Challenges in Panchromatic Modelling with Next Generation Facilities
Proceedings IAU Symposium No. 341, 2018
M. Boquien, E. Lusso, C. Gruppioni & P. Tissera, eds.

doi:10.1017/S1743921319002692

Which attenuation curves for star-forming galaxies?

Véronique Buat[1], David Corre[1], Médéric Boquien[2] and Katarzyna Małek[1,3]

[1]Aix Marseille Univ, CNRS, CNES, LAM Marseille, France
email: veronique.buat@lam.fr

[2]Centro de Astronomía (CITEVA), Universidad de Antofagasta, Avenida Angamos 601, Antofagasta, Chile

[3]National Centre for Nuclear Research, ul. Hoza 69, 00-681 Warszawa, Poland

Abstract. Dust attenuation shapes the spectral energy distributions of galaxies and any modelling and fitting procedure of their spectral energy distributions must account for this process. We present results of two recent works dedicated at measuring the dust attenuation curves in star forming galaxies at redshift from 0.5 to 3, by fitting continuum (photometric) and line (spectroscopic) measurements simultaneously with CIGALE using variable attenuation laws based on flexible recipes. Both studies conclude to a large variety of effective attenuation laws with an attenuation law flattening when the obscuration increases. An extra attenuation is found for nebular lines. The comparison with radiative transfer models implies a flattening of the attenuation law up to near infrared wavelengths, which is well reproduced with a power-laws recipe inspired by the Charlot and Fall recipe. Here we propose a global modification of the Calzetti attenuation law to better reproduce the results of radiative transfer models.

Keywords. galaxies: high-redshift–, dust : extinction –galaxies: ISM–infrared: galaxies

1. Introduction

Modelling the spectral energy distribution (SED) of galaxies is a method commonly used to derive physical parameters useful to quantify galaxy evolution like stellar masses or star formation histories. Dust plays a crucial role by strongly affecting and reshaping the spectral energy distribution (SED): it absorbs and scatters stellar photons, and thermally emits the absorbed energy in the infrared (IR) ($\lambda \sim 1 - 1000\ \mu$m). The simplest way to model this dust effect to introduce effective attenuation curves which account for the complex blending of dust properties and relative geometrical distribution of stars and dust within a galaxy. The most commonly used recipes are the ones proposed by Calzetti *et al.* (1995) (hereafter C00) and Charlot & Fall (2000). These two recipes include a differential attenuation between young stars/nebular emission and older stellar populations. Since these original works, several authors proposed a modification of these fixed recipes (e.g. Buat *et al.* (2018); Kriek & Conroy (2013); Salmon *et al.* (2016); Lo Faro *et al.* (2017)). In this work we adopt flexible recipes based on both formalisms, the method is fully described in Buat *et al.* (2018). The general behaviour of the two formalisms, in their flexible form, is illustrated in Fig. 1. While both recipes give similar trends in the UV-V range, the shapes of the attenuation curves are systematically different in the V-NIR range with a flatter shape for the recipe derived from the Charlot & Fall (2000) model.

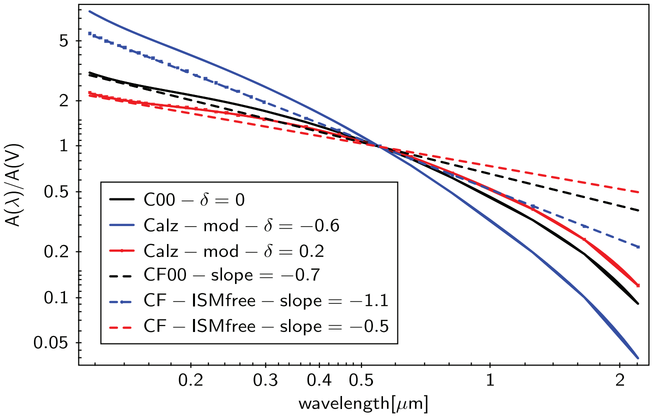

Figure 1. Flexible effective attenuation curves based on the Calzetti *et al.* original law (solid lines) and on the Charlot and Fall original power-laws (dotted lines, the curves refer only here to the attenuation in the interstellar medium (ISM) and not the birth clouds). Both recipes exhibit similar flexibility in the UV-V range. At V-NIR wavelengths the Calzetti-like recipes lead to much steeper slopes than the ones based on the power-laws introduced by Charlot and Fall

2. Determinations of dust attenuations laws in high redshift galaxies

We based our analysis on two different galaxy samples. The first one is presented in Buat *et al.* (2018). It consists of galaxies in the COSMOS field, detected with the PACS and SPIRE instruments of the *Herschel* satellite and for which low resolution spectra are available from the 3D-HST survey. The sample is made of 33 galaxies observed in 21 photometric bands from the NUV to the submm and with a Hα line measurement. The second galaxy sample was built by Corre (2018) and consists of 19 galaxies hosting a γ-ray burst (GRBHs), observed in at least 5 photometric bands starting in the UV rest frame and with Hα and Hβ line measurements.

The SEDs of all the galaxies were fitted with the CIGALE code which allows to fit simultaneously photometric and emission line fluxes (Boquien *et al.* (2018). Both measurements were very well fitted. The 3D-HST/COSMOS sample was fitted with both the modified C00 and Charlot and Fall recipes (Buat *et al.* (2018)). The GRBHs sample was only studied with the modified Calzetti recipe (Corre *et al.* (2018); Corre (2018)). For the purpose of the comparison between the two studies, we focus here on the results based on the modified Calzetti recipe.

The flexible recipe is defined as:

$$A(\lambda) = E(\mathrm{B}-\mathrm{V})_{\mathrm{star}} k'(\lambda) \left(\frac{\lambda}{\lambda_{\mathrm{V}}}\right)^{\delta}, \tag{1}$$

$\delta = 0$ corresponds to the original C00 recipe. The nebular component is extinguished with a simple screen model, a Milky Way extinction curve and a color excess $E(\mathrm{B}-\mathrm{V})_{\mathrm{line}}$. The ratio $E(\mathrm{B}-\mathrm{V})_{\mathrm{star}}/E(\mathrm{B}-\mathrm{V})_{\mathrm{line}}$ is defined as a free parameter in our recipe (it is fixed to 0.44 in the original C00 recipe).

The results are shown in Fig. 2. On the left plot, the color excesses for lines and stars are correlated and the two samples lead to consistent distributions. The average value of $E(\mathrm{B}-\mathrm{V})_{\mathrm{star}}/E(\mathrm{B}-\mathrm{V})_{\mathrm{line}}$ is found to be 0.56 ± 0.20, only slightly larger than the 0.44 value used by C00. The right panel of Figure 2 presents the correction δ to the slope of the attenuation law as a function of the attenuation, Av. The δ parameter spans a wide

https://doi.org/10.1017/S1743921319002692 Published online by Cambridge University Press

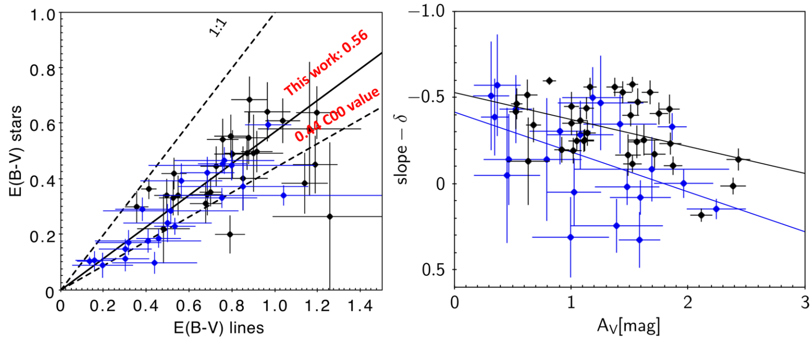

Figure 2. Attenuation characteristics obtained from the SED fitting analysis for the GRBH sample (blue symbols) and the 3D-HST/COSMOS sample (black symbols). Left: the color excess of the nebular emission is compared to the color excess of the stellar continuum, the average value of $E(\mathrm{B-V})_{\mathrm{star}}/E(\mathrm{B-V})_{\mathrm{line}}$ found for our samples and by C00 are also plotted as well as as the 1:1 relation. Right: the correction δ to apply to the original C00 attenuation curve is plotted against the global attenuation, represented by A_{V}

range of values, with most of the curves having steeper slopes than the original C00 law, corresponding to $\delta = 0$. The majority of the 3D-HST/COSMOS galaxies is well modelled by curves with $\delta < 0$, i.e. with higher levels of extinction at the blue wavelengths with respect to C00. Figure 2 also shows that, as Av increases the attenuation law flattens, consistently with previous observational and modelling studies (e.g. Salmon *et al.* (2016), Chevallard *et al.* (2013)). We stress that in the present study, the shape of the attenuation curve and the relative attenuation of young and old stars are taken free parameters which was not the case in previous published works.

3. Consistency of attenuation recipes with radiation transfer modelling

Radiation transfer models predict a flattening of the attenuation law when the global attenuation increase, and this flattening is seen up to the NIR. As shown in Fig.1, the Calzetti recipe, modified with the introduction of δ, does not allow for this flattening which is easier to get with power-laws modelling. We propose to modify the exponent δ in $\delta + \epsilon$ at wavelength longer than the V band as follows

$$\lambda < \lambda_{\mathrm{V}}, A(\lambda) = E(\mathrm{B-V})_{\mathrm{star}} k'(\lambda) \left(\frac{\lambda}{\lambda_{\mathrm{V}}}\right)^{\delta} \tag{2}$$

$$\lambda > \lambda_{\mathrm{V}}, A(\lambda) = E(\mathrm{B-V})_{\mathrm{star}} k'(\lambda) \left(\frac{\lambda}{\lambda_{\mathrm{V}}}\right)^{\delta+\epsilon} \tag{3}$$

The value of the correction ϵ can be inferred from the radiation transfer calculations of Seon & Draine (2016). Corre (2018) fitted the numerical results of their calculations with the Calzetti modified formalism, including the ϵ correction.

In Fig. 3 the values obtained of ϵ and δ are reported. The red curve is the result of a polynomial fit:

$$\epsilon = 0.35\ \delta^2 + 0.04\ \delta + 0.41. \tag{4}$$

The correction can be implemented either as this relation between δ and ϵ or as a single average value (Corre *et al.* 2019, in prep.).

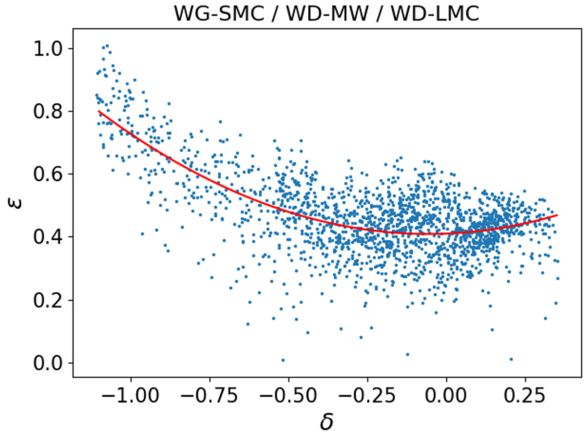

Figure 3. Correction of the slope of the attenuation law at wavelengths larger than the V band calculated with the models of Seon & Draine (2016). Several dust models are used, the blue points correspond to the results of the fits performed on the numerical results of Seon & Draine (2016). The red curve is the best fit (ϵ as a function of δ).

References

Boquien, M., Burgarella, D., Roehlly, Y., *et al.* 2018, arXiv:181103094B
Buat, V., Giovannoli, E., Heinis, S., *et al.* 2011, *A&A*, 533, A93
Buat, V., Boquien, M., Malek, K., *et al.* 2018, *A&A*, 619, A135
Calzetti, C., Armus, L., Bohlin, R. C., *et al.* 2000, *ApJ*, 533, 682
Charlot, S. & Fall, S. M. 2000, *ApJ*, 539, 718
Chevallard, J., Charlot, S., Wandelt, B. & Wild, V., *et al.* 2013, *MNRAS*, 462, 1415
Corre, D. 2018, *PhD thesis, Aix-Marseille Université*
Kriek, M. & Conroy, C. 2013, *ApJ*, 775, L16
Lo Faro, B., Buat, V., Roehlly. Y., *et al.* 2017, *MNRAS*, 472, 1372
Salmon, B., Papovich, C., Long, J., *et al.* 2016, *ApJ*, 827, 20
Seon, K.-I. & Draine, B. T. 2013, *ApJ*, 833, 201

Discussion

Gergo Popping: Do you see a correlation between extinction versus attenuation curve offset and SFR or main-sequence offset?

Veronique Buat: We found a flattening of the attenuation curve with SFR and no clear trend with sSFR. The offset between extinction and attenuation curves does not seem to be correlated to SFR but our sample remains very small and biased to extinction curves of LMC or MW types.

Tomotsugu Goto: What is the difference between modified Calzetti and CF2000? Which is better in the end?

Veronique Buat: The way to implement each of them in SED fitting is different. A single attenuation law (Calzetti-like) is easier to handle than an age dependent one. The most important issue is to keep some flexibility to represent the diversity of cases and to add a correction in NIR to the Calzetti-like recipe to fit dusty galaxies.

Yutaka Fujita: Did you study only Long GRBs

Veronique Buat: Yes, we did.

https://doi.org/10.1017/S1743921319002692 Published online by Cambridge University Press