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UV DUST ATTENUATION AS A FUNCTION OF STELLAR MASS AND ITS EVOLUTION WITH REDSHIFT

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Abstract. Describing the Universe in its early stages requires obtaining knowledge about the various components in distant galaxies (stars, gas, dust). This work aims to further constrain the relationship between the ultraviolet dust attenuation and stellar mass, as well as the evolution of the dust attenuation with redshift, by creating a three dimensional model for the dust attenuation, which uses these two galactic parameters (redshift and stellar mass). By combining data from different literature sources, we were able to compile a data set comprised of estimates of photometric redshift, stellar mass and dust attenuation calculated by the infrared excess (IRX) method, i.e. by converting the ratio of the infrared-to-ultraviolet luminosity of galaxies to ultraviolet dust attenuation. Using this result, we will be able to model and predict what the emission of galaxies at high redshifts is. This information will be useful to understand and interpret the data that the ELT will collect, especially the first imaging instruments MICADO and METIS.

Keywords: Galaxies: evolution – Galaxies: high-redshift – Cosmology: early Universe

1 Introduction

Cosmic dust, alongside the interstellar gas and the stars, is one of the main visible components of galaxies. Even though it takes up only a small portion of the interstellar medium (the gas-to-dust ratio is usually taken to be 100), it is nonetheless a very important constituent of the complex system that is a galaxy. Dust has several important roles within the galaxy; it plays a part in the creation of stars, it enables the creation of planets, and its presence is necessary to create molecules and thus have astrochemistry present in the interstellar medium.

The light emerging from a galaxy is heavily influenced by the presence of dust. The size of the dust grains is such that they are very efficient in absorbing the ultraviolet (UV) light. The young stars that can be found within a galaxy have strong UV radiation, which enables us to trace the formation of stars in galaxies, so, the fact that the UV part of the spectrum is attenuated by dust is very inconvenient. Due to the laws of energy balance, however, the absorbed UV light is then re-emitted by the dust as thermal energy, so we observe it as infrared (IR) radiation. If we look at the Spectral Energy Distribution (SED) of a galaxy, we can estimate the total IR luminosity $L_{\rm IR}$ of the galaxy, as well as the far-UV (FUV) luminosity emitted by the galaxy (and attenuated by dust) $L_{\rm FUV}$. The ratio of these two values is usually referred to as the Infrared Excess (IRX) (Meurer et al. 1999), can be translated to dust attenuation with the help of a conversion relation, such as the one proposed by Hao et al. (2011).

In this work, we are interested in the dust attenuation of galaxies throughout the history of the Universe, as well as the dependence of the dust attenuation on stellar mass M_*. The main goal is to model the dust attenuation as a function of both the galactic stellar mass and redshift so that it would be possible to give an estimate of the average of the properties of galaxies in the Universe knowing only these two parameters. This will be very useful in simulating how observations by different instruments would look like, which in turn would prepare us for the data and science these instruments of the future will bring.

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2 Dust attenuation vs. Stellar mass

The relationship between the stellar mass of a galaxy and the dust attenuation (or in some cases, directly the relation IRX-M_*) has been studied by a few different groups (Heinis et al. 2014; Whitaker et al. 2014, 2017; Pannella et al. 2015; Álvarez-Márquez et al. 2016; Bouwens et al. 2016; McLure et al. 2018). These groups came to the conclusion that the $A_{\rm FUV} - M_*$ relationship is the same throughout cosmic time. In this work, however, we start with the assumption that this relationship does in fact evolve, and thus we arrive at some results about the evolution of the average dust attenuation in the Universe that coincide with other studies of the same problem, where a different approach is used.

Finding a relationship between the stellar mass and dust attenuation that evolves with redshift included compiling existing data from the literature in as many redshift ranges as possible. The references and the redshifts studied by the different groups are shown in Fig. 1 (right), marked with the coloured squares. Taking each redshift given in the various papers as a separate redshift bin, as well as dividing galaxies in redshift bins of width $\Delta z = 1$ for where data of individual galaxies is given (Bouwens et al. 2016; Schaerer et al. 2015), we are left with 18 redshift bins, shown in Fig. 1 (left). Some of the bins purposefully have the same redshift, in order to avoid mixing data of different types (stacked vs. individual galaxies).

Once separated by redshift, the data has been fitted with a function that has the same shape in each redshift bin, differing only by a multiplicative factor between the redshift bins. The chosen function gives the lowest reduced chi-square on average throughout the redshift bins. As the amount of data for low mass galaxies is not very significant, the low-mass end of the function has been set to have a constant constant value until $\log(M_*/M_\odot) = 10.1$. For the high-mass end there has been evidence for saturation and flattening (e.g. Whitaker et al. 2014, 2017), so, for the high-mass range we chose first an increasing function until stellar mass $\log(M_*/M_\odot) = 13$, and then a decreasing function which reaches zero dust attenuation for $\log(M_*/M_\odot) = 14$. We justify this sudden drop in dust attenuation for high stellar masses by pointing out that there is an extremely low number of galaxies with such high masses, as indicated by the mass functions suggested by, for example, Song et al. (2016). The function has the following form, where the parameter a is different for each redshift bin, and the stellar mass is expressed in units of solar masses ($M_\odot$):

$$A_{\rm FUV}(\log M_*) = a \begin{cases} 0.85, & \log M_* < 10.1 \\ \log M_* - 9.25, & 10.1 < \log M_* < 13 \\ -3.75 \log M_* + 52.5, & 13 < \log M_* < 14 \\ 0, & \log M_* > 14 \end{cases} \tag{2.1}$$

We have updated our result in the time between the SF2A meeting and the writing of the proceedings, so here the latest results are shown. For the results presented in the meeting, refer to the paper published by the same authors.

3 Dust attenuation vs. Redshift

The main purpose of this work is to quantify the evolution of the average dust attenuation in the Universe as a function of cosmic time. Thus, the work of Sect. 2 is only the beginning. As the parameter a in Eq. (2.1) is the only difference between redshift bins, we fit its dependence on the redshift $a(z)$. The function used to fit this dependence is the following, with the best fit values for the parameters being $\alpha = 1.69$, $\beta = 2.51$, $\gamma = 0.30$, and $\delta = 0.92$:

$$a(z) = \delta \ (z+\gamma) \cdot \alpha^{(\beta - (z+\gamma))} \tag{3.1}$$

We now have the *dependence* of the dust attenuation on redshift, but, if we wish to calculate the numerical values of the dust attenuation we either need to do it for all stellar masses (in three dimensions, as in Sect. 4), or select a value for $\log M_*$, and show the dust attenuation only for this mass. This is equivalent to drawing a vertical line in Fig. 1 (left) at the given $\log M_*$ and selecting the intersections with the coloured lines as the values of the dust attenuation. That is exactly what is presented in Fig. 1 (right), for $logM_* = 8$, represented by the dashed black line.

Due to the fact that the evolution of the $A_{\rm FUV} - M_*$ has been disputed in the literature, we performed an additional check to make sure of the validity of our results. We calculated the average value of the dust

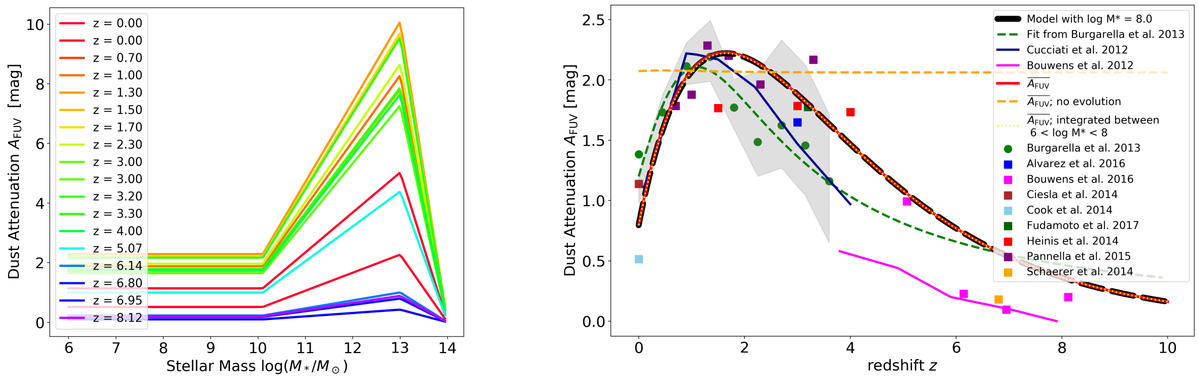

Fig. 1. Left: The dependence on the dust attenuation in the UV on stellar mass. The different lines represent the model given in Eq. (2.1) calculated in different redshift bins. **Right:** The evolution of the dust attenuation in the UV with redshift. The dashed black line gives the model of Eq. (3.1) calculated for a stellar mass $\log(M_*/M_\odot) = 8$. The full red line represents the average dust attenuation, calculated by integrating the model of Eq. (3.1), weighted by the mass function. The dashed purple line gives the same quantity as the full red line, but calculated only by integrating within different mass limits, namely $6 < \log(M_*/M_\odot) < 8$. The dashed orange represents again the mean dust attenuation calculated using a constant model for $a(z)$. The data points represented by squares are the values of the $A_{\rm FUV} - M_*$ relation of each redshift bin (Fig. 1, left) also for $\log(M_*/M_\odot) = 8$.

attenuation for each redshift bin by integrating the function of Eq. 2.1 and by weighting the integral by the mass function calculated at the given redshift. The mass function has been estimated based on work available in the literature (Tomczak et al. 2014; Grazian et al. 2015; Mortlock et al. 2015; Song et al. 2016). The result of this test is presented by the full red line. If instead of integrating Eq. (2.1) we use a constant function (corresponding to the idea that the $A_{\rm FUV} - M_*$ relationship does not evolve), we get the result represented by the dashed yellow line. This is supportive of the idea that the $A_{\rm FUV} - M_*$ relationship does not remain the same throughout cosmic time, as the red line corresponds to the results found by other authors, most notably Burgarella et al. (2013) and Cucciati et al. (2012), who use different methods to estimate the same quantity.

4 Synthesis in a 3D model

Being able to compute the dust attenuation of a large number of galaxies by assuming a realistic mass function in multiple points in cosmic time will enable us to simulate the SEDs of galaxies up to redshift $z \sim 10$. With that aim in mind, we first created a model for a set of redshift bins (Sect. 2) and then fitted the parameter $a(z)$ to be able to calculate such a model at any redshift, as opposed to only the redshifts for which we have data. This also enables us to extrapolate to higher redshifts. Combining, Eqs. (2.1) and (3.1), we obtain a 3D model for the dust attenuation $A_{\rm FUV}$ as a function of both redshift and stellar mass. This is shown in Fig. 2. The functional form of this, using the same parameters with the same numerical values as described before, is the following:

$$A_{\rm FUV} = \delta\ (z+\gamma)\cdot\alpha^{(\beta-(z+\gamma))} \times \begin{cases} 0.85, & \log M_* < 10.1 \\ \log M_* - 9.25, & 10.1 < \log M_* < 13 \\ -3.75\log M_* + 52.5, & 13 < \log M_* < 14 \\ 0, & \log M_* > 14 \end{cases} \tag{4.1}$$

Saying that we know how the dust attenuation behaves at redshifts as high as $z \sim 10$ is very ambitious and, in fact, untruthful. However, with the new generation of observing facilities, such as the *James Webb Space Telescope* (JWST) and the *Extremely Large Telescope* (ELT) we can hope to discover in more detail the truth about this behaviour (and many many others!). As the method used in this work is based on both UV and IR multiwavelength data, and we are interested in high-redshift galaxies, both of the aforementioned observatories would provide a lot of data useful for this project, especially if we combine the data from JWST with the one provided by the ELT instruments MICADO and METIS. Finally, it is interesting to note that it is possible to use the findings of this project to predict what the observations from any facility would look like by performing simulations with the code CIGALE (Noll et al. 2009), developed at LAM, which would prepare us to handle the data analysis, as well as the new science, which will be brought to the world of science by these instruments.

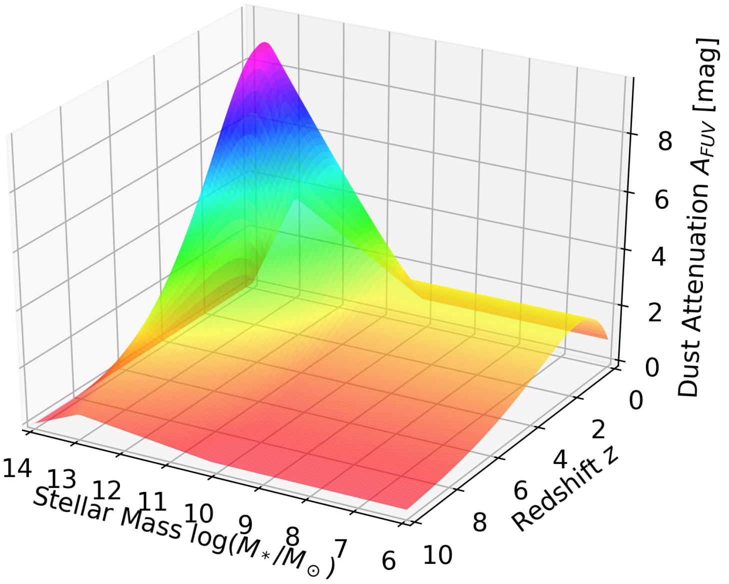

Fig. 2. Three-dimensional representation of the dust attenuation in the UV as a function of both redshift and stellar mass. The colour map used also represents the dust attenuation, and, as it does not provide any additional information, it is used only for improving the clarity of the figure.

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