Galaxy Main Sequence at z $\sim$ 1

Mateusz Rałowski[1], Katarzyna Małek[2] and Agnieszka Pollo[1,2]

1. Astronomical Observatory of the Jagiellonian University, Faculty of Physics, Astronomy and Applied Computer Science, ul. Orla 171, 30-244 Cracow, Poland
2. National Centre for Nuclear Research, ul. Andrzeja Sołtana 7, 05-400 Otwock, Poland

The influence of dust attenuation models on the relationship between star formation rate (SFR) and stellar mass (M^*) (so called "galaxy main sequence", MS) for star-forming galaxies was analyzed based on the sample of $\sim$ 24 000 galaxies from the VIMOS Public Extragalactic Redshift Survey (VIPERS[1]), selected based on the NUVrK$_s$ color-color diagram. For this sample of galaxies, physical parameters based on the Spectral Energy Distribution (SED) fitting were derived. The procedure was repeated for two different attenuation models: Charlot & Fall (2000) (CF00) and Calzetti et al. (2000). The significant difference between estimated values of M^* for different attenuation models was found, with the Charlot & Fall (2000) attenuation model providing, in general, higher values of stellar mass (M^*) and larger scatter for obtained SFR as compared to the Calzetti et al. (2000) attenuation model. The MS obtained with these two attenuation models was also found to differ, with the MS$_{\mathrm{CF00}}$ having a higher slope (0.7) than MS$_{\mathrm{Calzetti}}$ (0.3).

1 Introduction

The main focus of the presented article is the analysis of the influence of different attenuation models on the relationship between galaxy star formation rate (SFR) and stellar masses (M^*). When $\log_{10}$ SFR is expressed as a function of $\log_{10} M^*$, star-forming galaxies (so called blue population galaxies) form a robust sequence. This relation, first mentioned by Brinchmann et al. (2004) (called there "star formation sequence"), is now called "the galaxy main sequence" (MS; Noeske et al., 2007). It was shown to be preserved, albeit evolving, up to $z \sim 6$ (Daddi et al., 2007; Elbaz et al., 2007; Whitaker et al., 2012; Speagle et al., 2014).

Many factors can influence the shape or robustness of the MS. In practice, the two key parameters: SFR and M^* are usually obtained through the Spectral Energy Distributions (SED) fitting. The SED is the distribution of energy over wavelength, in which the information about types and amount of particular star populations, dust and gas are imprinted for the particular galaxy. When one carefully models the full spectrum, physical properties, including SFR and M^* can be derived.

Dust is a very important component of the interstellar medium of galaxies. It absorbs and scatters photons re-emitting the major part of the absorbed energy. This emission is mainly present in the infrared wavelengths. The term "dust attenuation" refers to the overall impact of dust absorption and scattering on the spectrum of an object, especially galaxy. To understand the galaxy evolution it is crucial to model the light that is coming out from the galaxy, and take into account the influence of the dust. Different dust attenuation laws are based on different assumptions and take into account different factors.

[1]The VIPERS web site is http://www.vipers.inaf.it/

The most widely used model was introduced by Calzetti et al. (2000). It was originally obtained based on a sample of 39 local starburst and blue compact galaxies. It provides a mean attenuation curve derived from the data in the UV and the optical range. Another, more complex, model was proposed by Charlot & Fall 2000 (here-after: CF00). In this model attenuation is considered separately from both birth clouds and interstellar medium (ISM), it has an idealized but more detailed description of the ISM. It also considers the ionization of HII regions in the dense clouds and the finite lifetime of these clouds. A more detailed characterization of the difference between these two attenuation models can be found in Lo Faro et al. (2017) and Buat et al. (2018).

Małek et al. (2018), based on a large sample of $\sim$ 40 000 galaxies from the photometric multiwavelength HELP project, selected in the far-infrared, found that SFR is very sensitive to the choice of dust attenuation models, due to the shape of the dust attenuation laws at longer wavelengths ($>$ 5000 Å). In particular, they have shown that two models mentioned above (Charlot & Fall 2000; Calzetti et al. 2000) can lead to differences in the estimated $\log_{10} M^*$, as high as 0.98 ± 0.14. This, in turn, affects the properties of the MS itself.

One may ask if the same is true for other samples, in particular for ultraviolet and optically selected galaxies, which can be expected to be less affected by dust. In this work, the data from the VIMOS Public Extragalactic Redshift Survey (VIPERS) were used to study this effect.

The article is arranged as follows: the VIPERS data and selection of the sample for the purpose of this work are described in Section 2; in Section 3 methods are shortly presented. Section 4 presents results and Section 5 contains conclusions.

2 Data

The VIMOS Public Extragalactic Redshift Survey (VIPERS) is an ESO Large Programme whose aim was to make spectroscopic measurements of $\sim$ 90 000 galaxies at $0.5<z<1.2$ over a sky area of 23.5 deg^2. The photometric observations were done with the Canada-France-Hawaii Telescope Legacy Survey Wide (CFHTLS-Wide), and spectroscopic observations were made with the Very Large Telescope (VLT). One of the main goals of the VIPERS project was to study galaxy evolution. The VIPERS survey has been outlined in detail in Guzzo et al. (2014), Garilli et al. (2014), and Scodeggio et al. (2018). The VIPERS is the largest extragalactic spectroscopic survey at redshift range from 0.5 to 1.2, made up to date. Thus VIPERS provides a large amount of data, including a wide range of auxiliary data useful for the SED analysis.

In particular, the VIPERS data were cross-correlated with the data from two all-sky surveys: the Galaxy Evolution Explorer (GALEX, Gil de Paz et al. 2007) and the Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010), providing consecutively the ultraviolet (UV) and mid-infrared (MIR) observations. In order to achieve the best SED fitting results, both GALEX and WISE observations were used in this work. However, it should be noted that both GALEX and WISE provided relatively shallow surveys, and only a fraction of VIPERS galaxies was bright enough in UV and/or MIR (51% for UV and 99% for 3.4 μm, 75% for 4.6 μm, 20% for 11.6μm and 5% for 22.1 μm) to have corresponding measurements.

To select star-forming galaxies for the MS studies, the following criteria were used. The spectroscopic redshift (hereafter z) range was limited between 0.5 and 1.2 (thus excluding any outliers). Only objects with flags indicating a high quality of the redshift measurement ($9 \geq z_{\rm flag} \geq 2$, the notation explained in Guzzo et al., 2014) were used. All selected objects have optical, UV and IR observations (at least one photometric measurement from UV or IR each range). Following these conditions, a sample of $\sim$ 24 000 galaxies was selected.

As the the next step, this sample was divided into quiescent and star-forming populations, using the rest frame $(NUV - r)$ versus $(r - K_{\rm s})$ color-color diagram (Arnouts et al., 2013; Moutard et al., 2016). We adopted a modified version of the criteria proposed by Moutard et al. (2016). According to these criteria, star-forming galaxies fulfill the equation:

$$[(NUV - r) \leq B_2] \cap [(NUV - r) \leq A \times (r - K_{\rm s}) + B_1], \qquad (1)$$

where B_1 is defined as the position where two normal distributions intersect, B_2 is defined as $B_2 = B_1 + 1.004$, and A is a constant with the value of $A = 2.25$. In the work by Moutard et al. (2016) both B_1 and B_2 are the functions of the look-back time ($t_{\rm l}$). However, for the analysis presented here only one redshift bin was taken. The so-called green valley galaxies (Schawinski et al., 2014) fulfill the same criterion within 10% of the B_1 parameter value. The exact equation allowing to select star-forming galaxies is then:

$$[(NUV - r) \leq 2.858)] \cap [(NUV - r) \leq 2.25 \times (r - K_{\rm s}) + 1.955)]. \qquad (2)$$

After removal of quiescent and green valley galaxies, the remaining 13 142 galaxies fulfilling criteria 2, were selected as star-forming galaxies. Only these galaxies were taken into account for further analysis.

3 Methods

The SED fitting for our analysis was performed making use of the Code Investigating GALaxy Emission (CIGALE[2]; Boquien et al. 2019). CIGALE works based on the energy balance principle and models spectra (from FIR to UV) of galaxies and estimates their physical properties. To fit broad-band spectra of the VIPERS galaxies, the following models were used inside CIGALE: the star formation history (SFH) model, which includes delayed SFR with an additional burst (described in detail by Małek et al. 2018), the stellar population synthesis models by Bruzual & Charlot (2003), with the initial mass function (IMF) given by Chabrier (2003). For dust emission, a model introduced by Draine et al. (2014) was used.

To describe dust attenuation, two models were used: Calzetti et al. (2000) and CF00 (Charlot & Fall, 2000). The SED fitting was performed two times for all galaxies, providing two sets of physical parameters, among them SFR and M_*, corresponding to each attenuation model.

4 Results

A comparison of the resultant values of M^* and SFR obtained by CIGALE using CF00 and Calzetti et al. (2000) models shows that different attenuation models result

[2]The CIGALE web site is https://cigale.lam.fr/

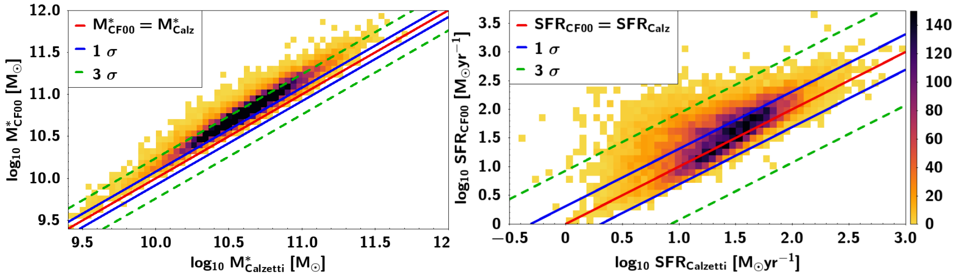

Fig. 1: Comparison of stellar masses (left panel) and star formation rates (right panel) of VIPERS galaxies obtained by SED fitting with CIGALE using CF00 and Calzetti et al. (2000) dust attenuation models. The red solid line corresponds to the 1:1 relation, the blue solid line represents 1 σ error, the dashed green line represents 3 σ error. With color, the amount of galaxies was showed.

in statistically different estimates of $\log_{10} M^*$ for 98% of the VIPERS star-forming (SF) and statistically different estimates of $\log_{10}$ SFR for 82% of the VIPERS SF galaxies. Fig. 1 shows the comparison between Calzetti et al. (2000) and CF00 for M^* in the left panel and for SFR in the right panel. The difference for the M^* is systematic. On average, the Calzetti et al. (2000) model underestimates $\log_{10} M^*$ for all VIPERS SF galaxies by about 0.18±0.08 and $\log_{10}$ SFR by about 0.18±0.31 with respect to CF00 (median values).

The difference between M^* obtained using CF00 and Calzetti et al. (2000) attenuation models can be written down as $\Delta M^* = M^*_{\mathrm{CF00}} - M^*_{\mathrm{Calzetti}}$. As expected, these systematic differences in M_* and SFR are reflected in the shape of the MS.

Fig. 2 shows the MS for CF00 (in the left panel) and Calzetti et al. (2000) (in the right panel) attenuation models. The MS for CF00 is not only shifted towards higher values of M^* and SFR, but it is also tighter and steeper, as compared to the MS for Calzetti et al. (2000) model. The slope for the $\mathrm{MS_{CF00}}$ is ~ 0.7 (which is close to the value obtained for galaxies at redshift $0.2 \leq z \leq 1.2$ by Noeske et al., 2007; Elbaz et al., 2007), while for the $\mathrm{MS_{Calzetti}}$ we measure the slope of ~ 0.3. As one can see a difference between the MS based on physical parameters obtained with different attenuation models is significant. The parameters of the most strongly star-forming galaxies, located in the top part of both MSs, are the most sensitive to the choice of the model; this is probably not surprising, given that we expect them to be also the dustiest.

5 Conclusions

In this work, we have applied Charlot & Fall (2000) and Calzetti et al. (2000) attenuation models to fit the SEDs of 13 142 star-forming galaxies selected in the redshift range $0.5 \leq z \leq 1.2$ from the VIPERS survey and to derive their physical parameters, in particular, M^* and SFR. We compared parameters resultant from both models, and the Galaxy Main Sequence based on them. We found that the choice of the attenuation model is substantial for the derivation of both M^* and SFR also for UV-selected galaxies. We found a difference $\sim 0.18 \pm 0.08 \log_{10}$ for M^* computed based on two different attenuation models. This difference is lower

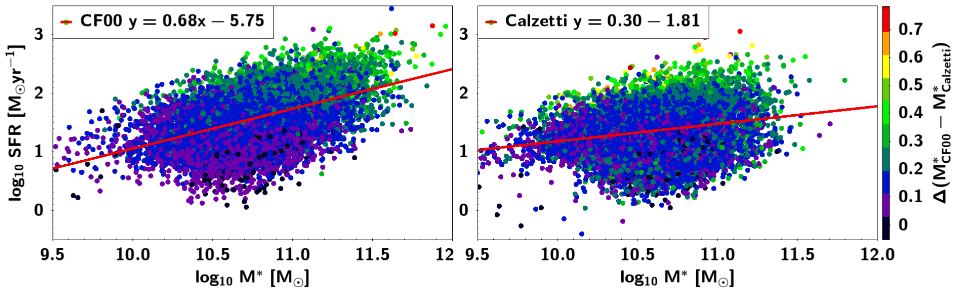

Fig. 2: The Main Sequence based on physical parameters obtained with CF00 (left panel) and Calzetti et al. (2000) (right panel) attenuation models. The red solid line corresponds to the fitted regression line with its equation given in the top part of each panel. With color, the difference between M^*_{CF00} and M^*_{Calzetti} was showed.

than the difference found by Małek et al. (2018) for IR-selected galaxies, but it is statistically significant and the trend (CF00 model giving a higher value of stellar masses than the Calzetti et al. (2000) model) is preserved.

A difference $\sim 0.18 \pm 0.31$ in $\log_{10}$SFR found for the VIPERS galaxies can be related to the lack of the near-far IR data, which makes it impossible to construct proper SFR ($\mathrm{SFR}=\mathrm{SFR}_{\mathrm{optical}}+\mathrm{SFR}_{\mathrm{IR}}$). Małek et al. (2018) have shown that the IR data are essential to reconstruct a proper SFR, and if they are taken into account, SFR remains consistent even if different attenuation laws are used. The lack of the IR data (see Małek et al. (2018) appendix B) results in the inconsistency between SFR obtained using CF00 and Calzetti et al. (2000) models: Małek et al. (2018) found $\mathrm{SFR}_{\mathrm{Calzetti}}=0.91\times\mathrm{SFR}_{\mathrm{CF2000}}+0.0$ while for the VIPERS data we find the inconsistency being even stronger ($\mathrm{SFR}_{\mathrm{Calzetti}}=0.65\times\mathrm{SFR}_{\mathrm{CF00}}+0.32$).

The most strongly star-forming galaxies have the highest differences in M^*. Our results indicate that also for galaxies bright in UV and optical ranges, supposedly less affected by dust than IR-selected galaxies, dust attenuation plays a significant role and needs to be carefully and accurately modeled. It should also be noted that differences of our results with respect to the results obtained by Małek et al. (2018) can be attributed not only to the differences in the sample selection, but also to the fact that for the majority of VIPERS galaxies in our sample available measurements in the infrared, both near-infrared and mid-infrared, are very limited. This may result in further bias in the estimation of physical parameters from SED fitting. Nevertheless, the achieved results remain in a broad agreement with those by Małek et al. (2018), Buat et al. (2018), Mitchell et al. (2013) and demonstrate the necessity of appropriate taking into account the dust attenuation in estimation and interpretation of the physical properties of galaxies, independently on their selection wavelength.

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References

Arnouts, S., et al., *AAP* **558**, A67 (2013)

Boquien, M., et al., *A&A* **622**, A103 (2019)

Brinchmann, J., et al., *MNRAS* **351**, 1151 (2004)

Bruzual, G., Charlot, S., *MNRAS* **344**, 1000 (2003)

Buat, V., et al., *A&A* **619**, A135 (2018)

Calzetti, D., et al., *ApJ* **533**, 2, 682 (2000)

Chabrier, G., *PASP* **115**, 809, 763 (2003)

Charlot, S., Fall, S. M., *ApJ* **539**, 2, 718 (2000)

Daddi, E., et al., *ApJ* **670**, 156 (2007)

Draine, B. T., et al., *ApJ* **780**, 2, 172 (2014)

Elbaz, D., et al., *AAP* **468**, 33 (2007)

Garilli, B., et al., *AAP* **562**, A23 (2014)

Gil de Paz, A., et al., *ApJS* **173**, 2, 185 (2007)

Guzzo, L., et al., *AAP* **566**, A108 (2014)

Lo Faro, B., et al., *MNRAS* **472**, 2, 1372 (2017)

Małek, K., et al., *A&A* **620**, A50 (2018)

Mitchell, P. D., Lacey, C. G., Baugh, C. M., Cole, S., *MNRAS* **435**, 1, 87 (2013)

Moutard, T., et al., *AAP* **590**, A103 (2016)

Noeske, K. G., et al., *ApJL* **660**, L43 (2007)

Schawinski, K., et al., *MNRAS* **440**, 889 (2014)

Scodeggio, M., et al., *AAP* **609**, A84 (2018)

Speagle, J. S., Steinhardt, C. L., Capak, P. L., Silverman, J. D., *ApJS* **214**, 15 (2014)

Whitaker, K. E., et al., *ApJ* **745**, 179 (2012)

Wright, E. L., et al., *AJ* **140**, 6, 1868 (2010)