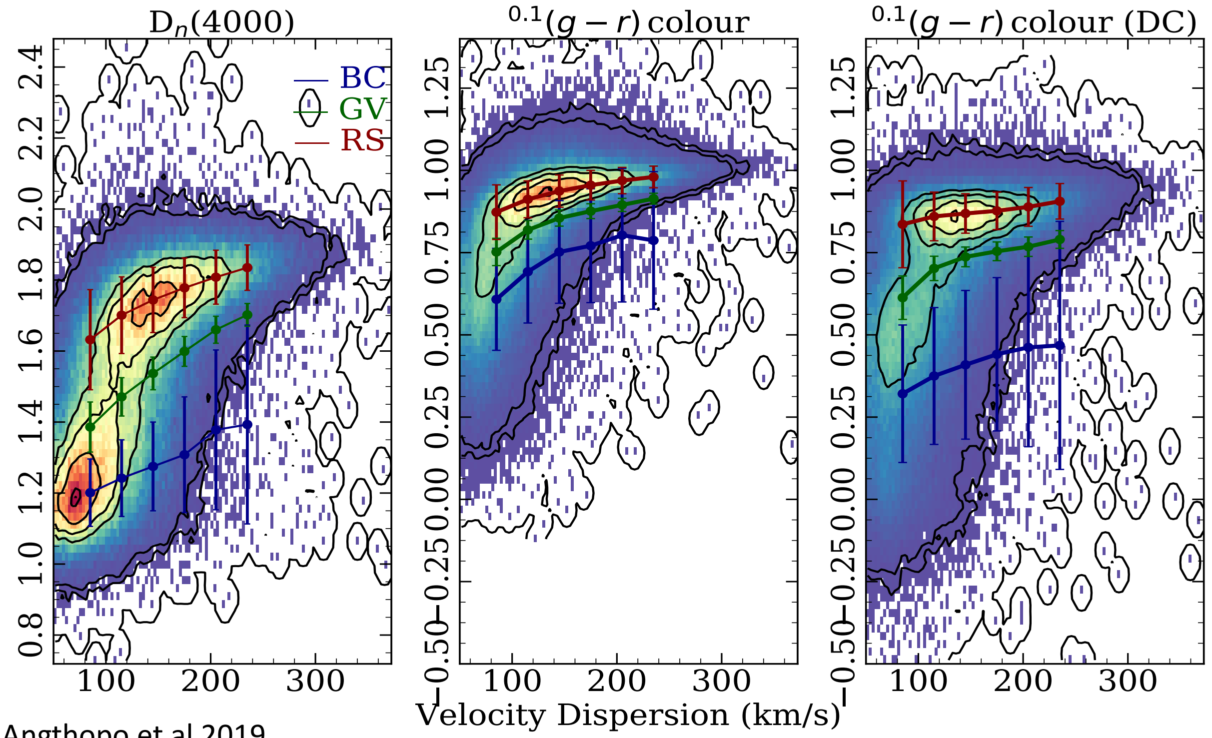
We follow a probability-based approach, defining a probability distribution function (PDF) for BC $\mathcal{P}_{\rm BC}$ using the SF subsample and PDF for RS, $\mathcal{P}_{\rm RS}$ using the RS subsample.

Assumption 1: All pdf (BC, GV and RS), are Gaussian, and depend on velocity dispersion (σ) and a parameter that serves as a proxy for age (π) (top panel of right figure).

Assumption 2: The mean of the GV distribution is given by the value of (π), where $\mathcal{P}_{\rm BC}(\sigma,\pi) = \mathcal{P}_{\rm RS}(\sigma,\pi)$ and the standard deviation of Q subsample is $s_{GV}(\sigma) \equiv \frac{1}{2} s_{RS}(\sigma)$.

The PDFs are used to create a realization of the SDSS set into BC, GV and RS galaxies.

Result 1 – Dust Effect



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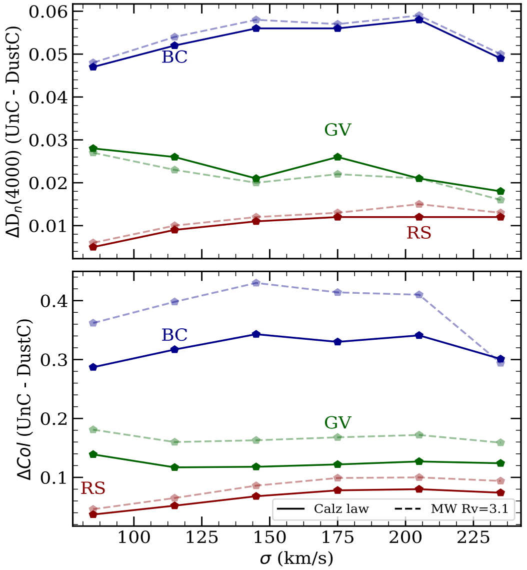
(Top Figure) Distribution of galaxies in SDSS for D$_n$(4000) break w/o dust correction (left), colour $^{0.1}$(g-r) w/o dust correction (middle) and colour $^{0.1}$(g-r) with dust correction against velocity dispersion.

Points with error bars show mean and standard deviation for each σ bin, where blue, green and red data points show BC, GV and RS regions. The density plots show the distribution of all galaxies.

(Right Figure) Systematics associated with dust correction. It is quantified by studying the differences in BC, GV and RS defined by D$_n$(4000) and colour with and without dust correction for two different dust attenuation laws.

D$_n$(4000) shows minimal dependence on dust, whereas the colour selection shows a large, ~ 0.1dex, systematics involved for BC.



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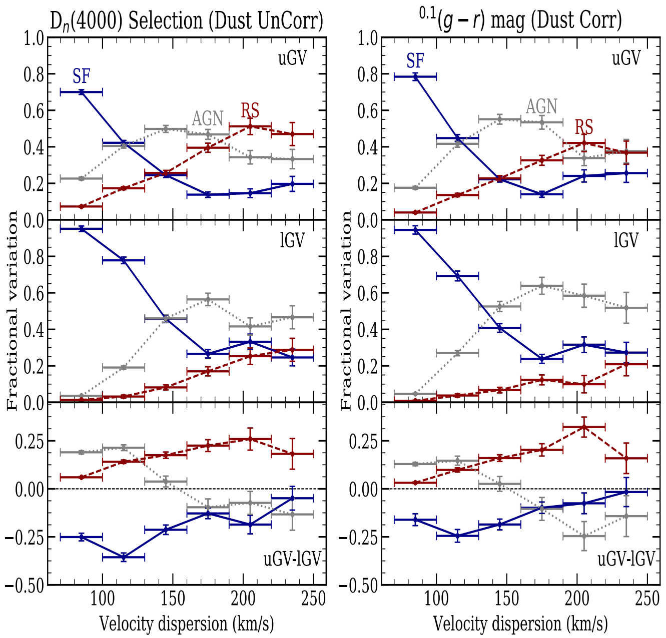
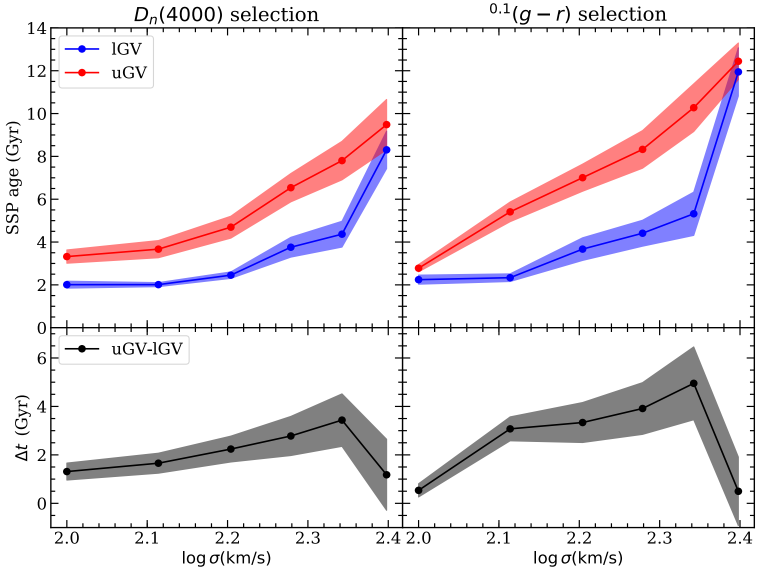


(Left Figure) Fraction of different types of galaxies in upper GV (uGV) and lower GV (lGV).

Both selection provides similar percentages of Q, SF and AGN. At $\sigma = 200 - 250$ km/s, colour selection shows $\sim 37 \pm 6(51 \pm 8)\%$ AGN in lGV (uGV). D$_n$(4000) selection shows $\sim 30 \pm 5(50 \pm 7)\%$ AGN in lGV (uGV).

Result 2 – Stellar Properties



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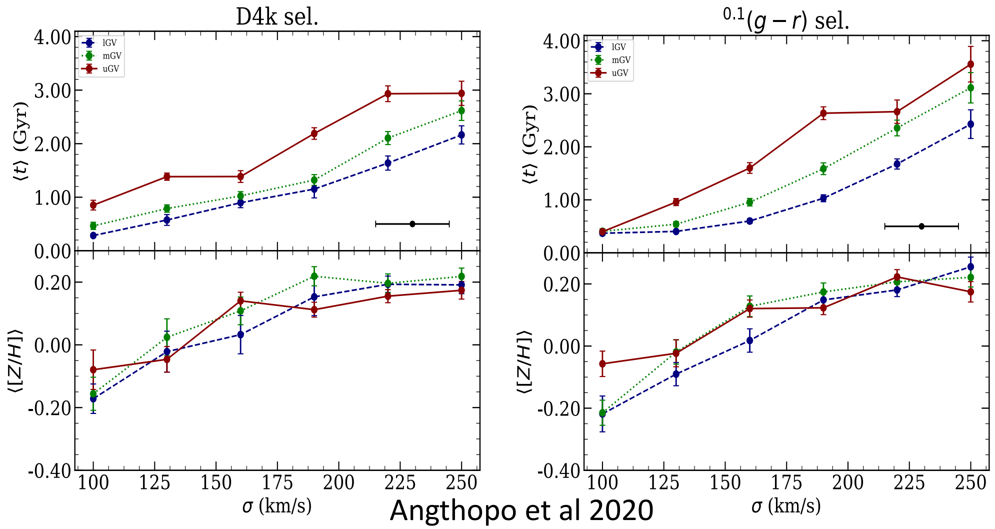
(Left Figure) We select only Q galaxies in lGV and uGV and stack spectra for each σ bin. Correct for emission and smooth and calculated SSP equivalent ages for each stack, using $H\beta, H\gamma_F, H\delta_F$ and D$_n$(4000), and metallicity-sensitive indices, Mgb, <Fe> and [MgFe]'.

Top panel shows a general increase in SSP equivalent ages w.r.t velocity dispersion, where D$_n$(4000) selection provides slightly younger ages.

Bottom panel shows transition timescale, obtained by taking difference between uGV and lGV ages. D$_n$(4000) selection gives Δt ~ 1.5 Gyr at $\sigma = 100$ km/s, with stead increase in Δt, showing maximum of Δt ~ 3.5 Gyr at at $\sigma = 200$ km/s. Highest velocity dispersion bin, $\sigma = 250$ km/s, there is a significant drop in transition timescale, Δt ~ 1.0 Gyr, indicating 2 mode, slow and rapid, of quenching (or a rejuvenation channel), depending on galaxy mass.



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(Top figures) We select Q, SF and LINER galaxies in lGV, mGV and uGV and stack spectra for each σ bin. We calculate average age and metallicity of galaxies using Spectral fitting code, **STARLIGHT** (Cid Fernandes et al. 2005).

The top panels show relatively young galaxies in GV, <t> < 4 Gyr, for both selection. D$_n$(4000) shows lGV and mGV have galaxies with similar ages compared to uGV, not seen in colour selection. The bottom panels show similar trends, where D$_n$(4000) shows lGV and mGV have similar metallicity values and behaviour compared to uGV.

We speculate this trend we see in D$_n$(4000) is due to a quicker transition between BC to GV and a slower transition between GV to RS.

Impact and Prospects for the future

We explore a novel, dust resilient, way of defining the GV, utilizing the 4000 Å break.

From this we explored the properties of GV galaxies by splitting GV into lower (lGV), middle (mGV) and upper (uGV) quartile. For general study, we look at the fractions of different types of galaxies in lGV(uGV) finding significant fraction of AGN population $\sim \mathbf{30 \pm 5 (50 \pm 7)}\%$.

Study of quiescent stellar population, using SSP equivalent ages, we find a transition timescale with heavy dependency on time where $\boldsymbol{\sigma} = \mathbf{100}$ **km/s** galaxies have a transition period of $\sim \mathbf{1.5}$ Gyr, that increases to $\sim \mathbf{3.5}$ Gyr at $\boldsymbol{\sigma} = \mathbf{200}$ **km/s**. For $\boldsymbol{\sigma} \geq \mathbf{200}$ **km/s**, corresponding to a stellar mass $\geq \mathbf{10^{10.5}}\ \boldsymbol{M_{\odot}}$, we find a decrease in the transition period down to $\sim \mathbf{1.0}$ Gyr. This result suggests two modes of quenching – one mode for low mass and another for high mass galaxies.

A more detailed analysis of the stellar populations in Q, SF and LINER galaxies, in lGV, mGV and uGV shows greater difference between uGV and mGV in comparison to mGV and lGV. From this we can speculate the transition from BC to GV could happen at a more rapid rate in comparison to the transition from GV to RS.

With these results we have a novel and accurate (dust resilient) method of defining the GV with little systematics involved, for future galaxy surveys. Owing to a cleaner definition of GV, we are able to study the subtle differences in stellar population of galaxies in different GV regions, thus different evolution stages, not seen in previous literatures.

Results presented in Angthopo et al. 2019 (MNRAS 488, L99) and Angthopo et al. 2020 (MNRAS, 495, 2720)