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An accurate determination of the slope of the UV continuum in $z \sim 3$ star-forming galaxies

Stefano Pilo

INAF - *Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio (RM)*

E-mail: stefano.pilo@oa-roma.inaf.it

Abstract. Measuring dust extinction in high-redshift galaxies is fundamental to estimate the star formation rate density and constrain galaxy evolution models. I measure dust extinction in Lyman break galaxies at $z \sim 3$ where a broad peak in the star formation rate density is thought to occur. On the basis of image simulations I perform a new method for accurate extraction of colours from images with different point spread functions. Taking advantage of a new colour selection criterion I select a sample of 225 LBGs at redshift $< z > \sim 3.2$. The UV slope of the sampled galaxies is determined by a linear fit of the observed magnitudes through a proper set of filters coherently with the original definition of the slope β. By performing measurements of β through IZY filters I find $< \beta > \simeq -1.79$; moreover I find that the β value strongly depends on the set of filters I use for linear fitting. I find a good agreement comparing the three bands fit in our sample with CANDELS GOODS-South data set at the same redshift. UV slope value fits well in the trend for which dust extinction increase at decreasing redshift.

1. Introduction

Since dedicated Lyman Break Galaxy (LBG) surveys has been composed about 20 years ago (e.g. [1,2]), a method called "Lyman break technique" has been improved in order to detect star-forming, moderately absorbed galaxies. Thanks to technical developments that have allowed to reach fainter magnitudes, LBGs have been detected at ever higher redshifts in a wide range of wavelengths. Surveys of this kind are very useful to explore statistical properties of high redshift galaxies in order to measure some fundamental physical quantities like star formation rate density (SFRD) [3], luminosity function (LF) [4, 5] and mass function (MF) [6] to better understand the dynamics of their evolution through cosmic time. Measuring SFRD relies on a proper conversion between the rest-frame UV luminosity and the ongoing star formation rate (SFR). Evaluating the slope of the UV range of a galaxy spectrum is a powerful tool to constrain physical properties that influence this conversion. This work concerns the dust extinction as the most important factor affecting the shape of the rest-frame UV spectrum. Assuming that dust absorption is the strongest reddening factor, the slope of the UV spectrum can be directly related to dust extinction of a galaxy assuming that the spectrum of a star forming galaxy can be well approximated by a power law longward the Ly-α wavelength until 3200Å as discussed in previous works (e.g. [7, 8]). This power law can be written as $F_\lambda = \lambda^\beta$ where β is actually the slope I want to measure and it is equal to about -2.2 for a dust-free stellar population with solar metallicity and constant SFR. Even if many galaxy samples have been collected up to now, β measurement is still affected by large uncertainties (e.g. [3], [9–11]). Discrepancies among different results can be explained by ineffective selection criteria and by the method used to

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measure the UV slope itself, often performed by using a single colour. In this paper I will show a possible way to avoid these limitations including infrared bands both in selection criteria and in the slope measurement: this enhances the efficiency of the selection criterion and can provide a more "stable" fit of the observed magnitudes. Moreover, I will present an original tailored method to perform aperture photometry when dealing with images with different PSFs. The structure of the paper is as follows: in section 2, 3 and 4 I will present dataset and two original methods I used for photometry and selection criteria; in section 5 results will be shown with an overview on critical points in the linear fitting through different sets of filters; summary and conclusions (section 6) will follow at last.

2. Dataset

For this work photometry has been extracted using SExtractor software [12]. I exploited 9 different images in as many different filters acquired in the COSMOS field [13]. Images have been acquired by LBC camera on Large Binocular Telescope (U_{035}, G_{047}, R_{062} having central wavelength 355nm, 475nm, 622nm respectively), Suprime-Cam on Subaru Telescope (I_{076}, Z_{090} having central wavelength 764nm and 903nm respectively) and Vir-Cam on Vista Telescope (Y_{102}, J_{125}, H_{165}, K_{215} having central wavelength 1020nm, 1250nm, 1650nm, 2150nm respectively). The total area covered by these observations is ~ 504 sq. arcmin. The measured limiting magnitudes for each image are the following: $U = 26.4$, $G = 26.8$, $R = 26.2$, $I = 26.0$, $Z = 24.8$, $Y = 24.8$, $J = 24.4$, $H = 24.2$, $K = 23.2$ at 10σ. A multiwavelength catalogue of the sources has been compiled using the R_{062} band as detection band.

3. A new method for accurate ground based photometry

Since the images have been acquired using different telescopes under different weather conditions, they have different PSFs. For this reason the shape of the same object in each image is smoothed in a different way with respect to the others. This implies that fixed aperture photometry is not the right choice because apertures with the same diameter don't recover the same flux fraction from sources in different images, that is in different bands. To avoid this problem I re-define a sort of *effective FWHM* ($FWHM_{eff}$) that depends, for each image, only on the flux that is measured from the sources. This flux fraction is measured on bright stars in the field and it is arbitrarily assumed to be $\frac{FLUX\_BEST}{FLUX\_APER} = 1.5$; this fixes the aperture recovering 66% of the total flux. So the diameter of the aperture that recovers this fraction of flux is the new measure of the PSF of the image, that is what I have previously called the $FWHM_{eff}$. Once I measured for each image its $FWHM_{eff}$, I make extended simulations using an high resolution image acquired by HST in GOODS field [13] (H_{160} image with $FWHM$=0.18arcsec): the idea that lies behind these simulations is that when smoothing a single input image to two images with different PSFs, their colour must be equal to zero (when we collect the same fraction of flux for each object) by definition, because the images have been generated by the same one. Making many tests comparing colours between images smoothed to different PSFs, I find, for every combination of images I have simulated, what are the right apertures to be applied to the measure images in order to have colours equal to zero and to maximize the signal to noise ratio. Tests lead to an empirical relation that allows to choose the right dimension of the aperture for the measure image in terms of its own $FWHM_{eff}$. The aperture for the detection image is fixed to be twice its $FWHM_{eff}$ corresponding to the aperture that has been proved to maximize the signal to noise ratio. So I apply the above mentioned relation, that is

$$Aper(meas) = [FWHM_{eff}(det) - FWHM_{eff}(meas)] + 2 \quad (1)$$

where *det* refers to the detection image and *meas* to the measured one. Thus I compile a catalogue of sources: total magnitude is measured as

$$MAG_{tot}(U) = MAG_{tot}(R) + (MAG(U) - MAG(R))_{aper} \quad (2)$$

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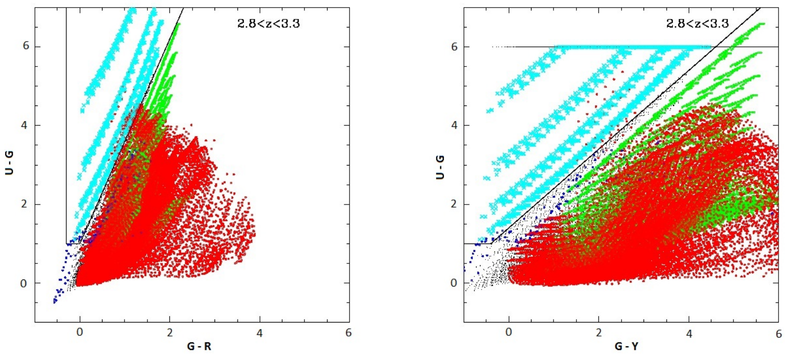
where colours are measured in a variable circular aperture according to equation 1. Recalling that the R band is the detection one, equation 2 is applied to all the other filters.

4. A new selection criterion

It has been proved that modifying usual colour-colour selection criteria for $z \sim 4$ galaxies including a redder band H instead of the usual one Z, provides a cleaner selection of LBGs in the selected redshift range [3]. To extend this approach to lower z, I make a comparison on the basis of stellar populations libraries between the usual *(U-G) vs (G-R)* selection criterion and a new one *(U-G) vs (G-Y)* for $z \sim 3$ galaxies. The two different criteria are plotted in figure 1.



(a) UGR selection criterion. (b) UGY selection criterion.

Figure 1: Comparison between UGR criterion (panel a) and UGY criterion (panel b). Different colours stand for the evolution of different kinds of galaxies in the diagram: LBGs in the labeled redshift range (cyan), LBGs out of the desired range (black), passively evolving elliptic galaxies at lower redshift (red), dusty galaxies (green), stars (blue). The lines indicate the adopted selection window.

Selection cuts of the UGY criterion have been empirically defined by models taken from [14, 15]. They have been chosen as follows, by looking at the position in the UGY diagram of the sources in the redshift range of interest:

$$(U - G) > 1$$
$$(U - G) > (G - Y) + 1.24$$

The main drawback I want to avoid in this kind of selections is the contamination of the sample by lower redshift interlopers. This contamination arises because very reddened galaxies and passively evolving ones at lower redshifts can mimic the same spectral features of $z \sim 3$ LBGs that I actually want to select. The comparison between selection criteria shows that the UGY one provides a better and cleaner selection than the usual UGR, avoiding in a better way spurious sources from the selection window in the redshift range of interest. The chosen selection criterion provides a robust sample of 225 galaxies with the bulk of them having absolute magnitude between -22.6 and -20.8 and redshift between $z_{min} \sim 2.8$ and $z_{max} \sim 3.6$ providing a distribution with a proved photometric redshift $< z > \simeq 3.2$.

5. Estimating the UV slopes

Once the sample has been acquired by applying the UGY selection criterion to real data, β is measured by fitting a linear relation through a proper set of filters in order to sample the rest frame UV spectral range of the sources. Figure 2 shows the result obtained in measuring the UV slope of the sample through a 3-filters set (IZY) and the distribution of β itself. I obtain $< \beta >= -1.79 \pm 0.05$ where the error is calculated as the r.m.s. value of the distribution divided by the square root of the number of sources that form the selected sample. Assuming the Calzetti law [16], this value corresponds to a mean reddening $< E(B-V) > (z \sim 3) = 0.44(1/4.39)(2.31 < \beta > +4.85) \simeq 0.07$. Moreover, the plot shows a modest dependence of β on the absolute magnitude of the sources estimated at 1600Å rest-frame, in the sense that for fainter objects its value seems to increase. Assuming that the slope of the UV spectrum is largely dominated by the presence of dust in a galaxy, this result fits well in the literature trend in which dust extinction in high redshift galaxies increases when redshift itself decreases (e.g. [3,11,17,18]). In order to test the results with a fainter magnitude sample I make a comparison with the CANDELS-GOODS field dataset. This consists of 296 galaxies in the same redshift range as the sample in the COSMOS field. As it can be seen in figure 3, the comparison with GOODS field sample shows a pretty good agreement with my β measurement: I obtain $< \beta >= -1.81 \pm 0.06$ for a linear fitting through I_{775}, Z_{850} and Y_{105} filters (with central wavelengths 771nm, 888nm and 1058nm respectively).

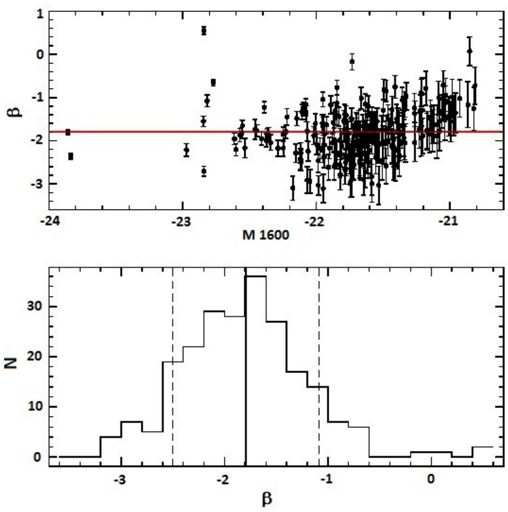


Figure 2: *Upper panel*: β vs rest-frame magnitude at 1600Å; the red line marks $< \beta >$. *Lower panel*: distribution of β where vertical central line is $< \beta >$ value and the dashed ones indicate $rms = 0.70$.

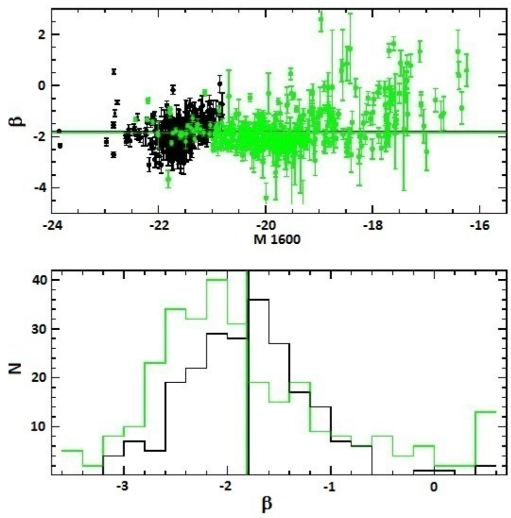


Figure 3: *Upper panel*: COSMOS sample β (black) and GOODS sample β (green) plotted together. *Lower panel*: the COSMOS and GOODS β distributions overplotted. Lines in both panels mark $< \beta >$ value for each dataset.

5.1. Considerations on filter choice

As already mentioned, an unbiased measurement of β is a matter of very precise and tricky photometry and it is tightly related to the range of the UV spectrum is actually chosen to be sampled, assuming it is well approximated by a power law. This comes out measuring β with a linear fit through the wider range of 5 filters ($RIZYJ$). This returns $< \beta >= -1.42 \pm 0.03$ that seems to indicate a too wide difference between values in literature. Moreover, looking at precedent works on $z \sim 4$ LBGs slope [3,18], reporting $\beta(z \sim 4) \simeq -1.9$, I argue that this value of β would indicate a too strong evolution in the dust extinction between these two stages of cosmic time. Comparing these two different approaches in measuring the β slope of a sample, both advantages and drawbacks should be taken into account. A 5-filters measurement provides a more stable linear fit because it is constrained by 5 points; on the other hand, a 3-filter linear fit will be necessarily more noisy, increasing the error bars of each galaxy slope measurement.

As a counterpart instead, a 3-filter fit most probably samples the UV range of the spectrum in which the power-law approximation still stands in the whole range of redshift distribution of the sample. "Extreme" bands in the fit (such as R and J bands) can introduce biases. Indeed the R band could be (partially) affected by the presence of the Ly-α line, while the J band samples the UV-continuum at ~ 3000Å rest-frame which is affected by the presence of old stellar populations.

6. Summary and conclusions

This paper presented a statistical study of high redshift LBGs. I have investigated their dust extinction by measuring the slope of the UV spectrum in a sample of 225 galaxies selected through a colour criterion in the redshift range $2.8 < z < 3.6$. The aim has been achieved by exploiting photometry extracted from a set of deep images in the optical-near infrared wavelengths in the COSMOS field. At a first stage a new method to measure colours from different PSF images has been applied in order to compile a catalogue of total magnitudes of the sources. Once the catalogue has been made, I exploited a new selection criterion based on UGY bands that have provided a robust sample of galaxies at $< z >\sim 3.2$. Finally the β slope has been measured by fitting a linear relation through a set of three filters (IZY) sampling the very central part of the rest-frame range $1500\text{Å} < \lambda < 3200\text{Å}$ within which the UV spectrum can be well approximated by a power law. I obtained $< \beta >= -1.79 \pm 0.05$ showing a modest dependence on the magnitude of the sources. This value is consistent with recent literature results and has been proved to be consistent with a fainter magnitude sample extracted from CANDELS-GOODS dataset; moreover it fits well in the well established trend for which dust extinction in galaxies increases when cosmic time runs from high redshifts to lower ones. Moreover this study has enlightened an interesting point in the β method itself of fitting a linear relation through a set of filters. Indeed I have found a strong dependence of the value of β on the set of filters used in the linear fitting procedure. Adding the R band at the very red part of the wavelength range and the J band at the bluer part I have found a value of $< \beta >= -1.42 \pm 0.03$: this probably relies on the fact that the two added extreme filters sample a part of the UV spectrum (partially) affected by some spectral features that influence the power law approximation and by the presence of old stellar populations. At the very end, although the value of β has been found to be consistent, an important caveat emerged, that is the necessity to sample, as accurately as possible, the same part of the UV spectrum when comparing the slopes at different redshifts.

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