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Invited Paper

VIPERS* view of the star formation history of early-type galaxies

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ABSTRACT

We investigate redshift evolution of the relation between stellar mass, and star formation history for a high quality sample of early-type galaxies (ETGs) observed by the VIMOS Public Extragalactic Redshift Survey (VIPERS). Among nearly 100,000 VIPERS targets more than 22% are ETGs, which makes it a perfect sample to study the star formation history based on galaxy spectroscopic features. We use two stellar absorption line indices, the 4000$\mathring{A}$ break strength, and the Balmer absorption line index $H\delta_A$ as the indicators of the present and past star formation in galaxies, and measure their dependence of the stellar mass. We find that the age of stellar population changes both with stellar mass and redshift. Lower mass ETGs have younger stellar populations than galaxies with higher mass. This trend is preserved in all the redshift range $0.4 < z < 1.2$ and it is similar to the trends observed in the local Universe. For all stellar mass ranges D_{4000} increases with redshift, while $H\delta_A$ gets lower, which can be interpreted as the confirmation of the "downsizing" scenario.

Keywords: galaxies:formation,evolution; galaxies: stellar content

1. INTRODUCTION

In the local Universe, galaxies come in many different colours, masses, sizes and shapes. The most common classification - the tunning fork diagram proposed by Edwin Hubble - distinguishes three main classes based on their visual appearance: elliptical, spiral, and lenticular. A fourth irregular class has later been added by G. de Vaucouleurs [17]. This classification was intended to reflect a Hubble's belief in the evolutionary path from elliptical through lenticular to spiral galaxies. Elliptical galaxies (together with lenticular galaxies forming a group called early-type galaxies, hereafter ETGs) in the local Universe are usually larger, brighter, redder and populated by older stars (Population II; old and cool stars characterized by low metallicity and red colours). They are nicknamed "red and dead", since usually there is no legible trace of formation of new stars within them. Spiral galaxies (called late-type galaxies) are in contrast smaller, less luminous, bluer and populated by young stars due to still on-going star formation [26]. A strong bimodality between early-type and late-type galaxies in

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[*] based on observations collected at the European Southern Observatory, Cerro Paranal, Chile, using the Very Large Telescope under programs 182.A-0886 and partly 070.A-9007. Also based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT), which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de lUnivers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada-France-Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS. The VIPERS web site is http://www.vipers.inaf.it/.
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many properties, such as colour distribution (e. g. [5], [18]), Hα [3] and [OII] emission [30], 4000 $\mathring{A}$ break [28], or star formation history (hereafter SFH) [7] has been observed at least up to $z \sim 1.5$.

The evolutionary scenario proposed by Hubble with young, spiral galaxies evolving into mature elliptical galaxies, seems quite natural at the first glance. However, there is a crucial problem: the passive evolution would need a lot of more time than the age of our Universe to lead to the formation of nowadays' elliptical galaxies. Moreover, spiral galaxies contain not only young stars, but also very old ones (Population I and II, where Population I are blue, young and massive stars with solar-like metallicites). It implies that galaxy evolution is much more complicated than the scenario presented by Hubble. In the presently considered scenarios based on the hierarchical model of the large scale structure evolution, late and early-type galaxies are of approximately similar ages while their different properties and shapes result from their different evolutionary paths. In particular, the environmental effects may play a crucial role here, both in the epoch of galaxy formation (the host dark matter halo mass controlling the dynamics of matter accretion on a newly formed galaxy) and later, through galaxy interactions and mergers [31]. However, a precise scenario of how and when different types of galaxies took their shapes and formed stars is still an open question. Thus, understanding the evolution of galaxies, and the history of star formation in them, is one of the most important problems in astronomy.

1.1 Early-type galaxies

An ideal candidate to study galaxy evolution and star formation history beyond the local Universe are early-type galaxies as they were found to have constant properties in a large range of redshift [27]. ETGs are a simple and homogeneous population in terms of their morphology, colours and stellar population content, at least in the nearby Universe (see [36] for a detailed review). Although ETGs' properties were deeply studied, their formation and evolution is still an unresolved question.

One of the scenarios suggests that the most massive ETGs (with stellar masses above $> 10^{11} M_{\odot}$) have assembled their mass at higher redshifts and have been already in place since at least $z \sim 1$ (e. g. [35]). Cowie et al. (1996) proposed a model known as "downsizing" - a scenario strictly related to the mass of galaxies. In this very popular scenario, lower mass systems have a more prolongated star formation than massive galaxies, i.e. stars were formed earlier and faster in massive galaxies than in lower mass galaxies. However, downsizing is not only restricted to the star formation, but can be also extended to the mass assembly. Hence, it implies that star formation moves to smaller, less massive systems with cosmic times, as massive galaxies contain an older stellar population (e.g. [33]). The arguments in favor for the downsizing scenario were delivered by a number of authors [10, 11, 19, 20, 33, 35, 36 and references therein]. In our work, we present the measurements of the indices of age and star formation histories of a large and unbiased sample of massive ETGs at $z \sim 1$ based on the data from the currently ongoing VIMOS Public Extragalactic Redshift Survey (VIPERS).

1.2 Spectral indicators

One of the most direct methods to study evolution of galaxies and their SFH is based on the main indicators of the recent star formation history of galaxy populations: 4000 $\mathring{A}$ (hereafter D_{4000}) and $H\delta_A$ parameters. In our work we will adopt the narrow definition of the D_{4000} break presented in [4]:

$$D_{4000} = \frac{\lambda_2^- - \lambda_1^- \int\limits_{\lambda_1^-}^{\lambda_2^+} F_\nu d\lambda}{\lambda_2^+ - \lambda_1^+ \int\limits_{\lambda_1^+}^{\lambda_2^-} F_\nu d\lambda}, \tag{1}$$

where $(\lambda_1^-, \lambda_2^-, \lambda_1^+, \lambda_2^+) = (3850, 3950, 4000, 4100)\mathring{A}$. Spectral regions used to calculate D_{4000} are marked with blue in Fig. 1, which presents an exemplary VIPERS stacked galaxy spectrum in the wavelength range 3800 - 4600$\mathring{A}$.

The D_{4000} break is the strongest discontinuity in the optical spectrum of a galaxy and is caused by the accumulation of a large number of metal absorption lines whose amplitudes are strictly correlated with the

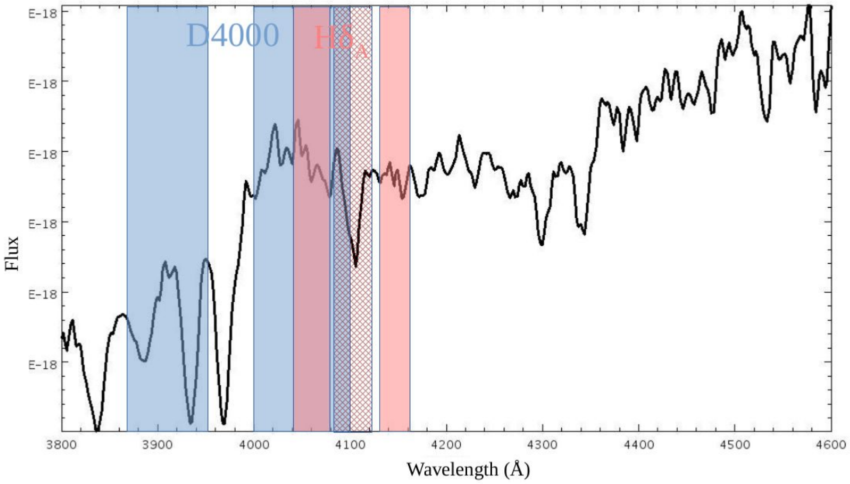

Figure 1. Exemplary VIPERS stacked galaxy spectrum in the wavelength range 3800 - 4600$\mathring{A}$. S/N ratio is high enough to measure D_{4000} and $[H\delta]\lambda 4102$, which will be used to characterize the process of evolution of galaxies and the star formation rate. The blue shaded areas show the ranges used to evaluate D_{4000} break. The red regions correspond to the pseudocontinua for the $H\delta_A$, while the hatched area shows the $H\delta_A$ bandpass.

galaxy age, and metallicity. On the other hand, D_{4000} is less dependent on SFH, and weakly dependent on dust and reddening (at least in some age and metallicity ranges). In hot stars the dust opacity decreases, and the D_{4000} becomes smaller for Population I and larger for old, low metallicity stellar populations [4, 8, 25, 32]. Thus, D_{4000} is ideal for studies of different stellar populations.

A complete set of twenty one absorption features, known as the Lick-IDS system, was designed to predict index strengths in the integrated light of stellar populations of different ages and metallicities [38]. In our work we use one of the Lick indices: $H\delta_A$ (Lick-IDS for [Hδ]λ4102 line), as defined by [39]:

$$index = (\lambda_2 - \lambda_1) \cdot (1 - F_I/F_C), \tag{2}$$

where F_I is defined as the continuum flux minus the absorption, and F_C is the continuum flux; $\lambda_2 - \lambda_1$ is the width of the bandpass used to measure the index. Absorption feature is composed of measurements of relative flux in the central "feature" bandpass and two flanking "pseudocontinuum" bandpasses: index range: 4083.50 - 4122.25 [$\mathring{A}$], blue conntinuum: 4041.60 - 4079.75 [$\mathring{A}$], and red continuum: 4128.50 - 4161.00 [$\mathring{A}$]. Regions used to calculate $H\delta_A$ are marked with red in Fig. 1.

Strong $H\delta$ absorption lines can be observed in galaxies that experienced a recent burst of star formation followed by passive evolution. The $H\delta$ line would be hidden in galaxies with ongoing star-formation due to dominance of hot O and B stars, which have weak intrinsic absorption [4].

Calculation of these two indices allows for detailed studies of SFH, as both are defined over a narrow wavelength range, and they are less affected by dust attenuation. These spectral features show clear separation of galaxies into two distinct families - those with an ongoing active star formation, and those where star formation has been quenched. Studies of conditional density distributions of D_{4000}, and $H\delta_A$ as a function of stellar mass show that in local, faint, low-mass galaxies, with low surface mass densities, the star formation is ongoing, and these galaxies have blue colours (the blue continuum is brighter than the red part of the continuum) and consist of young stellar populations. In contrast, local, bright, high-mass (above $3 \times 10^{10} M_{\odot}$) galaxies, with high surface mass densities, are redder, consist of old stellar populations and their star formation has been quenched (see e.g [28]). Kauffmann et al. (2003) based on the SDSS data, showed that for the local Universe the fraction of low mass galaxies that have experienced recent bursts of star formation is higher than for high mass galaxies (see Fig. 2).

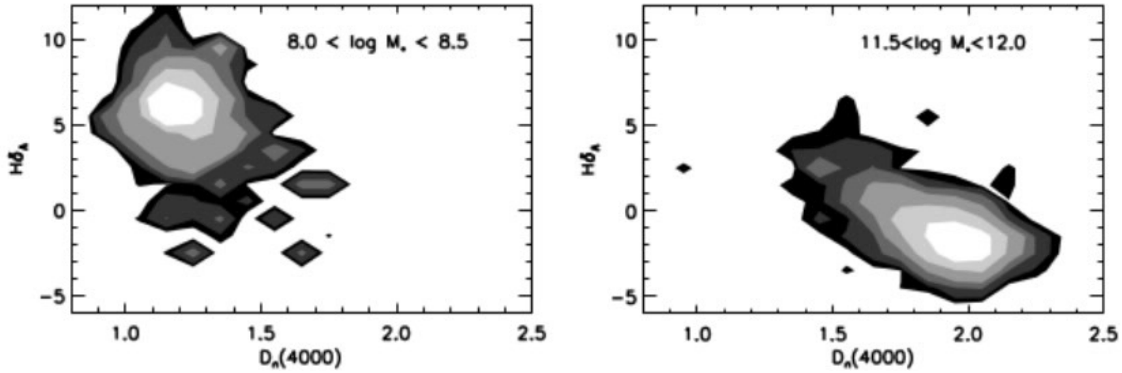

Figure 2. Distribution of $H\delta_A$ as a function of D_{4000} for two stellar mass bins ($10^8 - 10^{8.5}[M_\odot]$ and $10^{11.5} - 10^{12}[M_\odot]$) taken from [28] (Figure 3).

1.3 VIPERS

VIMOS Public Extragalactic Redshift Survey (VIPERS) [24] is an European South Observatory (ESO) Large Programme designed to map in detail the large-scale distribution of galaxies at $0.5 < z < 1.2$ with a unique volume (24 deg^2) and sampling rate ($\cong 45\%$). At this redshift, VIPERS fills a unique niche in galaxy surveys, and provides a exceptional opportunity to study galaxies and their evolution at an epoch when the Universe was approximately half its present age. VIPERS dataset can by considered as the $z \sim 1$ equivalent of current state-of-the-art local ($z < 0.2$) surveys like 2dFGRS [13] and SDSS [1, 40], which allow to compare measurements at these two different epochs. The final sample of this survey is going to reach nearly 100,000 galaxies. VIPERS increases significantly the completeness of the census of galaxy properties at these early epochs of the Universe's past history. VIPERS maps in detail the spatial distribution of galaxies with red magnitudes I(AB) brighter than 22.5 magnitude over an unprecedented volume of the $z \sim 1$ Universe. VIPERS is covering ~ 24 deg^2 area - splited over two areas in the W1 and W4 Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) fields. A robust colour-colour pre-selection allows the survey to focus its measurements on the $0.5 < z < 1.2$ redshift range, yielding an optimal combination of large volume ($5 \times 10^7 \mathrm{h}^{-3}\mathrm{Mpc}^3$) and highly effective spectroscopic sampling ($> 50\%$). The "Low-Resolution Red" grism (R=210), yields a spectral coverage between 5500 and $9500\mathring{A}$, for a typical redshift rms error of $\sigma_z = 0.00047(1 + z)$. The detailed introduction to the survey can be found in the survey description paper [24], and the First Data Release paper [21]. Such a combination of sampling and volume is unique among redshift surveys at $z > 0.2$. With these figures, the VIPERS data allow us to compare measurements at $z \sim 0$ and $z \sim 1$ with a comparable statistical significance.

2. SAMPLE SELECTION

The analysis presented in this paper is based on the VIPERS data. Our sample has been selected from spectroscopic measurements for 75 644 objects. We use stellar masses and absolute magnitudes computed by spectral energy distribution (SED) fitting [15, 16] using the HYPERZMASS code [6].

2.1 SELECTION OF EARLY-TYPE GALAXIES

We decided to study star formation history of ETGs, as they evolve smoothly in timescales much longer than their age difference. In order to fully exploit ETGs as reliable cosmic chronometers, the appropriate sample selection is necessary. There exist different methods to separate early-type from late-type galaxies, the most important among them being:

- classical approach - a fixed cut in rest-frame (U-V) colours, not evolving with redshift [5, 18, 19],

- bimodal (U-V) colour distribution - an evolving cut in (U-V) colours [19, 34, 37],
- NUVr classification - a rest-frame (NUV - r) - (r - K) colour selection [2, 19],
- Spectral energy distribution classification [19].

A detailed description of the methods listed above was presented by Fritz et al., (2013) [19]. Our results are based on the bimodal U-V colour distribution with the evolving cut in (U-V). We decided to use the bimodal approach, because this criterion has an almost constant and high ($\sim 90\%$) completeness for early-type galaxies up to $z = 1$ for VIPERS sample, as it was found by [19]. However, the contamination by late-type galaxies is $< 10\%$ up to $z = 0.8$ and reaches $\sim 30\%$ in the highest redshift bins. Other listed criteria result in a lower contamination, however, in the same time, they lead to much lower completeness [19]. Comparison of completeness and contamination by late-type galaxies for different ETGs selection criteria on the basis of VIPERS data is shown in Fig. 3 (from [19]).

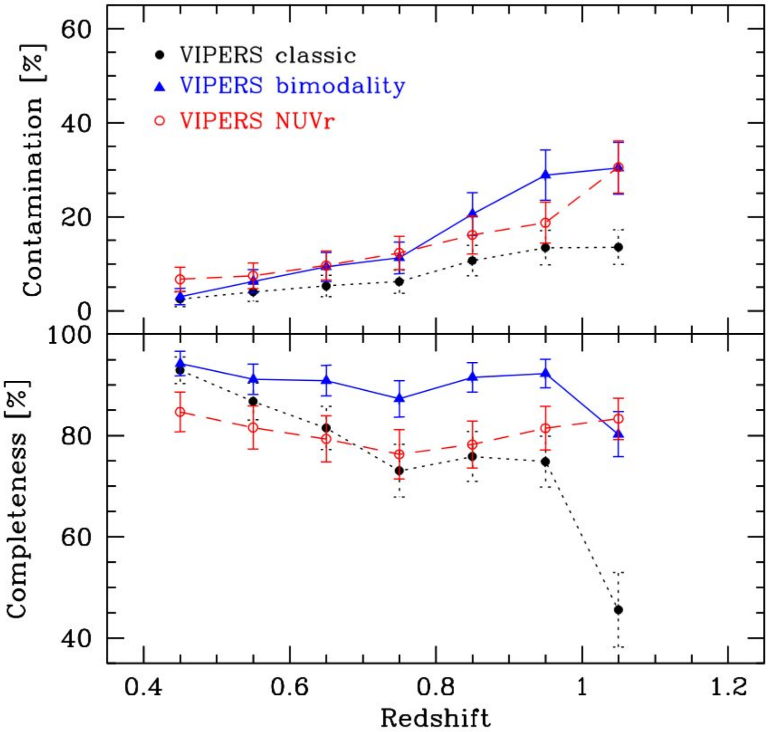

Figure 3. Completeness (*lower panel*) and contamination (*top panel)* of VIPERS ETGs by late-type galaxies as a function of redshift for different selection criteria. Figure taken from [19].

Using colour-bimodality criterion we selected 8,367 early-type galaxies covering the redshift range between $0.4 < z < 1.4$, and stellar mass range between $7 < \log(M_{star}) < 12$ [$M_\odot$] with redshift flag 3 and 4*. Fig. 4 shows exemplary rest-frame (U - V) distributions for two different redshift bins in a VIPERS sample with a division between red early-type and blue late-type galaxies. An adopted separation, given by $(U - V) = 1.1 - 0.25 \times z$ [19], is marked with a black solid line.

As it was shown by [12, 18, 22, 23], red galaxies selected only on the basis of colour distribution may still contain a non-negligible fraction of galaxies with an ongoing star formation. Thus, to remove them from our sample we have adopted an additional criterion based on the absence of the [OII]λ3727 emission line, in order to exclude the ongoing star formation or an AGN activity. Furthermore, to create a pure and high quality sample, we excluded from our dataset all the spectra with distortions caused by artifacts, like sky lines etc. For this

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*Redshift flags 3 and 4 correspond to spectra for which the confidence of redshift measurement is above 99% [24].

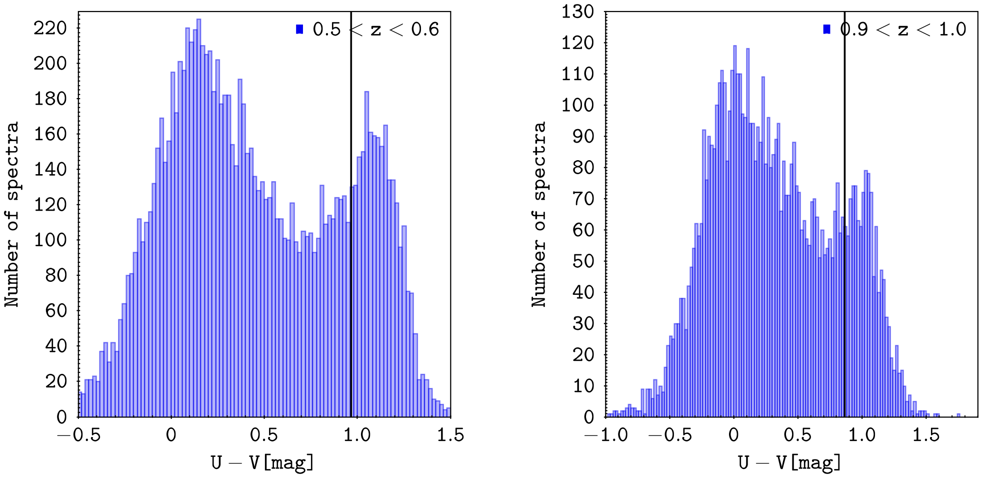

Figure 4. Rest-frame U - V colour distribution for VIPERS galaxies in the redshift bin $0.5 < z < 0.6$ (left panel) and $0.9 < z < 1.0$ (right panel). The vertical solid lines indicate the adopted separation for red early-type galaxies and blue late-type galaxies, defined by an evolving cut [19].

purpose we excluded all galaxies with gaps in the part where D_{4000} and/or $H\delta_A$ was located, reconstructed by Principal Component Analysis [29], and all the spectra cleaned in the reduction/validation phase. Due to these additional criteria our sample was further reduced from 8,367 to 4,539 galaxies.

3. STACKING PROCEDURE

Physical properties, like the amount of star formation activity, need to be derived from the observed galaxy properties by the use of a series of rather sophisticated tools. In addition, these features are very difficult to obtain for faint distant galaxies, like those in the VIPERS sample. In this case we make use of stacking procedures in order to obtain high quality data for "average" galaxies in our dataset, and from them we receive measurements that are simply impossible to obtain with the single galaxy detection.

As some of the absorption lines are weak and not detectable in a single VIPERS spectrum, we have to average (stack) together the spectra of different ETGs. Exemplary VIPERS spectra for single galaxies with redshift flag equal to 3 and 4, are presented in Fig. 5. It can be seen from them that even for high quality spectra (as indicated by high values of redshift flag) a signal to noise (S/N) ratio is too low to distinguish and measure some of the absorption lines, like $[H\delta]\lambda4102$. Thus, we decided to co-add galaxies in a two-parameter space of redshift and stellar mass in order to get a set of stacked spectra.

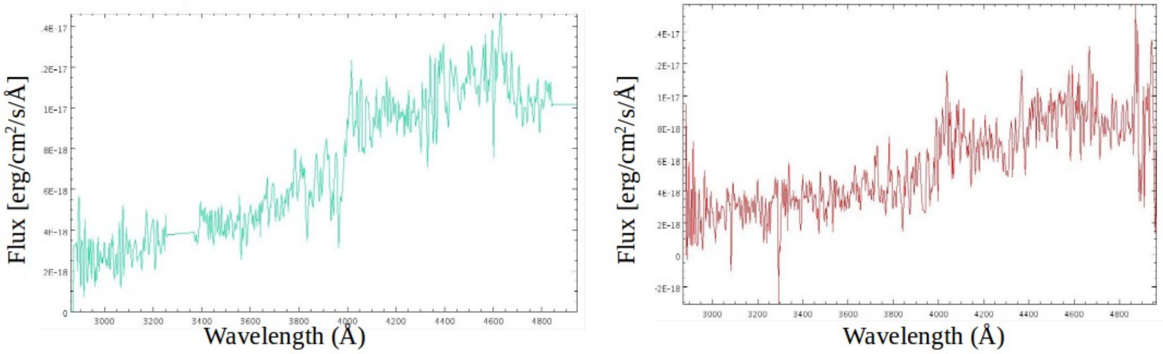

Figure 5. Examples of VIPERS spectra in the wavelength range 2900 - 5000$\AA$ with redshift flag equal to 3 (*left panel*) and 4 (*right panel*).

We have decided to co-add spectra within narrow redshift and stellar mass bins, and we divided our dataset into:

- 7 redshifts bins (δz = 0.1 from 0.4 to 1.0, and an additional, wider bin, from 1.0 to 1.4),
- 7 stellar masses bins (in logarithmic scale) (δsm = 0.25 dex, except for galaxies with $\log(M_{star})$ below 10.0 [$M_\odot$] and above 11.5 [$M_\odot$]. For them we decided to use wider bins (7-10 and 11.5-12), as the sample is less numerous).

In our work individual spectra are averaged, combined and normalized by median scaling, so that each galaxy contributes equally to the final stack. We build stacked spectra with preserved equivalent width of lines. An exemplary VIPERS stacked spectrum in the wavelength range 3800 - 4600$\mathring{A}$ is shown in Fig. 1. The signal to noise (S/N) ratio for a stacked spectrum is higher than for single spectra, and $[H\delta]\lambda4102$ absorption line is detectable.

For the following analysis only the bins with more than 20 co-added spectra were used, since this limit ensures S/N ratio high enough to measure spectral indicators used in this paper. Numbers of spectra used in each bin after all the selection criteria have been applied are shown in Fig. 6. Bins with an insufficient number of spectra (less than 20) are marked in blue. An additional requirement that the spectrum should not contain reconstructed features eliminated 4 additional bins marked in red.

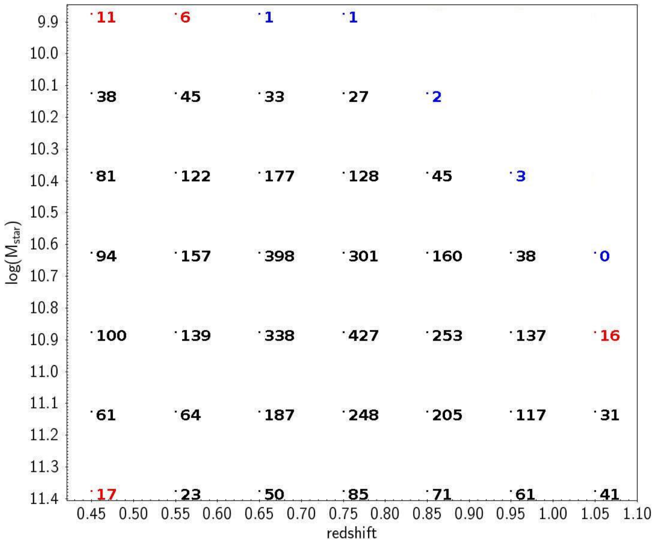

Figure 6. Numbers of spectra for each bin after the application of all the criteria of selecting high quality sample of early-type galaxies. Bins with insufficient numbers of spectra (20) after cut off on [OII] emission line, are marked in blue. An additional requirement of clean spectra, without reconstructed features, eliminated 4 additional bins marked in red.

We have calculated $H\delta_A$ and D_{4000} parameters for 34 redshift and stellar mass bins. To estimate the influence of removal of single spectra, and uncertainties of the derived spectral indicators we performed the Monte Carlo (MC) simulation. The standard deviation for MC simulated spectra gives us the information how sensitive the stacked spectra are to the properties of single co-added spectra. Thus, obtained values could be used as the uncertainties of calculation of $H\delta_A$, and of D_{4000} measurements.

The behavior of the $H\delta_A$, as a function of stellar mass for our sample of stacked ETGs spectra in six redshift bins is presented in Fig. 7. In all the investigated redshift range $0.4 < z < 1.0$ lower mass ETGs have stellar population younger than higher mass ETGs. A very similar trend was found by Kauffmann et al. (2003) [28] for local galaxies ($z < 0.2$).

Spectral indicators, both $H\delta_A$, and D_{4000}, strongly depend on stellar masses as it is shown in Fig. 7. This dependence is almost linear, and we conclude that the trends look similar in all considered redshift ranges.

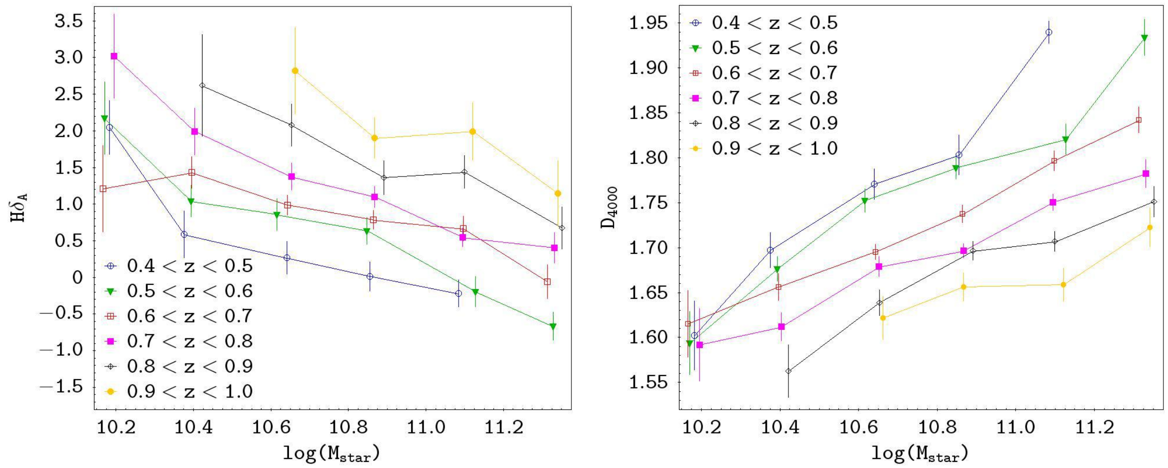

Figure 7. $H\delta_A$ (left panel) and D_{4000} (right panel) as a function of stellar mass. Error bars were obtained on the basis of the Monte Carlo simulation.

Fig. 7 shows that low mass ETGs have higher values of $H\delta_A$ and lower values of D_{4000}. As it was pointed out by [28], local galaxies with stellar masses above $\sim 10^{10}[M_\odot]$ are dominated by old stellar populations and for them the typical D_{4000} break is greater than 1.5. For the sample of ETGs selected from VIPERS survey, the minimum value of D_{4000} is equal to 1.56 ± 0.03 (the mean value of D_{4000} equals to 1.71 ± 0.08). The evolution in D_{4000} is very weak, which implies that all analyzed galaxies consist in majority of Population II stars. In the same time, the values of the $H\delta_A$ absorption line are very low. It suggests that the star formation processes were quenched in these galaxies. Thus, our sample consists mainly of the massive ETGs at redshift $z \sim 1$, with a clear evidence for the stellar population getting older with the increasing stellar masses.

Our results show that galaxies at lower redshift have always higher D_{4000} break than galaxies at higher redshift. Our findings are consistent with the downsizing scenario, as more massive galaxies have higher values of D_{4000} in each redshift bin than less massive galaxies, which implies they are older. Moreover, from the same plot we can deduce that the stellar populations in all ETGs are getting older with decreasing redshift.

4. SUMMARY

In this work we present one of the first results of studies of the star formation history of ETGs based on the unique VIPERS data. Our main results may be summarized as follows:

- Using a bimodal criterion with an evolving cut [19] and some additional quality-ensuring criteria, we have created a unique, pure, statistically unbiased sample of 4,539 ETGs in the redshift range from 0.4 up to 1.2.
- We have divided our sample into 34 narrow redshift and stellar mass bins, and performed the stacking procedure in order to calculate average values of $H\delta_A$ and D_{4000} parameters in each bin.
- We found that $z \sim 1$ lower mass ETGs contain stellar populations younger than higher mass ETGs.
- Our results show that both spectral indicators ($H\delta_A$ and D_{4000}) display an almost linear dependence with stellar mass, and the trends are similar in all the considered redshift ranges.

The presented results demonstrate the usefulness and robustness of data provided by the VIPERS. More detailed analysis of spectral indicators will follow.

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