Understanding the Role of Dust in Star Forming Galaxies through NUV and Optical Photometry

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I, Mónica Christel Tress Barojas, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.
Abstract

Dust is an important element in the universe. Dust effects are evident when one examines the wavelength dependency of the dust attenuation law: it absorbs and scatters at shorter wavelengths and re-emits in the infrared. Good constraints on the dust attenuation law allow us to calculate robust star formation rates, stellar masses, and other stellar parameters. The main goal in this work is to test the non-universality of the dust attenuation law for galaxies. As a first step to analyse the dust attenuation law of star-forming galaxies at $z \sim 2$, we compared sets of synthetic population models from Bruzual and Charlot (2003) to UVOT and SDSS simulated photometry, using a parametric dust attenuation law to characterise the dust attenuation parameter $E(B-V)$. The next step was to test this method with simulations similar to the Survey of Red and Dead Sources (SHARDS) photometry. Thus, finding the best way to assess SHARDS data. This analysis involved taking into account $R_V$, NUV bump and redshift as new parameters in our methodology, which allowed us to constrain the dust attenuation law of $\sim 1700$ galaxies at redshift $1.5 < z < 3$. A wide range of dust parameters were found, a contrast from the often assumed universality of the dust attenuation law. Another intriguing result was the correlation between $R_V$ and the NUV bump strength, which can be explained either by a variation on the dust geometry or due to a trend in the grain size distribution of the dust. To discriminate between these two explanations, we built a set of simulations. They share the important characteristic of having the same underlying dust extinction properties, to explore the role that dust geometry plays. Finally, this analysis points to geometry as the main driver for the $R_V$ and NUV bump trend.
Impact Statement

This thesis focuses on dust in the interstellar medium of star-forming galaxies. More specifically, I explore variations of the dust attenuation law – i.e. the wavelength dependence of the combined absorption and scattering processes – and the consequences on the analysis of the stellar component of galaxies. The study combines population synthesis models with a generic law that encapsulates the effects of dust into three parameters, making use of photometric data sets, both real and synthetic, to constrain the dust-related parameters. Various statistical procedures related to model fitting are applied, including chi2, likelihood analysis and Bayesian inference. The main conclusion of this work is the confirmation of the non-universality of the dust attenuation law, challenging the paradigm where the dust attenuation curve is considered universal across all galaxies. The significance of variations in the dust attenuation curve among galaxies is evident since they introduce biases in the derivation of critical measurements such as star formation rates, stellar ages and masses.

Consequently, this thesis provides additional, robust evidence to the non-universal dust attenuation scenario. The wide range of dust properties found in the galaxies of our SHARDS sample and the correlations observed give additional proof that adopting a fixed law for galaxies is not a good approach. Despite the observed variation of the dust properties, we verified that diagnostics such as the UVJ bi-colour plot, which differentiates between quiescent and star-forming galaxies, remains unaffected. This is an important result, as many photometric studies of galaxies classify the star formation activity by use of this UVJ diagram. Finally, it was possible to mimic the observed dust trends with a time-dependent extinction
Impact Statement

at fixed dust composition, giving support to the birth cloud model, whereby dust mostly affects the youngest populations in stellar clusters, and gets progressively dissolved as the populations age and disperse within the host galaxy. This thesis has produced two refereed papers published in MNRAS. Both papers have been well received and are being cited by groups that actively work on dust attenuation in galaxies. This work was also presented at various meetings in Europe and the USA.

Beyond academia, this thesis also produced an impact in outreach and public engagement. Astrophysics is, arguably, the most engaging topic to attract newer generations to the natural sciences. In particular, the description of galaxies is particularly amenable for this purpose. Additionally, on the more technical side, the methodology used in this thesis could be applied to other problems over a wider scope of disciplines, such as market processes or engineering analysis.
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Chapter 1

Introduction

Dust is everywhere in the universe. Dust grains are formed mainly of O, C, Si, Mg and Fe existing in the interstellar medium (ISM). In particular, less than 1% of ISM mass is in the form of dust grains which are homogeneously combined with the gas in the ISM (Galliano et al., 2018, Sparke and Gallagher, 2000). The size of dust particles ranges from $\sim 0.001\mu m$ to $\sim 1\mu m$. These particles affect light by obscuring mostly at visible and UV wavelengths (Whittet, 2003). These effects are wavelength-dependent: radiation suffers more scattering and absorption in the blue and ultraviolet region than in the infrared. So, dust makes objects appear dimmer and redder (Sparke and Gallagher, 2000). Despite their small contribution to the total mass, these particles have a remarkable impact on the view of the Universe due to their efficiency in scattering, absorbing and re-radiating light. The fact that only one photon in every $10^{12}$ reaches the telescopes, between us and the centre of the Galaxy at visible wavelengths, is sufficient proof of the influence and importance of dust (Whittet, 2003).

1.1 Historical outlook

Historically, making use of optical data to obtain information about the properties of dust—like extinction, scattering and polarisation— has been pivotal. The main driver for the majority of the early studies on dust was to understand the extinction and wavelength-dependence effects. These early works were done to compensate for its effects on observations, which were their primary concern. William Herschel
discovered the existence of extinction in the 18th century (Evans, 1994). He investigated the distribution of stars, and he thought the lack of stars in fixed areas were due to “holes” in the stellar distribution. This paradigm did not change until early 20th century. In the decade of 1930, the first evidence of the size of dust particles was given by studies on the wavelength-dependence of extinction in the optical and near-infrared. Moreover, thanks to long exposure photographs of objects like the Pleiades, the existence of scattered light from interstellar dust was discovered (Evans, 1994).

It may be considered that the studies of dust extinction started with Wilhelm Struve’s analysis of star counts in 1847 (Whittet, 2003). He showed that the apparent number of stars per unit volume of space decreases in all directions with distance from the Sun. Consequently, Struve realised that the absorption of light is proportional to the distance travelled. Another contribution was the photographic survey of “dark nebulae” by Edward Barnard, which gave a proof for spatial variations. These dark regions were viewed as true voids in the distributions of stars. Nevertheless, Barnard thought at least some of these voids contained interstellar matter that absorbs and scatters starlight (Whittet, 2003).

Astronomers also realised that most of the stars close to the galactic plane appear redder than expected (Whittet, 2003). In other words, many stars that show spectral characteristics of an “early-type” (high surface temperature) have colour indices more suitable to “late-type” stars (much cooler temperature). This discrepancy was resolved assuming the stars are reddened by foreground interstellar dust along the line of sight (Whittet, 2003).

A breakthrough occurred in the decade of 1930, when Lick Observatory astronomer Robert Trumpler showed that extinction ($A_\lambda$) roughly behaves as $A_\lambda \propto \lambda^{-1}$. To arrive at this conclusion, he contrasted the apparent brightness of stars with similar spectroscopic types and different degrees of reddening over a wide range of wavelength. He deduced that there is a component between stars that absorbs light. This result suggested the presence of solid particles with dimensions comparable to the wavelength of visible light (Whittet, 2003). This outcome constitutes one of the
1.2 Dust matters

The motivation to study dust in astronomy has changed through time. Early studies of dust were mainly aiming at correcting photometric data rather than having an intrinsic interest on dust physics because this absorbing material was seen as a problem for star studies. Nevertheless, the importance of dust is evident nowadays. First, dust is an active participant in early star formation processes and is essential for the formation of molecules (Evans, 1994). Furthermore, chemical and physical interactions between gas and dust are responsible for many polyatomic constituents. In the ISM, dust stores the chemical elements that made possible terrestrial planets and life (Whittet, 2003).

Dust is an important constituent in the analysis of star-forming regions. It is an essential element in the formation and evolution of stars and planetary systems: stars are born within clouds of dust and gas. Therefore, dust acts as a catalyst for the gravitational collapse of protostars (Whittet, 2003). In galaxies, young stars are more luminous and are surrounded by dust. This fact is used by various dust-related Star Formation Rate (SFR) tracers (Galliano et al., 2018). Younger stellar populations are more deeply embedded in their dust clouds, than older populations. So, dust extinction/attenuation within a galaxy influences the derivation of a galaxy Star Formation History (SFH) (Calzetti, 2001b). Ultimately, the old motivation remains relevant: to analyse how the dust affects light of the studied objects, as the wavelength dependence of dust varies with its characteristics. These properties like size, composition and shape of the dust grains depend on both their history and the environment.

1.3 Dust grain general properties

In this section, we revisit the discussion given in the Draine (2003) review on Interstellar Dust Grains. Taking into account dust composition, one can obtain a model that explains and produces the observed dust properties. Mathis et al. (1977) used a two-component grain model to render the average interstellar extinction success-
1.3. Dust grain general properties

fully. These two components are graphite and silicate grains. These materials are considered due to their observed abundances. They adopt a power-law size distribution for both. In this model, the graphite particles are supposed to be spherical, with sizes varying from about 0.005 \( \mu m \) to 1 \( \mu m \). The cosmic abundances were taken as constraints on the possible distribution of particle sizes.

Laor and Draine (1993) extended its graphite-silicate model to the X-ray region. Polycyclic Aromatic Hydrocarbon (PAH) molecules were not included when this model was built, because their importance was not well understood at that moment (Draine, 2003). Therefore, the natural step was to extend this model to include the grains with PAH composition. The approach taken was that the carbonaceous grains shifted from PAH-like to graphite-like as grain size increases. Thus, carbonaceous grains correspond to PAH molecules when they have a smaller size, and have physical and chemical characteristics close to grains of bulk graphite when bigger (\( \gtrsim 0.01 \mu m \)).

Dust evolution involves dust itself suffering changes on its grain distribution due to environmental processes. These processes can be associated with star formation in different ways (Galliano et al., 2018). First, they can be related to the creation of molecular clouds and its evaporation. This photoevaporation is the result of heat conduction of electrons from the hot to the cold gas (Vieser and Hensler, 2000). Specifically, UV light from massive OB stars impacts the thermal balance, dynamics, structure, and chemistry of the surrounding gas. The structure of the molecular clouds is greatly modified by UV photons. First, extreme UV photons and/or far-ultraviolet photons heat the upper layer of clumps, which results in the loss of their cold molecular mass. This cold mass is ionised or photodissociated and then converted into warm ionised/atomic gas (Bertoldi, 1989, Hollenbach and Tielens, 1999, Vallini et al., 2017). Second, these dust processes may be linked to stellar ejecta, associated to SN shock waves, or connected to UV and high-energy radiation (Galliano et al., 2018). The impact of these dust processes is mostly focused around the star formation area with short timescales, around the order of the lifetime of massive stars (\( \lesssim 10 \) Myr) (Galliano et al., 2018). Thus, the specific
1.4. Dust extinction vs dust attenuation

Star Formation Rate (sSFR) provides indication for sustained dust processing. Dust evolution has a dependency on its history as well, e.g. the elemental enrichment of the ISM is apparent around $\simeq 1 \text{ Gyr}$, which occurs gradually and it exemplifies the long-term evolution of dust.

The aforementioned two timescales of dust evolution affects the Spectral Energy Distributions (SED) of nearby galaxies (Galliano et al., 2018). Effects of star-formation activity and metallicity are entwined. Low metallicity galaxies have more young stars and their lower dust-to-gas mass ratio gives a more translucent ISM enabling massive star formation to greater affect the ISM. So, instead of their low metallicity, some characteristics in dwarf galaxies can be a consequence of their intense radiation field (Galliano et al., 2018).

An example of a dust size distribution model is given by Weingartner and Draine (2001). On Figure 1.1, they present the size distributions for the average diffuse clouds of their dust model. For this case, the peak in the mass distribution occurs near $\sim 0.3 \mu m$ to recreate the observed extinction in the optical range. Changes in size distribution can reproduce the diverse extinction curves in the Milky Way (MW) with their differences being associated to the total-to-selective ratio $R_V$: a decrease of $R_V$ values is linked with a larger presence of smaller grains. These smaller grains are likely present in massive star formation regions (Galliano et al., 2018). Evidence for this result is clear if we compare the corresponding $R_V$ values for the Large Magellanic Cloud (LMC) supershell and the LMC average, or the respecting values for Small Magellanic Cloud (SMC) wing and the bar region (Galliano et al., 2018, Gordon et al., 2003). Likewise, the MW, LMC and SMC dust curves present a trend for smaller grains corresponding to a lower metallicity (Galliano et al., 2018).

1.4 Dust extinction vs dust attenuation

So far we have discussed the importance of dust in the Universe, but it is also necessary to distinguish between two different effects of dust: dust extinction and dust attenuation. Extinction is the absorption and scattering of light out of the line of
1.4. Dust extinction vs dust attenuation

Figure 1.1: Dust size distribution taking into account Weingartner and Draine (2001) dust model. $R_V$ corresponds to the MW value (Draine, 2003, 2010, Weingartner and Draine, 2001).

sight due to dust. As we see in Figure 1.2 (left), dust extinction is represented as a foreground screen in front of a background unresolved source. Attenuation, on the other hand, involves a more complicated arrangement of dust and stars. Figure 1.2 (right) shows stars surrounded by their birth clouds of dust, so it affects their light in different ways by them. In particular, light is scattered and absorbed both in and out of the line of sight, since starlight may encounter a different number of clouds along the way. These clouds can be clumpy or smooth and have different depths or behave like foreground dust. The effect of scattering into the line of sight is seen as a bluer SED with a shallower dust attenuation curve. This interpretation is valid if compared to a scenario where only scattering out of the line of sight is considered. A uniform combination of dust and stars renders a SED which remains blue even at UV wavelengths. In other words, this case presents a grey attenuation. More dust in this scenario does not change the shape of the SED but only dims it. The difference between a mixed dust and stars configuration and a dimmer SED scenario without dust is small, but only if we look at the Optical and UV data. So, to differentiate them, far-infrared (FIR) data are needed (Calzetti, 2013).

In conclusion, the main difference between attenuation and extinction is that the former takes into account the “geometry” of dust, i.e. its distribution (Galliano...
1.5 Dust curves: general properties

The extinction (or attenuation) law refers to how the extinction (attenuation) properties depend on wavelength. This curve was seen as an uncomplicated way to determine observationally the effects of dust (Evans, 1994). Shorter wavelengths present more absorption and scattering, so blue light is more extinguished than red light. It is important to note that, over a limited spectral range, the appearance of a stellar spectrum is not severely modified; i.e. the wavelengths and relative strengths of characteristic lines are not changed due to dust extinction (attenuation). Therefore, dust does not change the shape, but only attenuates the flux at UV/optical wavelengths (Calzetti, 2013, Whittet, 2003).

Figure 1.2: Illustration for both extinction and attenuation. On the left, we see a foreground screen of dust in front of an unresolved source, i.e. dust extinction. On the right, we have dust attenuation, where a more complex configuration of dust is shown. In this case, dust affects light by absorption and scattering of light, in and out of the line of sight (Battisti et al., 2016, Calzetti, 2013) et al., 2018). This disparity means that the distribution of dust is not important for extinction (Calzetti, 2013). On the other hand, taking into account the complex geometrical configuration is crucial to understand dust attenuation. Only for nearby galaxies is it viable to resolve individual stars; so, it is possible to determine the dust extinction in these systems. Nevertheless, this is not feasible for galaxies at higher redshift; thus dust attenuation is analysed instead.
1.5. Dust curves: general properties

Now, let us examine the expression that describes how extinction —behaving like a foreground dust screen— affects the stellar spectrum (Calzetti, 2013). To do this, we consider the radiative transfer equation for light through dust at UV/Optical/near-IR wavelengths (i.e. no emission):

\[
\frac{dI_\nu}{d\tau} = -I_\nu + \frac{a_\nu}{\pi} \int I_\nu \phi(\nu, \cos \Theta) d\Omega, \quad (1.1)
\]

where \(I_\nu\) is the light intensity which traces the decrease in intensity of the beam as it passes through dust, \(\tau\) is the optical depth, \(a_\nu\) is the dust albedo — defined as the ratio of the scattering coefficient and the sum of the scattering and absorption coefficients—, and \(\Theta\) is the angle between the scattered photon and the line of sight. Finally, \(\phi(\nu, \cos \Theta)\) is the scattering phase function: this refers to the light added to the beam due to scattered light into the line of sight.

As we mentioned before, if we refer to the case where the dust screen is located in front of a point-like source, with no scatter into the line of sight, i.e. \(\phi(\nu, \cos \Theta) \rightarrow 0\), we then have

\[
\frac{dI_\nu}{d\tau} = -I_\nu. \quad (1.2)
\]

Thus, the solution for the extinction of a stellar spectrum by foreground dust is given by:

\[
I_\nu = I_0^\nu e^{-\tau}, \quad (1.3)
\]

with \(\tau_\lambda\) as the optical depth given by

\[
\tau_\lambda = 0.921 A(\lambda) = 0.921 E(B - V) \kappa(\lambda). \quad (1.4)
\]

Here, \(I_0^\nu\) is the incident light, \(\kappa(\lambda)\) is the extinction curve and \(E(B - V)\) is the colour excess (see Equation 1.5 below).

The effects of dust on the optical-UV light can be described by two parameters: the reddening and the total extinction or obscuration. The former refers to the colour excess, and the latter to the total obscuration. They may be parametrised as \(E(B-\)
1.5. Dust curves: general properties

1.5.1 Colour Excess

The dust law as a function of wavelength gives all the information one would need about dust extinction and it is customary to assume a generic law. Thus, a normalisation factor accounting for the amount of dust is required. This normalisation is usually parametrised by the colour excess $E(B-V)$, given by:

$$E(B-V) = A_B - A_V,$$  \hspace{1cm} (1.5)

where $A_B$ is the absorption in magnitudes in the photometric B band and $A_V$ is the absorption in magnitudes in the V band (Pogge, 2011).

Since extinction is larger in the B filter than in V, the colour excess is always positive (Whittet, 2003). Because of this, the object appears redder, so dust both extinguishes light and reddens it. For this reason, colour excess is also referred to as reddening (Evans, 1994).

1.5.2 Total-to-selective ratio $R_V$

Reddening gives a straightforward measure of extinction. Nevertheless, one can define a simple relation between the selective extinction, $E(B-V)$, and the absorption in magnitudes in the V band $A_V$ (Tielens, 2005). This constitutes a way to normalise dust extinction or attenuation curves. The ratio of total-to-selective extinction is given as

$$R_V \equiv \frac{A_V}{E(B-V)} \equiv \frac{A_V}{A_B - A_V}, \text{ with } A_B > A_V.$$  \hspace{1cm} (1.6)

In principle, $R_V$ depends on the composition and size of the distribution of the grains (Whittet, 2003). Larger $R_V$ implies a shallower wavelength dependence, indicating larger grain sizes and a greyer attenuation curve (Pogge, 2011). For the diffuse ISM, a typical value for $R_V$ is 3.1. For dense clouds, a higher value of 5 is observed (Glassgold, 2008, Pogge, 2011, Tielens, 2005). $R_V$ correlates with the level of UV extinction, as was demonstrated by Cardelli et al. (1989). In a nutshell,
1.5. Dust curves: general properties

Figure 1.3: On the left panel, different extinction and attenuation curves are shown. $R_V$ variations in the MW extinction curve given by the grey area, from 2 to 5. The average MW curve corresponds to the white line. Magellanic clouds’ extinction curves are as noted. For comparison, the Calzetti law (Starburst curve) is shown in green and M31 curve in orange. Sections of the dust attenuation curve are labelled, specifically the Far-UV rise and Knee. On the right panel, we observe the MIR LMC average dust values in red circles (and error bars). The Galactic centre curve is given by the blue line and the Diffuse ISM curve is in black. Absorption features due to silicates are also labelled. Yellow bars correspond to $\nu$ and $\kappa$ transmission curves (Galliano et al., 2018).

smaller $R_V$ values tend to have a higher UV extinction. All things considered, the $R_V$ parameter is seen as a measure of the slope of the extinction curve: larger values of $R_V$ match to flatter (greyer) or low extinction curves —See Figure 1.3, different values for the MW (Fitzpatrick, 2004, Whittet, 2003).

A flatter attenuation curve corresponds to a higher value of $R_V$. Likewise, larger values of $R_V$ are associated with a shift in the size distribution, namely a decline in the number of small particles or an increase in larger particles (Draine, 2010).

1.5.3 NUV Bump 2175 Å

The 2175 Å bump (Stecher, 1965) is a striking feature on the UV dust curve —see Figure 1.3. This characteristic tells us about the absorbing materials present in dust (Tielens, 2005).
The bump is generally located at $\lambda_p = 2175$ Å with a mean deviation of 9 Å. The width has a typical value of 480 Å (Tielens, 2005). The feature is consistently strong which suggests that the element responsible must be abundant. Therefore, the grain component must be $C, O, Mg, Si$ or $Fe$. The responsible carrier of the 2175 Å feature is believed to be $C$ in PAHs due to the estimates of PAH abundance. Furthermore, they present a strong absorption around 2200 Å, and a shape similar to cyclic aromatic aromatics, like benzene (Iglesias-Groth, 2013, Jones, 2018). Each $C$ atom in graphite has 4 valence electrons ($2s^22p^2$), 3 are in trigonal $sp^2$ or $\sigma$ orbitals and the last electron is in a delocalised $\pi$ orbital, with $C-C$ bonds sharing this orbital. Then, an excitation of a $\pi$ electron to an excited orbital $\pi^*$ can occur due to the absorption of a photon. This $\pi \rightarrow \pi^*$ transition is believed to be responsible for the 2175 Å bump (Draine, 2010). Any potential candidate responsible for this absorption feature should fulfil the following requirements. It has to be cosmically abundant, sufficiently robust to survive in a variety of interstellar environments and capable of matching the observed width and shapes (Draine, 2010, Whittet, 2003).

The NUV bump absorption feature is not exclusive to our Galaxy (see Figure 1.3). It is also present on the Large Magellanic Cloud (LMC), NGC 2207 and M82 (Draine, 2003, 2011, Hutton et al., 2014, Whittet, 2003). The 2175 Å bump is a feature that does not appear in every dust attenuation law for galaxies at lower redshift (Battisti et al., 2017a, Calzetti et al., 1994, Conroy, 2010, Gordon et al., 2003, Wild et al., 2011). In particular, this feature is absent from the nominal Calzetti law, but appears in the MW and LMC. The Calzetti law is the dust curve most commonly used for starburst galaxies. In star-forming galaxies, the presence of the 2175 Å NUV bump with dust composition similar to MW or LMC, is expected according to radiative transfer dust models (Conroy, 2013). Nevertheless, the lack of rest-frame UV spectra has made it difficult to test this. Although, there have been studies which found the NUV bump in star-forming galaxies with varying strengths e.g. Burgarella et al. (2005), Noll et al. (2009), Wild et al. (2011), among others. For the case of galaxies at high redshift, there is some evidence supporting the existence of the 2175 Å bump (Kriek and Conroy, 2013, Noll et al., 2007, Salmon et al., 2016,
1.5. Dust curves: general properties

1.5.4 Dust parametrisations

Even though dust curves present a wide range of characteristics, there are common features that unify different environments. In the infrared, the curve follows an inverse power law. In the ultraviolet region, the 2175 Å bump is a feature with a constant position and profile shape but with variable strength.

There are different dust parametrisations in the literature (See e.g. Calzetti, 2001a, Cardelli et al., 1989, Fitzpatrick, 2004, among others). They try to account for these different scenarios. In the UV, the three-component empirical model is used to account for variations in the appearance of the dust curve (Whittet, 2003). Thus, Fitzpatrick (2004) parametrisation is:

\[
\frac{E_{\lambda} - V}{E_{B-V}} = (c_1 + c_2 x) + c_3 D(x) + c_4 F(x). \tag{1.7}
\]

Here, \(c_1, c_2, c_3\) and \(c_4\) are constants given by a line of sight and \(x = \lambda^{-1}\). The first two terms \(c_1 + c_2 x\) encode the linear contribution to the parametrisations. On \(c_3 D(x)\), \(D(x)\) is the Drude profile representing the NUV absorption bump \(D(x) = \frac{x^2}{(x^2-x_0^2)^2 + \gamma^2 x^2}\). In general, the Drude profile is obtained by small spheres employing either a single Lorentz or Drude oscillator (Rouleau et al., 1997). The latter is based on the Drude theory of metals (Bohren and Huffman, 1983) and it is normally chosen since it better describes the shape of the feature (Draine and Malhotra, 1993, Whittet, 2003). Finally, \(c_4 F(x)\) is a far-UV term with \(F(x) = 0.5392 (x - 5.9)^2 + 0.0564 (x - 5.9)^3\) for \(x > 5.9 \mu m^{-1}\), with \(F(x) = 0\) for \(x \leq 5.9 \mu m^{-1}\).

Now, let us look into another parametrised dust curve. Cardelli et al. (1989) gives a mathematical representation of the dust curve, which is also called CCM extinction law determined by:

\[
\frac{A_{\lambda}}{A_V} = a(x) + \frac{b(x)}{R_V}, \tag{1.8}
\]

where \(a(x)\) and \(b(x)\) are unique coefficients for a wavenumber \(x = \lambda^{-1}\). The coefficients are obtained from the slope and the correlation of both \(R_V\) and \(A_{\lambda}/A_V\).
1.5. Dust curves: general properties

Figure 1.4: Different Conroy, Schiminovich and Blanton (2010) dust attenuation laws (CSB10) from Hutton et al. (2015). Fitzpatrick law is also compared (F99, dashed line). On the left, we observe different cases for CSB10 corresponding to the same $R_V$ value (Milky Way $R_V = 3.1$) but different NUV bump strengths, including no bump. On the right panel, the total-to-selective ratio varies from 1 to 4. The Milky Way attenuation law is given by the black line. The panel on the left shows the NUV region, and the right panel includes the optical region. Transmission curves used on Hutton et al. (2015) study are also shown, respectively. This plot illustrates different values for CSB10.

The coefficients are defined in equations 1.12 for another dust parametrisations. To summarise, a power-law for $A_\lambda$ in the infrared, a Drude profile for the NUV bump and polynomials for the visible and UV region, is what Cardelli et al. (1989) study employs to calculate the coefficients.

The parametrisation used by Kriek and Conroy (2013) is particularly relevant because we make a direct comparison with their results from the best-fit dust slope $\delta$ and UV bump strength $E_b$ — See Chapter 4. The parametrisations follows the prescription by Noll et al. (2009) which is defined by:

$$A(\lambda) = \frac{A_v}{4.05} (k'(\lambda)) + D(\lambda) \left(\frac{\lambda}{A_v}\right)^\delta,$$  \hspace{1cm} (1.9)

with $D$ the Lorentzian-like Drude profile to parametrise the UV bump given by

$$D(\lambda) = \frac{E_b (\lambda \Delta \lambda)^2}{(\lambda^2 - \lambda_0^2)^2 + (\lambda \Delta \lambda)^2}.$$  \hspace{1cm} (1.10)

It is of particular interest to present the expression for the dust attenuation law with an arbitrary UV bump strength from Conroy et al. (2010, CSB10), because
this dust parametrisation is adopted in the analysis of Chapter 2 and 3. In this case, CSB10 obtained the average dust attenuation curve using UV photometry for disk galaxies. The MW dust curve was recovered with the strength of the bump $B$ equal to 1, and $R_V$ to 3.1. If $B$ vanishes, no UV bump is expected as is in the case for the Calzetti law —See Figure 1.4. Recalling the previous expression:

$$
\frac{A(\lambda)}{A_v} = a(x) + \frac{b(x)}{R_V}.
$$

(1.11)

where $x$ has units of $\mu m^{-1}$, $A_v$ is the extinction in the V band and $A(\lambda)$ is the wavelength-dependent extinction. In addition, $a(x)$ and $b(x)$ are defined:

In the infrared: $0.3 \mu m^{-1} < x < 1.1 \mu m^{-1}$

$$
a(x) = 0.574x^{1.61},
$$

(1.12a)

$$
b(x) = -0.527x^{1.61}.
$$

(1.12b)

In the optical/near-IR: $1.1 \mu m^{-1} < x < 3.3 \mu m^{-1}$ and $y \equiv x - 1.82$, $a(x)$ and $b(x)$ are defined:

$$
a(x) = 1 + 0.177y - 0.504y^2 - 0.0243y^3 + 0.721y^4 + 0.0198y^5 + 0.775y^6 + 0.330y^7,
$$

(1.12c)

$$
b(x) = 1.4113y + 2.283y^2 + 1.072y^3 - 5.384y^4 - 0.622y^5 + 5.303y^6 - 2.090y^7
$$

(1.12d)

In the near/mid-UV: $3.3 \mu m^{-1} < x < 5.9 \mu m^{-1}$, $a(x)$ and $b(x)$ are defined:

$$
a(x) = 1.752 - 0.316x - \frac{0.104B}{(x-4.67)^2 + 0.341} + f_a
$$

(1.12f)

$$
b(x) = -3.09 + 1.825x + \frac{1.206B}{(x-4.62)^2 + 0.263}.
$$

(1.12g)
In the far-UV: $5.9 \, \mu m^{-1} < x < 8.0 \, \mu m^{-1}$,

\begin{align*}
    f_a &= -0.0477(x - 5.9)^2 - 0.00978(x - 5.9)^3, 
    & \text{(1.12h)} \\
    f_b &= 0.213(x - 5.9)^2 + 0.121(x - 5.9)^3, 
    & \text{(1.12i)} \\
    a(x) &= 1.752 - 0.316x - \frac{0.104B}{(x - 4.67)^2 + 0.341} + f_a, 
    & \text{(1.12j)} \\
    b(x) &= -3.09 + 1.825x + \frac{1.206B}{(x - 4.62)^2 + 0.263} + f_b. 
    & \text{(1.12k)}
\end{align*}

\section{1.6 Dust models}

The dust attenuation curve is already known to be non-universal, and it might be the result of the different geometries and star formation histories of each galaxy (Kriek and Conroy, 2013, Salmon et al., 2016, Walcher et al., 2010). The dust law describes the dependence of $A_{\lambda}$ on wavelength (Evans, 1994). Generally, a simple power-law $A_{\lambda} \propto \lambda^{-0.7}$ can account for the effective attenuation in galaxies (e.g. Charlot and Fall, 2000, Walcher et al., 2010). Nevertheless, there are different dust models whose main goal is to explain how dust is distributed in the galaxy and its effects on different stellar properties. On this section, we will explore different dust models with special emphasis on Charlot and Fall (2000), Witt and Gordon (2000) and Draine models (Draine and Li, 2007, Seon and Draine, 2016).

In the Charlot and Fall (2000) model, older stars experience the attenuation only from the ISM. On the other hand, young stars are surrounded by their dusty birth clouds, so they undergo additional attenuation. A consequence of this model is that UV light associated with the short-lived massive stars is more obscured than the optical light associated with the longer-lived stars (e.g. Walcher et al., 2010) (See Figure 1.5). Therefore, one of the main advantages of this work is that it gives a physical scenario of a two-component model. Likewise, this dust model has a widespread use by modelling dusty SEDs. However, the model does not fully encode the whole picture of dust and star geometry, such as bulges, disks and clumpiness (Walcher et al., 2010).
1.6. Dust models

Figure 1.5: Schematic representation of the ISM and birth cloud in stars. Young stars ionise \( H\text{II} \) regions in the inner parts of the dense clouds in which they are born. These clouds have a finite lifetime; thus, photons emitted by older stars propagate only through the ISM (Charlot and Fall, 2000).

An important strength of the Charlot and Fall (2000) two-component model is that it provides a framework for the Calzetti law (see Section 1.8). The model takes into account the ionisation of \( H\text{II} \) regions in the dense birth clouds of the younger stellar populations. Hence, emission lines from \( H\text{II} \) regions and the non-ionising continuum from new stars suffer the same attenuation by dust, both from the ISM and from the outer \( H\text{I} \) regions of the birth clouds. In contrast, the non-ionising continuum from stars that are older than the birth clouds are only affected by the ambient ISM. This physical scenario is covered in the model by using a finite lifetime of birth clouds. With all of these considerations, the Charlot and Fall (2000) model could match ultraviolet observations of a sample of nearby starburst galaxies, by also obtaining the UV slope (\( \beta \)), the ratio of \( H\alpha \) to \( H\beta \) luminosities (\( L_{H\alpha}/L_{H\beta} \)), the ratio of far-infrared to ultraviolet luminosities (\( L_{dust}/L_{1600} \)) and the \( H\alpha \) equivalent width. These properties are shaped by the model parameters: the lifetime and effective optical depth of the birth clouds, the effective age of the starburst, the fraction of dust in the ionised gas, and the effective optical depth in the ISM (Charlot and Fall, 2000).
1.6. Dust models

Using this dust model, Charlot and Fall (2000) assess the wavelength dependence of the effective absorption in the ISM—as described by a power law—with the relation of $L_{\text{dust}}/L_{1600}$ and $\beta$ in starburst galaxies. They understood it as a sequence in the dust content of galaxies. Another outcome is that a foreground dust screen would produce a much steeper curve like MW, or LMC, SMC, if compared to the retrieved effective absorption curve. They conclude that to account for the effective absorption curve with low dust content, a mixed-slab model for the ISM is needed. The lack of a mixed geometry is one of the weaknesses of the modelling. Therefore, the effective absorption curve fails to reproduce the observations of starbursts which have a redder UV spectra. Instead, an effective absorption curve proportional to $\lambda^{-0.7}$ affecting the line and continuum radiation from stars with a lower normalisation by a factor of 3 after $10^7$ yr is sufficient to describe the observed mean relations of starburst galaxies. This last point portrays the lifetime of the birth clouds used on this model.

By contrast, Witt and Gordon (2000) dust model considers mixed environments and dust distributions. They use two different dust types in their model. First, they use properties similar to the average diffuse medium of the MW and also the Bar of the Small Magellanic Cloud. In their model, they take into consideration three different galactic environments, as well as two dust distributions: homogeneous or two-phase clumpy dust. All of these, within a range of dust column densities. A sketch of these different scenarios is seen in Figure 1.6. Three types of galactic environments were studied, DUSTY, SHELL and CLOUDY. The first corresponds to a mixed spherical distribution of dust with stars; the second describes a scenario where stars are surrounded by a dust shell and the last one characterises a mixed region of stars where dust is embedded in an interior area, and dust-free elsewhere. An advantage of this model is its diversity of geometry and dust distributions, even though it has only limited options.

In Witt and Gordon (2000), the authors analyse how different effects may result from a range of dust distributions within a diverse geometry emerging from their dust model. Specifically, they study the UV to near-IR wavelength dependence in
1.6. Dust models

attenuation and reddening effects. They found that most model types (except the homogeneous SHELL model), have a saturation of smaller values of reddening. They also observed a flatter attenuation curve, with increasing dust column density. This outcome was obtained as a result of the embedded clumpy dust distributions. As in Charlot and Fall (2000), they can account for the Calzetti attenuation law, when using a dust composition similar to SMC and a clumpy shell-type dust distribution. The ratio of integrated far-IR to the far-UV flux —measured near 1600 Å— was found to be a dependable and consistent measurement for the UV attenuation. Additionally, they observed a dependency on dust distribution, dust/star geometry and dust type, while using the UV spectral index $\beta$ and colour excess. With these considerations, Witt and Gordon (2000) argue that observations over the entire range of rest-wavelengths, including FIR are needed. An important characteristic of this study is that it also strengthens the non-universality of the dust attenuation curve.

Up to now, we have revisited geometric dust modelling. In contrast, Draine models are radiative transfer models. Draine and Li (2007) present a model for infrared emission from dust. They determined the IR emission from the starlight-heated dust with different amounts of PAH particles and a diverse mix of silicate and graphitic grains. PAH absorption properties of the model are compatible with PAH emissions from dust, attained from spectroscopic observations from nearby galaxies. This characteristic constitutes a clear strength of the model. It is worth mentioning that the model is constrained to reproduce the average MW extinction. Furthermore, the comparison of their models with the photometry from Spitzer provides PAH abundances, total dust masses and starlight intensities. The Seon and Draine (2016) radiative transfer models also tackle the attenuation in a spherical, clumpy ISM. They analyse the dust extinction properties of the MW, LMC and SMC. In Seon and Draine (2016) model, these extinction properties are independent of the attenuation curves shape, with the wavelength dependence of absorption playing a bigger role. A Calzetti attenuation curve is retrieved given a silicate-carbonaceous dust model for the MW, but with a suppressed NUV bump. In contrast, other studies (e.g. Witt and Gordon (2000)) found that a dust composition similar to the SMC
Figure 1.6: Witt and Gordon dust models with the three different geometries they used in Witt and Gordon (2000). These correspond to SHELL, DUSTY and CLOUDY. The grey area depicts the dust distribution.
was responsible for the Calzetti law. Another strong point on this dust model is that they were able to retrieve MW values for dust when using a modified Calzetti law with a NUV bump and slope as free parameters. As Seon and Draine (2016) state, a possible caveat of the dust model is the use of theoretical albedos, which may explain the observed differences in their model.

We already mentioned the more relevant dust models for this thesis, but to finish we can briefly mention the dust models by Zubko et al. (2004), da Cunha et al. (2008), Granato et al. (2000), Panuzzo et al. (2007) and Narayanan et al. (2018). The first model is retrieved by taking into account the elemental abundances constraints. These settings are determined by dust from different interstellar medium abundances and fitting both the diffuse infrared emission and the FUV to NIR extinction. In Galliano et al. (2008), they use the Zubko et al. (2004) dust model for the optical, IR, and submillimeter photometry and mid-IR spectroscopy of galaxies. Their goal is to retrieve parameters like total dust mass and fraction of dust mass in PAHs, etc, with a general correspondence to Draine and Li (2007). Specifically, they aim to study the trend between gas-phase metallicity and PAH mass fraction. The da Cunha et al. (2008) model uses Bruzual and Charlot (2003) SPS models with Charlot and Fall (2000) dust attenuation. They also consider dust emission by using multiple components: warm and cold thermal dust emission, emission from stochastically heated grains and an empirical spectrum for the PAH emission. With mock data, they found it was possible to constrain parameters like FIR emission and total dust mass. Likewise, comparing the retrieved dust masses, they concluded that their masses agreed within 50% of the SINGS galaxies studied by Draine and Li (2007) (Conroy, 2013). Considering the geometry of dust, Granato et al. (2000) argue the molecular clouds are optically thick, so the number of stars within these clouds is a function of age (Panuzzo et al., 2007). These models can emulate the Calzetti attenuation law with MW dust. Finally, considering cosmological hydrodynamic simulations, Narayanan et al. (2018) provides a theoretical model for dust attenuation curves in galaxies. They use the cosmological “zoom in” technique which involves cosmological galaxy formation simulations. They employed 3D Monte
Carlo dust radiative transfer simulations to constrain the absorption and scattering of starlight, and then provide a model for dust attenuation in galaxies. An important part of their analysis was to assume the same underlying extinction properties to assess how radiative transfer effects modify the attenuation curves. Narayanan et al. (2018) conclude that even with the same dust extinction properties, the dust attenuation law varies due to different star-dust geometry. In particular, a flatter attenuation curve results from a larger fraction of unobscured young stars, but older stars contribute to a steeper attenuation curve. Besides, the strength of the NUV bump fluctuate greatly within their models. These results render a greyer attenuation curve along with a weaker NUV bump, because unobscured young stars flattens attenuation curve slopes and reduces the NUV bump.

To summarise, we have explored geometric dust modelling and radiative transfer models. Relative to the former, Charlot and Fall (2000) and Witt and Gordon (2000) models are relevant because we will contrast our dust results against these modelling. Both models give a framework similar to the "birth cloud" model, with the younger population experiencing more attenuation because the stars are still embedded in their dusty birth clouds. The Charlot and Fall (2000) model does not provide a full picture for dust/star geometry, but Witt and Gordon (2000) presents a different approach by considering three different galactic environments and two dust distributions. With these characteristics, Witt and Gordon (2000) models outline diverse clumpy distributions. Regarding transfer models, an important work is given by Draine and Li (2007). The most relevant element in this study is their use of PAH properties to parameterise their model. This work will be compared to our results in subsequent chapters.

### 1.7 Stellar population models

To obtain the dust attenuation curves of galaxies, two different approaches may be taken: the pair method or the SED fitting method (Salim et al., 2018). With stars, the pair method consists of taking observations of two stars with the same spectral type, but with different extinction: one with a high extinction and the other with
the opposite. Then, the extinction is obtained from the differential spectrum, with the same dust properties in both sightlines. This approach can also be applied to galaxies (Galliano et al., 2018). With local star-forming galaxies, the comparison involves the Balmer decrement —observed ratio of $I(H_\alpha)/I(H_\beta)$— and the anticipated value corresponding to no nebular reddening (Calzetti et al., 1994).

The second approach, the SED fitting method, uses stellar population synthesis models and gives an attenuation curve for each galaxy studied. In general, this second method detects steeper dust attenuation laws (Salim et al., 2018). Since the second approach —which is used in this work— employs stellar SED modelling, synthetic stellar populations models are pivotal. In this case, studies have been done on galaxies at lower redshift (e.g. see Burgarella et al., 2005, Salim et al., 2018) and at higher redshift (e.g. see Kriek and Conroy, 2013, Salmon et al., 2016). Of course, there are several different synthetic models (Leitherer et al., 1999, Maraston, 2005, Vazdekis et al., 2010, etc.). We will discuss them in general, but we will put special attention on the population models given by Bruzual and Charlot (2003), as they will be relevant later on.

In order to construct stellar population synthesis models (See Fig. 1.7 Conroy, 2013), the first step involves defining a simple stellar population (SSP). SSPs cover the evolution of a single stellar population with a given metallicity and abundance pattern. The three ingredients needed for this Simple Population are isochrones, stellar spectral libraries and an Initial Mass Function (IMF). Finally, SSPs combined with Star Formation Histories (SFH), chemical evolution, and dust models are needed to form a composite stellar population (CSP).

Other examples of stellar population models include Leitherer et al. (1999), that use young massive stars and the effects of nebular emission on the spectra. Another set of models proposed by Maraston (2005) involves a semi-empirical usage of Thermally-Pulsing Asymptotic Giant Branch (TP-AGB) with Carbon star spectra. Also, Conroy et al. (2009) examine the global uncertainties on evolutionary population synthesis.

Broadly speaking, there are some common points between the models. First,
1.7. Stellar population models

Figure 1.7: Sketch of the stellar population synthesis. (a) Initial mass function (IMF), isochrones for a variety of ages and metallicities with stellar spectra corresponding to different $T_{\text{eff}}$, $L_{\text{bol}}$, and metallicity: together forms the elementary components for building simple stellar populations (SSPs). (b) We see now the parts to form composite stellar populations (CSPs): SSPs, chemical evolution, star formation histories and dust models for both attenuation and emission. (c) Differences between a dust-free and dusty CSPs are depicted (Conroy, 2013).
they cover all the important evolutionary phases with variations in the TP-AGB phase (Maraston, 2013). Due to nuclear burning happening between hydrogen-rich and helium-rich shells, this phase is complex to model. The helium-rich shell burns explosively creating thermal pulses, because of the instability of the helium shell. During this phase, the mass-loss increases and the star reaches the end of its life (Conroy, 2013). The second point in common among those models is that the spectral resolution is good within the optical and UV range (Maraston, 2013).

The Bruzual and Charlot (2003) models have a method to retrieve population synthesis models by using isochrones. In particular, it is a model that obtains the spectral evolution of populations with different metallicities for ages from $1 \times 10^5$ to $2 \times 10^{10}$ yr. The model re-creates colour-magnitude diagrams for the observed optical and near-infrared spectral windows of Galactic star clusters with different stellar properties. Also, the observed integrated colours of star clusters in the Magellanic Clouds and NGC 7252 are explained by stochastic variations in the stars in different evolutionary phases. Bruzual and Charlot (2003) also added thermally pulsing stars located on the asymptotic giant branch to their modelling. Furthermore, this model can reproduce galaxy spectra from SDSS (Sloan Digital Sky Survey), using the aforementioned spectral fit and providing parameters like star formation history, metallicity and dust. Also, this model was the first to make studies on absorption-line strengths in galaxies with a variety of stars. Regarding dust attenuation, Bruzual and Charlot (2003) follow the model by Charlot and Fall (2000), with a giant molecular cloud lifetime of $10^7$ yr.

1.8 Dust attenuation curves in galaxies at low redshift

Due to their proximity, close-by galaxies constitute ideal laboratories to explore the dust properties, particularly from our very own Milky Way (MW). Nearby galaxies also provide an example of more diverse scenarios, namely different star formation histories and metallicity, although the range of properties is still limited. Furthermore, if we hope to understand galaxies at higher redshift, we also need to com-
prehend these galaxies that are spatially resolved and in general have better data (Galliano et al., 2018).

Thanks to the relationship between the shape of the average dust curves of galaxies, the dust grain properties, and dust geometry, one can extract information on the characteristics and features of the distribution of dust in galaxies. For example, a flatter UV attenuation curve is expected from mixed geometry dust and stars. This situation occurs because stars do not suffer as much extinction, plus the younger population contribute more to the fraction of the total blue light (compared to red light). We will discuss the overall picture of dust attenuation studies both in nearby and low redshift galaxies.

For the case of galaxies closer to us, it is possible to determine their dust extinction law since individual stars can be resolved (Evans, 1994). In particular, the Milky Way (MW), Large and Small Magellanic Clouds (LMC and SMC) are galaxies where knowledge of their dust components is the greatest (Draine, 2003).

A seminal work on the Magellanic clouds is given by Pei (1992). In this study, a graphite-silicate grain model was extended from the MW to explain the observed extinction curves in the Magellanic Clouds (MC). A diverse abundance of graphite and silicate grains is needed along with fixed properties from the MW extinction curve. Gordon et al. (2003) provide a comparison of the extinction curves in both Magellanic Clouds and the MW. They did a qualitative comparison, using the determined $R_V$ values for the Magellanic Clouds (MC). The MW extinction curves differ from the MC, and Gordon et al. (2003) argue this happens due to a diversity of environments being examined in the MC curves, compared to the sample from MW. Specifically, the authors discuss this is a consequence of dust extinction curves having a continuum of properties from the MW to the SMC bar.

The LMC presents two distinct mean extinction curves, as stars in the vicinity of 30 Doradus differ from stars more widely distributed in the LMC. Figure 1.8 shows both extinction curves, displaying a weaker NUV bump (Whittet, 2003). The area near the star-forming region 30 Doradus has $R_V = 2.76 \pm 0.09$ : a steep curve without a strong bump. In contrast, the average $R_V$ value for LMC is com-
1.8. Dust attenuation curves in galaxies at low redshift

Figure 1.8: Milky Way (MW) extinction curve (dotted line) compared to the Large Magellanic Cloud (LMC) dust law (black line) and the mean extinction curve around 30 Doradus (dashed line) (Whittet, 2003).

Figure 1.9: Comparison between the mean dust attenuation curve for the Milky Way and the SMC (Whittet, 2003).

parable with the MW (Galliano et al., 2018). The stars in the bar region of the SMC have extinction curves that appear to lack the 2175 Å feature (Draine, 2003, 2011, Galliano et al., 2018, Whittet, 2003, etc). Nevertheless, this bump is weakly present in some regions of the galaxy (Hagen et al., 2017). SMC extinction curve has $R_V = 2.74 \pm 0.13$ which corresponds to a steeper law (Galliano et al., 2018), which may be associated with the presence of smaller grains.

Analysing nearby galaxies is a first step towards understanding galaxies at
higher redshift. With starburst galaxies at lower redshift, a very important study is given by Calzetti et al. (1994). It suggests that the ionised gas emission has twice the attenuation than the stellar continuum. In Calzetti et al. (1994), the authors analysed the average attenuation curve of 39 starburst galaxies, making use of the ratio of Hydrogen recombination lines (Balmer line ratio $H_\alpha/H_\beta$). The Calzetti law does not present a NUV bump, and it is flatter than the LMC and the SMC extinction curves, with a $R_V$ around 4.05 (Calzetti, 2001a). Their results show that the optical depth obtained with the Balmer lines is almost twice as large as the one measured from the continuum, because older stars are attenuated by the ISM but the younger stellar population is still surrounded by its birth clouds (Conroy, 2013, Witt and Gordon, 2000). A model that represents the scenario of Calzetti et al. (1994), where the younger stars experience not just the attenuation from the diffuse ISM but also from their birth clouds, is given by Charlot and Fall (2000). In this model, the time it takes for the birth cloud to dissipate is needed, plus the attenuation curves for the cloud and ISM. These attenuation curves are often assumed to be power laws (Charlot and Fall, 2000). Calzetti et al. (1994) employs the comparison method, which may raise two possible issues (Salim et al., 2018). First, an important assumption in this approach is that the attenuation curves remain identical with dust content (Chevallard et al., 2013, Wild et al., 2011). However, this assumption has not been completely validated according to Chevallard et al. (2013) and Salim et al. (2018). Then, the attenuation curve will be biased toward the flatter slopes of dusty galaxies because in this comparison approach these galaxies have a greater influence in the derivation of the curve (Salim et al., 2018). Secondly, the galaxies considered in the comparison method are chosen according to how red (and/or unred) they are, based upon a proxy for continuum attenuation. In Calzetti et al. (1994), the parameter used to categorise different attenuations is the nebular Balmer decrement. Nevertheless, it may be a poor proxy for continuum attenuation because of the scatter observed between the two parameters (Charlot and Fall, 2000, Salim et al., 2018). Salim et al. (2018) states that highly attenuated galaxies have a Balmer optical depth $\tau_{Balmer} \sim 0.7$ with a continuum attenuation of $A_{FUV} = 3.0$, below the most opaque
galaxies of $A_{FUV} \sim 4.5$. In the case of galaxies with weaker attenuation, they have a Balmer optical depth $\tau_{Balmer} < 0.1$ and $A_{FUV} = 1.3$. Therefore, if galaxies are selected as dusty or dust-free according to the Balmer decrement, the differences in attenuations between dust and assumed dust-free galaxies could be smaller by a factor of two (Salim et al., 2018). In this case, a flatter attenuation slope is the outcome of obtaining an attenuation curve by dividing the SED of a red galaxy by the SED of a dust-free galaxy (Salim et al., 2018).

The Calzetti mean attenuation curve is the most favoured law for starburst galaxies. At lower redshift, there are studies that support a bump-less mean attenuation curve scenario. Johnson et al. (2007) obtained average attenuation curves as a function of the 4,000 Å break strength and stellar mass. These curves agreed with the Calzetti law, following a power law $\lambda^{-0.7}$. Employing the same method to explore the dust attenuation law as the Calzetti comparison approach, Battisti et al. (2016) studied $\sim 10,000$ star-forming galaxies at $z \lesssim 0.1$ using data from both GALEX (Galaxy Evolution Explorer) and SDSS. In the same manner as in Calzetti et al. (1994) their mean attenuation curve lacks the 2175 Å bump. Along the same lines, Battisti et al. (2017b) analysed the dust attenuation law in the near-infrared of local galaxies. They compared their resulting average attenuation curve to the dust law frequently used in local star-bursting systems (Calzetti et al., 1994), but it was not a perfect match as they found a lower value in the far-ultraviolet.

On the other hand, studies have also found dust attenuation curves inconsistent with the bump-less Calzetti et al. (1994) law. For instance, Burgarella et al. (2005) compared the SEDs from two galaxy samples in the NUV to FIR SEDs models. FIR-selected galaxies have dust curves similar to the MW law and their UV-selected galaxies rendered dust laws comparable to the LMC extinction. Generally speaking, their study found evidence for the NUV bump in their dust attenuation laws, with a stronger NUV feature in FIR-selected galaxies. Using different SFHs and dust properties, including the NUV bump. They concluded that FIR data are needed to yield accurate UV dust attenuation from SED modelling.

There is evidence of the NUV bump for the case of galaxies M81 and M82.
1.8. Dust attenuation curves in galaxies at low redshift

Figure 1.10: Correlations between $R_v$, bump strength $B$ and $E(B-V)$ of M82. Grey dots are measurements. Blue dots and error bars are the median and root mean square values of the data, binned at a fixed number of data points per bin. Red stars represent measurements within 30 arc sec of the position of SN2016J. As we observe here, M82 shows the presence of the NUV bump and a wide range of dust parameters (Hutton et al., 2015).

Hoversten et al. (2011) used Swift UV/Optical Telescope UV photometry to analyse the galaxy M81. In their study, they found a strong NUV bump with a Milky Way dust extinction providing the best fit. In the same line, we include the Hutton et al. (2015) study of nearby starburst galaxy M82. In particular, the authors explored the extinction curve parametrised as a function of $R_v$ and the strength of the 2175 Å feature. They found that both parameters correlate with galactocentric distance: both increasing inwards. Colour excess also follows this behaviour. Their findings point out a correlation between $R_v$ and the NUV bump: a stronger bump corresponds to a higher $R_v$, suggesting a distribution with larger dust grain sizes (See Figure 1.10). Furthermore, they concluded that the extinction curve of M82 is in better agreement with a Milky Way standard extinction curve, rather than with a Calzetti bump-less law.

Conroy et al. (2010) provides an important study of galaxies at lower redshift which also finds the presence of the NUV bump. Their sample includes galaxies at
0.01 < z < 0.05. They analysed star-forming galaxies as a function of inclination using UV-NIR photometry. The standard dust attenuation models could not explain their dependency between FUV-NUV and NUV-\textit{u} colours, so the existence of the 2175 Å bump in this sample was inferred. The discovered feature was weaker than the NUV bump from the MW.

A study analysing the variations of the attenuation curve as a function of specific SFR (sSFR) is Wild et al. (2011) work. Their sample of 23 000 galaxies exhibited the NUV bump. In particular, they found a weak trend with the specific star formation rates: a higher sSFR associated with a smaller NUV bump strength.

If we look at the impact of inclination on the dust attenuation curve of local star-forming galaxies, we should mention Battisti et al. (2017a) which uses the same sample from Battisti et al. (2016). Their findings correspond to a shallower UV dust law that is associated with a greater inclination. This work also has a section of their sample having evidence for the presence of the NUV bump: the subset with the greatest inclination has a NUV excess in their average selective attenuation. This NUV bump would have 17 to 26% of MW bump strength.

A more extensive study regarding the diversity of attenuation curves is the analysis done by Salim et al. (2018). Around 230,000 galaxies constitute their sample from GALEX, SDSS and WISE photometry, with calibration of Herschel-Atlas. This calibration includes the comparison of IR luminosity estimates obtained from full IR SED to the Herschel sample, to derive corrections that are applied to the IR estimates. They used a method to fit SEDs with infrared luminosity, along with parametrised attenuation curves. Their results show that there is a diversity of dust slopes but with an average similar to the SMC curve. They observe a stronger optical opacity correlates with shallower curves and a trend with massive galaxies having flatter slopes. Regarding the NUV bump, its presence varies from MW strength to none. Another important result from Salim et al. (2018) is that the sightlines which are not enshrouded into molecular clouds are associated with steeper curves. This outcome is important because it shows the wide range of possible NUV bump values for galaxies at low redshift, each with their different environment.
1.9. Dust attenuation curves at high redshift

In summary, the Calzetti law is used to describe the average attenuation curve of star-forming galaxies because this law characterises properly most dust attenuation properties in galaxies. This scenario is the case for local and low redshift galaxies. Nevertheless, there are studies showing a variation in the attenuation curve with other stellar properties (e.g. Conroy, 2013, Galliano et al., 2018, Narayanan et al., 2018, etc), which may suggest that the whole picture is more complex. It is worth wondering if a similar scenario is the case for galaxies at high redshift.

1.9 Dust attenuation curves at high redshift

The importance of dust is especially significant when interpreting the cosmic star formation history as depicted in the Madau plots (Madau et al., 1996, 1998, Madau and Dickinson, 2014). These plots show the Star Formation Density as a function of redshift (SFRD(z)) (Meurer, 2004). In the first models, the lead view was that SFRD(z) peaks around \( z \sim 1 \), just to decline at higher redshifts with dust not taken into account (Madau and Dickinson, 2014).

Cosmic Star Formation Histories (SFHs) from UV and IR give a best-fitting function for the cosmic star formation form (black line, Figure 1.12 from Madau and Dickinson, 2014):

\[
\psi(z) = 0.015 \frac{(1+z)^{2.7}}{1+[(1+z)/2.9]^{5.6}} M_\odot yr^{-1} Mpc^{-3}
\]  

(1.13)

Figure 1.12 shows the SFH has a rising period, scaling as \( \psi(z) \propto (1+z)^{-2.9} \) at \( 3 \lesssim z \lesssim 8 \). It slows down and reaches its maximum when the Universe was \( \sim 3.5 \) Gyr, or around \( z = 2 \) or \( z = 1.5 \). There is a gradual decrease to now, which goes as \( \psi(z) \propto (1+z)^{2.7} \) (Madau and Dickinson, 2014).

According to Calzetti (2001b), due to the fact that observations at shorter wavelengths have been improved along the years, more studies on the dust effects on rest-frame regions for objects at higher redshifts have been done. In this sense, there is more evidence on how dust attenuation plays a role in these galaxies (Calzetti, 2001b).

Figure 1.11 (a) shows the SFR densities in the FUV and the FIR as a function
1.9. Dust attenuation curves at high redshift

Figure 1.11: (a) SFR densities in the FUV and FIR. Symbols correspond to Magnelli et al. (2013) (red hexagons), Wyder et al. (2005)(dark blue hexagon), Gruppioni et al. (2013) (dark red hexagons), Dahlen et al. (2007) (blue pentagon), Cucciati et al. (2012) (green square), Schiminovich et al. (2005) (blue triangle), Reddy and Steidel (2009) (green triangle), Robotham and Driver (2011) (dark green pentagon), Schenker et al. (2013) (star), Sanders et al. (2003) (brown circle), Takeuchi et al. (2003) (dark orange square) and Bouwens et al. (2012) (magenta pentagons). (b) Mean dust attenuation according to redshift. Same symbols. Cyan pentagons are from Salim et al. (2007) and Burgarella et al. (2013) correspond to olive green dots. Two different attenuation factors are considered from Reddy and Steidel (2009) and Bouwens et al. (2012): The open symbols are integrated for the observed population and the filled symbols are extrapolated down to $L_{FUV} = 0$ (Madau and Dickinson, 2014).

Figure 1.12: History of cosmic star formation with FUV + IR rest-frame estimates. Same symbols. The solid curve represents the best-fit SFR density (Madau and Dickinson, 2014).
1.9. Dust attenuation curves at high redshift

of redshift (Madau and Dickinson, 2014). The FUV is uncorrected for dust attenuation. To build Figure 1.11, Madau and Dickinson (2014) converted UV and IR luminosities to instantaneous SFR densities. Each symbol corresponds to different data sets. The Madau and Dickinson (2014) work is restricted to post-2006 galaxy surveys with SFRs from rest-frame FUV or MIR estimates. Local data on the rest-frame FUV region uses GALEX measurements as is the case for Robotham and Driver (2011), Wyder et al. (2005) and Schiminovich et al. (2005). For $0.1 < z < 4$, Cucciati et al. (2012), Dahlen et al. (2007), Reddy and Steidel (2009) work on FUV luminosity densities is used. Bouwens et al. (2012) and Schenker et al. (2013) covers redshifts $4 \leq z \leq 8$. In Madau and Dickinson (2014) SFRZD$(z)$ study, they use local IR estimates from Sanders et al. (2003) and Takeuchi et al. (2003), Spitzer measurements at $0.4 < z < 2.3$ from Magnelli et al. (2009, 2011) and finally, Herschel estimates from Gruppioni et al. (2013) and Magnelli et al. (2013). On Figure 1.11, FUV data have not been corrected for dust. The difference between UV and IR data grows along with redshift up to $z \approx 1$ and it narrows from 1 to $z = 2$.

In order to transform FUV luminosity to total SFRD, a good estimate from dust attenuation is important. Figure 1.11 (b) depicts the mean dust attenuation in magnitudes as a function of redshift used in Madau and Dickinson (2014) work. Here, the data are based on stellar population model fitting and UV spectral slopes. They used the mean extinction factors from each survey to correct the corresponding FUV luminosity densities. From this figure, we observe that the local estimates of UV attenuation show some scatter, which implies that more work is needed on this quantity (Madau and Dickinson, 2014). Finally, Figure 1.12 shows both FUV and IR measurements (Madau and Dickinson, 2014). In general, these studies show that the Star Formation Rate Density increases with redshift up to $z \approx 2$ (Madau and Dickinson, 2014).

Now, let us present a general view of studies analysing the dust attenuation curves and the NUV bump of galaxies at higher redshift. In general, the 2175 Å bump is detected in most of the studies at different redshifts. For galaxies at $z > 1$, we have evidence of the NUV bump with the average dust attenuation curve
agreeing with the LMC and MW extinction laws (Buat et al., 2011). The bump has an amplitude of 35% of the MW and was found to affect the derivation of the UV slope in Buat et al. (2011). Looking at galaxies at \( z \sim 1.5 \), the NUV bump is present to a certain extent. Buat et al. (2012) used photometric data to study galaxies at \( 0.95 > z > 2.2 \), retrieving dust attenuation through SED fitting. In this sample, one fifth has a NUV bump and 90% of this sub sample are galaxies at \( z < 1.5 \). Regarding the other aspects of the attenuation law, the steepness of the curve is similar to the Calzetti law, in around 20-40% of the sample. The parameters characterising the NUV bump and the UV dust slope vary, which the authors suggest occur due to different environments within the stellar populations and intrinsic fluctuations of the attenuation curve in the galaxies (Buat et al., 2012).

If we now take a look at a higher redshift, the dust attenuation curve exhibits the 2175 Å absorption feature. In Noll et al. (2009) study at \( z < 2.5 \), 30% of their sample has a NUV bump. This sub-sample coincides with redder galaxies. The UV attenuation curve that better describes their sample would lie between LMC and SMC values. For star-forming galaxies at \( 1.36 < z < 2.59 \), Reddy et al. (2015) obtained a dust attenuation law with a NUV bump, but a slope comparable with the SMC curve. This curve is similar to the Calzetti (2001a) relation but with a lower \( R_V \) obtained at a shorter wavelength. At even higher redshift, \( 2 < z < 6.5 \), Scoville et al. (2015) found a dust attenuation law comparable to the Calzetti law but with the presence of the 2175 Å bump.

An important work on the dust attenuation law at high redshift is given by Kriek and Conroy (2013). Their sample is formed by stacked photometry of galaxies at \( z \sim 1.5 \). These composite SEDs were fitted with flexible stellar population synthesis models using the parametrisations of the dust attenuation law given by Noll et al. (2009), meaning that their parametrisations curve is based on the Calzetti law plus a Lorentzian-like Drude profile to fit the NUV bump. This study shows that the dust law depends on galaxy type. There are cases in their study that do not follow the usual Calzetti law which was derived from local starbursts. The authors identified a strong correlation between the best-fit dust slope and the strength of the
1.9. Dust attenuation curves at high redshift

UV bump: steeper laws having stronger bumps (See Figure 1.13). Active galaxies present shallower dust curves with weaker bumps; thus, the authors conclude the dust attenuation curve is correlated with the specific star formation rate. The diversity on the dust attenuation laws from Kriek and Conroy (2013) may be explained in different ways. First, dust laws may depend on dust composition, line-of-sight geometry and grain size. In consequence, they could change due to the stellar population ages or when the objects are viewed at different orientations (Salmon et al., 2016).

![Figure 1.13](image.png)

**Figure 1.13:** In this figure from Kriek and Conroy (2013) (a) we have the bump strength $E_b$ and the slope of the best-fit attenuation curve $\delta$ corresponding to different SED types. Small grey squares are different sightlines. The size indicates how many galaxies were used for the composite SED. Colour is associated to $A_V$. As an example, values for Calzetti law, MW, LMC and SMC dust curves are also included. Panel (b) and (c) compare the previous dust parameters with $W_{H\alpha}$, the $H\alpha$ equivalent width. Here it can be seen that a shallower curve is associated with a weaker UV bump (Kriek and Conroy, 2013).

Kriek and Conroy (2013) adopt two different parameters to model the dust attenuation: $E_b$ and $\delta$, which would be relevant later on. These are directly related to the strength of the NUV bump $B$ and the total-to-selective ratio $R_V$, respectively. The correlation between these two dust parameters $E_b$ and $\delta$, consequently between $B$ and $R_B$, is characterised by:
1.9. Dust attenuation curves at high redshift

\[ E_b = (0.85 \pm 0.09) - (1.9 \pm 0.4) \delta \]  \hspace{1cm} (1.14)

A relevant conclusion from this study is that they found that neither the MW, LMC, SMC nor the Calzetti laws provide a good fit to this correlation. This result contributes to the idea of the non-universality of the dust attenuation curve in galaxies. The authors also detected a trend between their dust parameters and a proxy for star-formation, the equivalent width of $H_\alpha$ ($W_{H\alpha}$, [\AA], See Figure 1.13). They found that smaller values of this proxy are associated with a steeper attenuation curve and a more prominent NUV bump. Stellar mass could be underestimated and both the attenuation and the sSFR are overestimated for the case of high $W_{H\alpha}$ galaxies. Additionally, Kriek and Conroy (2013) assessed the effect of $E_b$ on the UV slope $\beta$. They compared a UV slope recovered by the use of photometric data and a UV slope obtained from their composite SED. As attenuation increases, larger biases are found, meaning the NUV bump could render underestimated dust corrections.

There are studies at high redshift where the preferred dust attenuation curve lacks the NUV bump and is more similar to a Calzetti law. On the $z \sim 1$ range and employing Balmer decrements to constrain dust attenuation law similar to Calzetti (2001a) and Calzetti et al. (1994), the work of Price et al. (2014) found an agreement with the two-component dust model, where the young stellar populations suffer attenuation both from their birth cloud and the ISM. Furthermore, they identified a trend with dust attenuation in the star-forming regions as it decreases with sSFR and increases with SFR and mass.

Along the same lines, a study worth mentioning is given by Salmon et al. (2016). With Bayesian techniques, Salmon et al. (2016) model the SEDs of galaxies from CANDELS at $z \sim 2$. They did not find evidence, based in testing their model fits, which would agree with the presence of the NUV bump. They identified galaxies with a stronger reddening have a flatter law, similar to a starburst galaxy (i.e. Calzetti law). On the other hand, a low colour excess corresponds to a law similar to SMC (i.e. a steeper law). No correlations were found between the dust attenuation curves and the stellar properties, such as stellar mass or SFR. In
1.9. Dust attenuation curves at high redshift

In this work, Salmon et al. (2016) associate these outcomes with a model describing a mixed star-dust geometry, scatter, and/or a trend with stellar population age, dust grain size and metallicity.

A relevant result from Salmon et al. (2016) is the comparison between the Witt and Gordon (2000) dust models and their results, as shown in Figure 1.14, top panel. The dust attenuation law from radiative transfer models gives a greyer curve with increasing optical depths, considering a clumpy, SMC and SHELL models (Witt and Gordon, 2000). From this figure, we can observe that the steepest curves are not as well constrained by the \( \delta \) parametrisation since the curvature is higher than the fit a power law can provide. Nonetheless, the relation between \( E(B-V) \) and \( \delta \) is in accord at high and low optical depths.

Regarding the relation between colour excess \( E(B-V) \) and the dust slope \( \delta \), Salmon et al. (2016) provide an important insight. In particular, they found that the amount of dust increases for the flatter dust attenuation laws. In this way, low optical depth corresponds to steeper dust curves —See Figure 1.14, bottom panel. These relations seemed not to be affected by the NUV bump and were fitted by:

\[
\delta = (0.62 \pm 0.05) \log(E(B-V)) + 0.26 \pm 0.02.
\]  

In turn, Salmon et al. (2016) compares this trend to the relation between \( R_V \) and \( E(B-V) \), since the former is inversely proportional to \( \delta \) around \( \lambda = \lambda_V \).

To summarise, the overall view of dust attenuation in galaxies at high redshift is that there is not a homogeneous law that encompasses all the wide range of dust properties observed. In particular, the absence/presence of the NUV bump is not a universal feature of the dust attenuation curves, which in turn, cast doubts on the use of a unique attenuation law for all galaxies, as is in the case of the Calzetti curve on star-forming galaxies. This point of view is important not only for dust studies but also to obtain good constraints on dust, which help provide robust estimates of other stellar properties like ages, SFR, etc.
1.10. Toolkit to understand dust in galaxies

1.10.1 UV slope $\beta$ and $IRX$

Calzetti et al. (1994) define the UV-spectral slope $\beta$, and it is usually seen as an indicator of dust attenuation. They fitted the UV continuum to a power law, given by $f_\lambda \propto \lambda^{\beta}$ with $1250 \leq \lambda \leq 2600\,\text{Å}$ and $\beta$ as the power-law index. To avoid the
presence of different absorption features, the authors chose 10 different windows within the aforementioned range for the definition of $\beta$. Similarly to $\beta$, the IRX or infrared excess is also used as a dust indicator. The IRX is the ratio of the infrared-to-UV luminosity $\log(L_{IR}/L_{UV})$ (ratio between FIR and UV flux), and is a tool for dust obscuration as well.

The UV slope $\beta$ is mainly used because it is easy to measure, particularly at higher redshift (Lo Faro et al., 2017, Theios et al., 2018). In this range, it has been used as a proxy for dust attenuation, although this slope is susceptible to changes in star formation history, age, metallicity and IMF. This slope was defined from UV spectroscopy in Calzetti et al. (1994), using carefully defined spectral windows. Nevertheless, it can also be obtained from UV colours. In this last case, they fit a power-law to the photometric data which may render a redder $\beta$ than using the Calzetti definition (See e.g. Salmon et al., 2016).

By using IRX and $\beta$, Meurer et al. (1999) found that starburst galaxies follow a specific region from the IRX-$\beta$ plot — e.g. Fig. 1.15 —, thus associating $\beta$ to the FUV dust attenuation. This relation has been used as a dust attenuation estimator when $\beta$ is available. Nevertheless, there are studies that suggest not only dust but also other stellar population parameters may affect the galaxy location on the IRX-$\beta$ plane, like SFH or dust/star geometry (see, e.g. Boquien et al., 2012, Buat et al., 2002, 2005, Conroy, 2013, Conroy et al., 2010, Johnson et al., 2007, Panuzzo et al., 2007, Reddy et al., 2012). Problems with the $IRX - \beta$ appear to be solved by taking into account different dust attenuation laws or star formation histories (Conroy, 2010, Panuzzo et al., 2007, Salmon et al., 2016).

As discussed before, the lack of an NUV bump is not universal in star-forming galaxies. Therefore, it is important to bear in mind that relations like the $IRX - \beta$ are prone to be affected by this feature. A discussion on this issue is given in Chapter 4. The UV slope $\beta$ does not only correlate with the infrared excess but also with $E(B - V)$. This outcome implies that a greater value of $E(B - V)$ corresponds a larger amount of dust, i.e. a larger attenuation and more reddening (Calzetti, 2013).

Finally, let us consider studies of $\beta$ in galaxies at higher redshifts. Bouwens
1.10. Toolkit to understand dust in galaxies

Figure 1.15: $IRX - \beta$ relation. The relation for starburst given by Meurer et al. (1999) corresponds to the dashed line. On the left panel, we see the $IRX - \beta$ for galaxies at $z \sim 0$ from the Local Volume Legacy Survey (LVL) (Dale et al., 2009). The symbols show different data and galaxy morphological type, specified below. On the right panel, we have the $IRX - \beta$ relation for galaxies at $z \sim 2$. In this panel, symbols represent galaxies selected in different manners: with X-ray, 24$\mu$m fluxes, young light-weighted age and bolometric luminosity. We observe that for redder UV slopes, larger IRX values are expected. Furthermore, there is a scatter for galaxies at a given value for $\beta$ (Conroy, 2013).

et al. (2012) and Finkelstein et al. (2012) analysed the UV slope of galaxies at $z > 2$. There is a correlation with an increase in $\beta$ value as the redshift decreases with less luminous galaxies. At the highest redshifts and faintest luminosities, $\beta$ varies from 2.0 to 2.5, which suggests these galaxies are dust-free (Conroy, 2013). For the case of dust-obscured IR luminous galaxies around $z \sim 2$, their best UV dust attenuation curve being described on the $IRX - \beta$ plot by a power-law with a slope varying between -0.7 and -0.1 (Lo Faro et al., 2017).

1.10.2 UVJ diagram

A possible way to separate quiescent galaxies and star-forming galaxies (dusty or non-dusty) is to locate them on the UVJ plot. This tool is a colour-colour diagram
1.10. Toolkit to understand dust in galaxies

with the rest frame colours $U - V$ and $V - J$ (Whitaker et al., 2011, Williams et al., 2009, Wuyts et al., 2007, see Figure 1.16). It can be seen as a way to break the age-dust degeneracy because it divides quiescent and dusty star-forming galaxies. This colour-colour plot is especially useful to separate galaxy types when data availability is limited, as is the case in more distant galaxies (Conroy, 2013).

Wuyts et al. (2007) show how this colour-colour diagram is a good indicator of galaxies at higher redshift. Using HST, VLT and Spitzer photometry, Wuyts et al. (2007) analysed galaxies at $2 < z < 3.5$. They found galaxies that had a redder rest-frame $U - V$ colour are also associated with a redder $V - J$. They demonstrated the possibility to discriminate between young and dusty galaxies from old galaxies, because, for a given a $U - V$ colour, there is a range in possible $V - J$ colours. They detected that more massive galaxies have redder rest-frame $U - V$ colours, compared to less massive galaxies. This result holds even after taking into account complex star formation histories.

Photometry from UKIDSS, Subaru-XMM and Spitzer is used by Williams et al. (2009) study which analysed star-forming and non-star-forming galaxies at $z \leq 2.5$. An important finding from this work is that their galaxy sample resides in two different areas of the $U - V$ and $V - J$ colour space. They had an area corresponding to red and quiescent galaxies, and another from blue to red $U - V$ colours, associated with star-forming galaxies. In general, their study shows star-forming and quiescent galaxies were separated almost equally for the case of the brightest objects at redshift 1-2. On the other hand, the most luminous galaxies are quiescent at lower redshift.

Whitaker et al. (2011) provide further evidence of the bimodal colour distribution from the two different galaxy types: star-forming and quiescent galaxies. In addition, the evidence in this work supports this behaviour up to $z \sim 3$. Figure 1.16 shows where the bimodal colour distribution of quiescent and star-forming galaxies. In particular, the diagonal limits follow Whitaker et al. (2011), namely:
$$(U-V) > 0.88 \times (V-J) + 0.69 \quad [z < 0.5]$$

$$(U-V) > 0.88 \times (V-J) + 0.59 \quad [z > 0.5]$$  \hspace{1cm} (1.16)

Furthermore, the limits in $U-V$ and $V-J$ are defined as follows:

$$(U-V) > 1.3, \ (V-J) < 1.6 \quad [0.0 < z < 1.5]$$

$$(U-V) > 1.3, \ (V-J) < 1.5 \quad [1.5 < z < 2.0]$$  \hspace{1cm} (1.17)

$$(U-V) > 1.2, \ (V-J) < 1.4 \quad [2.0 < z < 3.5] .$$

**Figure 1.16:** UVJ diagram from Whitaker et al. (2011). It corresponds to the rest-frame UVJ colours for NEWFIRM Medium-Band Survey galaxies with S/N > 8 in the K band. The density of points is given by the greyscale and the lines are the separation between quiescent galaxies and star-forming galaxies. On the highest redshift interval $2.5 < z < 3.5$, the quiescent galaxies can still be located.

An example of dust attenuation effects on the UVJ diagram is given by Figure 1.17 from Salmon et al. (2016) study. We observe the different assumed dust attenuation laws produce changes in the positions of star-forming galaxies. These variations are degenerate with SFHs and age/metallicity differences (Salmon et al., 2016). Nevertheless, Salmon et al. (2016) conclude that the dust law does not essentially affect the division between quiescent and star-forming galaxies.
1.11. Main sequence of galaxies

Both star formation rate (SFR) and stellar mass are correlated, which in turn defines the Main Sequence of galaxies (MS, Buat, 2014, Rodighiero et al., 2011, Speagle et al., 2014). Figure 1.18 shows a very simple diagram showing the number of existing stars vs number of stars forming. This schematic illustrates how this relation separates different types of galaxies. The main sequence is given by the blue line and the green valley (green line) is located between the red cloud, associated with red and dead galaxies, and the main sequence. A galaxy in the red cloud has, at a fixed number of stars, fewer stars if compared to galaxies from the main sequence. On the other hand, the outliers that produce more stars with the same number of stars than the main sequence are starburst galaxies, represented by the pink line in Figure 1.18.

We will use the definition of main sequence (MS) of star-forming galaxies.
1.12. Emission by dust

Dust is responsible for the absorption, scatter and re-emission of light at different wavelengths. Energy re-emitted at longer wavelengths, i.e. mid-IR to sub-mm range, originates from the energy absorbed by dust in the UV-optical range. For the case of normal disk galaxies, dust is responsible for the re-emission in the infrared of around 30% of the light and about 99% in ultraluminous IR galaxies (Galliano et al., 2018). This radiation sheds light on the characteristics of their environments (Li and Greenberg, 2003). The optical properties and sizes of dust particles also relate to their temperatures and the interstellar radiation field. The observed Far-IR

\[ \log \phi(M_*, t) = (0.84 \pm 0.02 - 0.026 \pm 0.003 \times t) \log M_* - (6.51 \pm 0.24 - 0.11 \pm 0.03 \times t), \]

(1.18)

with $\phi$ describing the evolution of the SFR as a function of mass ($M_*$) and time ($t$). This equation gives a good fit from $z = 0$ to $\sim z = 6$. An example of the fits that this relation produces, can be seen in Figure 1.19. Here, we observe the MS relation for six different redshift from 1 to 4.

Figure 1.18: Schematic of the main sequence (blue) of galaxies showing the green valley, the red cloud (red and dead galaxies) and starburst (pink) (Buat, 2014).
1.12. Emission by dust

Figure 1.19: Different Main Sequence relations corresponding to several redshift given by the different colours. This best fit is taken from Speagle et al. (2014). The scatter is associated to the scatter from Equation 1.18 (±0.2 dex), rather than the most likely observed scatters (∼0.3 dex). Changes in the MS slope can be observed at fixed mass for different redshift (Speagle et al., 2014).

emission result from cold dust, while PAH emission is responsible for the emission from 3 to 12 µm (Draine, 2003, Marshall and Herter, 2004). The dust IR emission gives information on different physical galaxy characteristics. Namely, properties like bolometric luminosity, dust mass, dust temperature and the abundance of PAH molecules or grain size (Conroy, 2013).

If we look at the SED of a normal galaxy, dust emission dominates at λ ∼ 10µm, but around λ < 12µm the emission is mainly because of the presence of PAHs. At longer wavelengths (λ < 50µm), the IR emission contributes to ∼ 33% of the total IR emission. At λ > 50µm, dust emission supplies ∼ 66% of the total IR luminosity. In this case, it is controlled by grains at a temperature ∼ 15 – 20 K (Conroy, 2013).

IR emission is a tracer of the SFR and, as expected, suffers systematic effects. This may happen because dust emission does not take into account the light that is not absorbed by dust at shorter wavelengths, in the same manner that UV and optical indicators do not consider the light that is not attenuated. Dust IR emission will systematically render a lower value of the SFR if not calibrated, because on average
dust attenuates $\sim 50\%$ of the integrated starlight of galaxies (pp. 552, Kennicutt and Evans, 2012). Nevertheless, the opposite scenario may be also possible due to older stars being one of the main contributors to dust heating, resulting in this SFR indicator to overestimate SFR (Kennicutt and Evans, 2012).

To summarise, the overall picture of dust attenuation law in galaxies at low redshift is that there is not a homogeneous view of how a universal dust attenuation law would look like. As we explored, this is evident with studies that find the presence of the NUV bump in their dust attenuation curve (e.g. Conroy et al., 2010, Hutton et al., 2015, Salim et al., 2018, etc). Nevertheless, the empirical Calzetti law has showed to be successful, so a unique dust attenuation law is usually applied for dust correction (e.g. Calzetti, 2001a, Fischera et al., 2003, etc). For galaxies at high redshift, there is evidence of the NUV bump in some galaxies but more studies are needed to prove/disprove if there is a universal dust attenuation law. Thereby, the main goal is to test the non-universality of the dust attenuation law in galaxies at $z \sim 2$ and to explore possible inaccuracies on diagnostics derived from this assumption. As a first step into achieving our main goal of analysing the dust attenuation in galaxies at high redshift, we test our methodology in Chapter 2. We examine it with low redshift synthetic photometry from SDSS and UVOT. The latter is especially important since it probes the area of the NUV bump. Chapter 3 fully explores the methodology we eventually apply to our Survey for High-z Absorption Red and Dead Sources (SHARDS) sample, examining how to deal with the extra parameter of redshift and the special characteristic of the instrument used in SHARDS. We constrain $E(B-V)$, $R_V$ and the NUV bump for our SHARDS sample in Chapter 4, finding dust parameters spread within their whole possible range but in some cases, correlating with one another. Furthermore, we analyse how the diversity of dust parameters affect the NUV slope $\beta$, in particular how the NUV bump presence may influence its derivation. We explore if there is any correlation between the retrieved dust parameters and this slope. This is relevant since any systematic may influence on usual dust attenuation tools like the infrared excess (IRX-$\beta$ relation). Chapter 5 analyses the effect of dust in different diagnostics further. We examine the UVJ dia-
gram and the main sequence of galaxies to discern if they have been affected by the wide range of dust parameters on SHARDS. Also, we contrast different theoretical dust models while looking for clues on what drives the trends we observed between the SHARDS dust attenuation parameters. Finally, in Chapter 6, we explore the general conclusions and outlook.
Chapter 2

Methodology and a test with UVOT + SDSS simulated photometry

In this chapter, we will explain the methodology used in this thesis. The base of our SED fitting methodology is to compare simple stellar population models to data (simulated or not) and therefore, constraining the dust attenuation parameters.

The intention at this stage is to calibrate the methodology, and to characterise possible problems we may encounter. This test would be ideally done in a simpler data set than the main target data from Survey for High-z Absorption Red and Dead Sources (SHARDS). Hence, we will apply our methodology to Ultraviolet/Optical Telescope (UVOT) and Sloan Digital Sky Survey (SDSS) synthetic photometry and test if the derived dust properties correspond to the original simulated value and in turn, we aim to demonstrate the method applied does not have a systematic and that it is indeed robust.

2.1 Methodology

First, we will explain the basis of the methodology and then we will apply it to a simple simulated sample. The methodology involves a comparison between synthetic population models and our simulated data to retrieve the best-fit parameters, both stellar and dust-related. We use the population synthesis models from Bruzual and Charlot (2003, hereafter BC03). These synthetic models are based on simple stellar populations (SSPs). On the BC03 models, each SSP represents a population
with a single age and metallicity and they allow for a wide range of possible values of these two parameters. We combine these with a range of parameters describing the attenuation law to build a large grid of models. The size and range of the grid will vary depending on the data we would like to analyse, but always trying to maximise the size and, thus, resolution.

To obtain the best-fit to any data we analyse, we will use the $\chi^2$ statistic:

$$\chi^2(\pi_i) \equiv \sum_j \frac{[m_j^{OBS} - m_j^{MOD}(\pi_i)]^2}{\sigma^2(m_j)},$$

(2.1)

where $\pi_i$ represents all possible choices of the parameters. Likewise, $m_j^{MODEL}$ and $m_j^{OBS}$ are the model magnitudes and observed magnitudes. Equation 2.1 compares the models (MOD) and the measured data (OBS), and $\sigma^2(m_j)$ is the observational error for each flux measurement.

The likelihood of a given set of parameters is determined by:

$$\mathcal{L} \propto e^{-\Delta \chi^2/2},$$

(2.2)

with $\Delta \chi^2$ defined as $(\chi^2 - \chi^2_{\text{min}})$.

We follow a Bayesian approach, so that the parameters are computed using the likelihood as a probability distribution function (PDF), namely:

$$\langle \pi_j \rangle = \frac{\int \pi_j \mathcal{L}(\pi_i) d^n \pi_i}{\int \mathcal{L}(\pi_i) d^n \pi_i}.$$

(2.3)

We assume these best-fit parameters describe the stellar population in the data at hand, simulated or real. The variance is defined as:

$$\sigma^2_{\pi_j} = \langle \pi_j^2 \rangle - \langle \pi_j \rangle^2$$

(2.4)

However, this expression can lead to round-off errors so instead, we will use the two-pass algorithm to obtain the variance. This approach goes through the data twice, one to compute the mean, and then another time to calculate variance (Chan et al., 1983). The two-pass algorithm manages the problem of numerical instability,
2.2 Ultraviolet/Optical Telescope (UVOT) and Sloan Digital Sky Survey (SDSS)

Although with an increase in computing time, this technique is more stable (Bennett et al., 2009). The two-pass algorithm follows the subsequent steps:

1. Compute the mean according to:

\[
\bar{x} = \frac{\sum_{j=1}^{n} x_j}{n} \quad (2.5)
\]

2. Calculate the sum of squares of the differences from the mean, namely:

\[
s^2 = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1} \quad (2.6)
\]

In these equations, \( x \) represents the stellar and dust parameters (\( x_i \) is the parameter analysed in each case) and \( j \) index varies from 1 to \( n \), which is the number of steps in the model grid.

In our Bayesian modeling, we adopt so-called ‘flat priors’. In other words, the probability is equal in the range of parameters on the analysis.

2.2 Ultraviolet/Optical Telescope (UVOT) and Sloan Digital Sky Survey (SDSS)

Now that we have described the methodology, the next step is to test it with mock data, to be able to assess how well the methodology is in returning the dust-related parameters. The simulated data we use is synthetic photometry from both the UV and optical range with the Ultraviolet/Optical Telescope (UVOT) (Roming et al., 2005) and Sloan Digital Sky Survey (SDSS) (York et al., 2000). We stress that for this chapter we will only use the passbands associated with both UVOT and SDSS filters.

As the UVOT telescope is located in space, the main spectral region targeted is the UV, since this region suffers more from absorption by the atmosphere. The Swift Gamma-ray Observatory has three different telescopes (Breeveld et al., 2011), including the Burst Alert Telescope (BAT, Barthelmy et al., 2005) and the X-ray Telescope (XRT, Burrows et al., 2005). The UVOT is a modified Ritchey-Chrétien
telescope with a 17 x 17 arcmin\(^2\) field of view, with a wavelength range from 1600 to 8000 Å. Nevertheless, UVOT presents a particular photon-counting detector that behaves in a way comparable to an X-ray detector (Poole et al., 2008). The main goal of the UVOT is to observe and locate Gamma Ray Bursts. In the NUV region, UVOT has three broadband filters $UVW2$, $UVM2$ and $UVW1$ — See Table 2.1 and Figure 2.1. A fast readout, micro-channel-plate (MCP), intensified, photon-counting CCD detector with 256 x 256 active pixels is employed by the UVOT (Breeveld et al., 2010). This detector differs from a regular CCD since the UVOT detectors acts as a photon counter. In general, what the photocathode does, is to convert an incoming photon into an electron signal. This, in turn, gets amplified by a photomultiplier, so the signal is intensified, and detected by the CCD as a single photon event.

![Figure 2.1](image-url): Filter transmission curves including $UVW2$, $UVM2$ and $UVW1$. The dashed line gives the \emph{white} filter transmission curve. The transmission curves shown were measured in the laboratory (Poole et al., 2008).

Since higher energy photons render higher energy electrons in the detector photocathode, the Point Spread Function (PSF) of the NUV images tends to be broader. In the case of UVOT, the PSF narrows with high count rates, because of the effect of coincidence. Coincidence loss happens when two or more photons hit the same location within one CCD readout frame. Thus, a systematic is introduced with an undercounting of the true photon flux, since just one photon is counted.
2.2. Ultraviolet/Optical Telescope (UVOT) and Sloan Digital Sky Survey (SDSS)

(Breeveld et al., 2011). In this way, the PSF is deeply distorted at high count rates. To deal with this, the stars used to measure the PSF do not have high count rates (Breeveld et al., 2011).

Since UVOT is a photo-counting detector, there are some corrections needed to be performed to the data. To begin with, both UVW2 and UVW1 have a red leak. What this means is that longer wavelengths can pass through the filters, due to the presence of an extension of the filter tail which translates into the filter allowing for a fraction of the red incoming light (Breeveld et al., 2011, Hutton, 2016).

The reason to use UVOT filters for our analysis is that the three NUV filters are ideal to analyse the 2175 Å absorption feature. Studies have already explored this approach. Hoversten et al. (2011) couples UVOT with SDSS fluxes to study galaxies M81 and Holmberg IX, finding a dust extinction law with a NUV bump, as both SMC and Calzetti curves were ruled out. In particular, the Milky Way dust extinction law is the curve that better fits both galaxies. Similarly, Hagen et al. (2017) combines UVOT data with optical and infrared observations. They fitted models to the star-forming regions to constrain their ages, masses and dust extinction parameters. In this work, an NUV bump was detected in most of the SMC sightlines, being stronger to the north-east of the galaxy. Likewise, they found a steeper attenuation curve compared to the Milky Way.

In addition to the UVOT transmission curves, we will use SDSS passbands. From SDSS, the filters used are u, g, r, i and z — See Table 2.1 and Figure 2.2. SDSS provides wide-band CCD. The photometric data cover from 3000 to 11 000 Å (Fukugita et al., 1996) and it makes use of a 2.5 m telescope at Apache Point Observatory (APO) in New Mexico (Aihara et al., 2011).

Similarly, SDSS has been used to constrain dust attenuation. For instance, Koyama et al. (2018) studied stellar light and nebular emission lines in galaxies at low redshift. They used the AKARI-SDSS-GALEX catalogue to compare the $L_{IR}/L_{UV}$ ratio from stellar light and the $H_\alpha/H_\beta$ ratio from nebular emission lines. They found more massive galaxies are associated with stronger attenuation in the nebular regions. Also, galaxies with high sSFR (specific Star Formation Rate, which
2.3 Simulated data

In the first part of this test, we will employ the UVOT and SDSS transmission curves as a starting point to build a set of simulated data from BC03 models. These models were obtained using the random estimates for the stellar and dust parameters, which are needed to build the simulated data. We built a code which uses BC03 libraries to get the SEDs and then, with the random estimates of the dust parameters, we attenuate the SEDs. In other words, our methodology takes the parameters and renders an unattenuated SED corresponding to an SSP, which would be attenuated afterwards.

To constrain the parameters, a grid of these simple stellar population synthesis models was built. The range of simulated measurements for the age, metallicity and colour excess for these models are shown in Table 2.2. As a first approach and
2.3. Simulated data

Table 2.1: Properties of UVOT + SDSS passbands

<table>
<thead>
<tr>
<th>Filter</th>
<th>((\lambda)) Å</th>
<th>FWHM Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVOT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UVW2</td>
<td>2033</td>
<td>657</td>
</tr>
<tr>
<td>UVM2</td>
<td>2229</td>
<td>498</td>
</tr>
<tr>
<td>UVW1</td>
<td>2591</td>
<td>693</td>
</tr>
<tr>
<td>SDSS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SDSSu</td>
<td>3551</td>
<td>599</td>
</tr>
<tr>
<td>SDSSg</td>
<td>4686</td>
<td>1379</td>
</tr>
<tr>
<td>SDSSr</td>
<td>6165</td>
<td>1382</td>
</tr>
<tr>
<td>SDSSi</td>
<td>7481</td>
<td>1535</td>
</tr>
<tr>
<td>SDSSz</td>
<td>8931</td>
<td>1370</td>
</tr>
</tbody>
</table>

Table 2.2: Parameter range of model grid

<table>
<thead>
<tr>
<th>Observable</th>
<th>Parameter</th>
<th>Range</th>
<th>Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>(\log(t_0/\text{Gyr}))</td>
<td>([-2, +0.9])</td>
<td>20</td>
</tr>
<tr>
<td>Metallicity</td>
<td>(\log(Z/Z_\odot))</td>
<td>([-2, 0.3])</td>
<td>20</td>
</tr>
<tr>
<td>Colour Excess</td>
<td>(E(B-V))</td>
<td>([0, 0.5])</td>
<td>20</td>
</tr>
</tbody>
</table>

for simplicity, colour excess is the only dust parameter included in this first test. \(E(B-V)\) is the parameter that accounts for the reddening, from the parametrisation of the dust law from Conroy et al. (2010) —See Section 1.5.4. \(R_V\) the total-to-selective ratio and the strength of the NUV bump \(B\) are fixed to the Milky Way equivalent values: \(R_V = 3.1, B = 1\).

Following the methodology outlined before, we compare a set of 100 simulated NUV and Optical fluxes with a grid of synthetic models mentioned above to find the best fit. The simulated data was created with random estimates for stellar age, metallicity (\(Z_H \equiv \log Z/Z_\odot\)) and colour excess considering the range given in Table 2.2, to build the corresponding SSPs. This range covers the most usual values we would expect from our simulations, and works as a first test before analysing high-z simulations. The comparison with the models was done using the \(\chi^2\)-based likelihood as a probability distribution function (PDF) (Eq. 2.1 and 2.2) for the transmission curves mentioned in Table 2.1. It is important to note that we assumed
2.4 Results

In this section, we present the results on how well the methodology can retrieve the values from the simulations. Figure 2.3 makes a direct comparison between the input dust parameters (horizontal axes) and our retrieved parameters.

The input values are the random estimates of the stellar parameters and the output is the retrieved stellar and dust parameters obtained with our methodology. On Figure 2.3, we have plotted the desired behaviour with a 1:1 reference line. As can be seen from the plot, the results are generally in agreement with the input data. The red line shows an interpolated curve between the median and the error bars are RMS values. The only dust parameter included in this first test was reddening, and from the plot, we notice the rendered colour excess was well-constrained. We can interpret the scatter as a rough estimate of the accuracy in retrieving the underlying stellar and dust parameters. Thus, we could expect a variance for log age of \(\simeq 0.4 - 0.6\) Gyr and \(\simeq 0.2 - 0.3\) mag for the reddening \(E(B-V)\). In contrast, \(\Delta ZH\)
Figure 2.4: Residue for Metallicity with $\Delta ZH = ZH_{\text{Input}} - ZH_{\text{Output}}$. The black line corresponds to zero, which shows the desired residue value. The most scatter is observed for $\Delta ZH$, as $\Delta ZH \in [-1, 1]$. 

varies from -1 to 1 dex (Figure 2.4). Thus, the output values for metallicity present more scatter. To better observe this behaviour, Figure 2.4 shows the differences between the expected value and the input value. The black line marks the expected value of zero, i.e. a perfect retrieval of the input parameters. Compared with the other parameters, metallicity is the worst constrained. This result on the parameter has been observed Hutton et al. (e.g. 2014). Therefore, we will treat metallicity as a nuisance parameter. The main goal for the tests is to observe which parameters are better constrained in preparation for the SHARDS observational data. How to deal with the worst constrained parameters will be explored in context of the SHARDS sample. Nevertheless, we want to emphasise that the parameters we want to be best constrained are the dust parameters, in this case $E(B - V)$, because our analysis does not look to draw conclusions from the retrieved age or metallicity.

The next step in our analysis was to include additional dust parameters: NUV bump strength $B$ and the total-to-selective-ratio $R_V$. Table 2.3 presents the range for these two dust parameters: $R_V$ varies from 0.5 to 5, and the strength of the bump $B$
2.4. Results

Table 2.3: $R_V$ and $B$ range

<table>
<thead>
<tr>
<th>Observable Parameter</th>
<th>Range</th>
<th>Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total-to-selective ratio</td>
<td>$R_V$</td>
<td>[0.5, 5.0]</td>
</tr>
<tr>
<td>NUV bump strength</td>
<td>$B$</td>
<td>[0.0, 1.5]</td>
</tr>
</tbody>
</table>

spans from no bump to 50% stronger than the MW. The results are shown in Figure 2.5. Similar to the previous case, we observe how well the original values were retrieved and what can be expected from a “brute-force” method, i.e. a large grid approach.

A convenient way to visualise how good our methodology retrieves the dust-related parameters is to look at their corresponding PDFs. The reason why this may be a good approach is that these plots allow us to see the behaviour of the probability for each one of the possible values of the parameters. Therefore, if we observe a wide PDF, it means the likelihood spreads in the sample parameter space and we could expect the value not to be as well constrained. In contrast, if the PDF is narrow and centred in the expected value, we would expect a better agreement between the input and output values. Figures 2.6a to 2.6c are output examples for $E(B-V)$, $R_V$ and the strength of the NUV bump $B$. They show their corresponding PDF and Cumulative Distribution Function (CDF) with the expected value given by a vertical
2.4. Results

From Figure 2.6 we conclude that the best-retrieved parameter in this example is the colour excess. However, the three parameters are well constrained. Figure 2.7 shows the PDF and CDF corresponding to an example of metallicity. In this figure, the vertical dashed line corresponds to the input value that we expect to retrieve. Nevertheless, the peak of the PDF does not correspond to this “true” value.

The observed outcome from this test leads us to discard metallicity as one of our parameters for further study. Nevertheless, this parameter is needed to build the BC03 models; thus, metallicity will be considered as a nuisance parameter, i.e. it will be marginalised and will not be part of any analysis or conclusions after getting the unattenuated SED for the grid of models.

This chapter focused on testing the simulated data for UVOT and SDSS filters. This study allowed us to address the methodology in a clear and straight-forward way to identify and account for any systematic present. From the behaviour of Figures 2.3 and 2.6, we conclude that the code was verified. Furthermore, we determined that metallicity has to be treated as a nuisance parameter because, even in this simple test, our approach was not able to retrieve the correct values. Therefore, we will simply marginalise over metallicity, only because this parameter is required for the models. In the case of the other stellar and dust parameters, this test showed us what to expect from the retrieved values in this simple and best-case scenario. Different ways to improve them can be implemented, and we will explore them when we apply this methodology to SHARDS simulated data.

This thesis aims to probe the dust attenuation law of galaxies at high redshift. In this scenario, SHARDS photometry represents a more complex problem compared to the one presented in this chapter, particularly due to the specifications of the SHARDS instruments. The relevance of SHARDS photometry for the research goals of this thesis is given by the spectral range of the SHARDS filters, which is undeniably suitable to explore the rest-frame NUV bump region for galaxies at $z \sim 2$. In the next chapter, we will probe the methodology with SHARDS-like simulations by extending the methodology using more filters and now considering redshift. Furthermore, we explore ways to improve the better determination of dust parameters.
Figure 2.6: Probability Distribution Function (PDF, top panel) and Cumulative Distribution Function (CDF, bottom panel) for an output value corresponding to colour excess $E(B-V)$, total-to-selective ratio $R_V$ and NUV Bump strength $B$. The vertical dashed line in the top panels marks to the expected value.

on the next chapter.
Figure 2.7: Probability Distribution Function (PDF) and Cumulative Distribution Function (CDF) for metallicity. The vertical dashed line shows the input or expected value for ZH.
Chapter 3

Simulations using medium and broad-band photometry

In this chapter, we will apply the method described in Chapter 2 used to constrain the dust values for a set of UVOT + SDSS simulated photometry, but now using simulated data from the Survey for High-z Absorption Red and Dead Sources (SHARDS). The main objective for this chapter is to find systematics and optimise the code which will be used later on SHARDS data. Because our SHARDS sample comprises of galaxies covering a wide range of redshift, out to $z \sim 2$, a major difference from the approach discussed in the previous chapter is the addition of redshift as a new free parameter.

3.1 Survey for High-z Absorption Red and Dead Sources (SHARDS)

The Survey for High-z Absorption Red and Dead Sources (SHARDS, Pérez-González et al., 2013) is an ultra-deep optical survey taken at the 10.4m Gran Telescopio Canarias (GTC) with the OSIRIS (Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy) instrument. The main aim of this spectro-photometric survey was to analyse the properties of galaxies at $0 < z < 4$, focusing in particular on non-star forming massive galaxies at $z \lesssim 2$. It covers the GOODS-N (Great Observatories Origins Deep Survey-North) field, over 130 arcmin$^2$ area, detecting sources with AB magnitude up to 26.5. The data are ob-
tained through 25 medium-band filters, at wavelengths from 500 to 950 nm. Figure 3.1 depicts the layout of the filter set of SHARDS. The combined set of images produce an effective spectral resolution of $R \sim 50$.

The OSIRIS instrument is an optical imager with two CCDs, covering a total field-of-view of $7.4\,\text{x}\,8.4\,\text{'}$. An important point to remember is OSIRIS special characteristics (Cepa, 2010, Pérez-González et al., 2013). Sky flats for SHARDS dataset have gradients across the field with differences ranging from 10% to 50% in brightness. The variations occur from one edge of the field of view (FOV) to another, as well as in temporal variations. The spatial variations are a consequence of how the OSIRIS instrument works off-axis for the observational setup. This conclusion was drawn after the analysis of both night and day-time data (Pérez-González et al., 2013). Light has different angles of incidence (AOI) when reaching the detector ($-2^\circ \lesssim AOI \lesssim 22^\circ$). This, in turn, results on every single frame having its pixels seeing different filters, for a given passband. In other words, this issue affects the images taken with the passbands by shifting the central wavelength (CWL) of the filters seen by separate sections of the detector. This situation results from the dependence on the AOI of the CWL width of the filter set. The gradient observed on SHARDS data is a radial profile with its centre in the optical axis. The position and strength of the gradient structures of different brightness depend on time and the filter. Strong sky emission lines are seen by different passbands for each physical filter because of the CWL varying along the FOV. These strong emission lines are the locations for the brightest structures on the gradient. A calibration of the actual passbands was done to overcome this issue (Pérez-González et al., 2013). In the subsequent discussion, this particular aspect of the OSIRIS instrument will be referred to as the offset of the medium-band filters.

In Pérez-González et al. (2013), the authors verify that emission lines for sources with different redshift are retrieved from the SHARDS data. Absorption features can also be detected for objects at intermediate and high redshift. This is an important step as it is part of the main goal of SHARDS. They conclude that by taking into account SHARDS data it may be possible to break degeneracies associ-
3.1. Survey for High-z Absorption Red and Dead Sources (SHARDS)

Figure 3.1: Filter set layout for 25 SHARDS filters. This was designed to probe the optical wavelength range between 500 and 950 nm with filters of width $\sim 17$ nm. For reference, the sky spectrum is shown in green. Also stacked spectrum of 13 quiescent massive galaxies are displayed at 4 different redshifts from Pérez-González et al. (2013).

The SHARDS survey is associated with the study of stellar populations that are slowly evolving at higher redshift, because the statistical significance increases by 10%-20% compared to an analysis only based on broad-band data.

Regarding studies using SHARDS and star formation histories, we can mention the analysis performed in Hernán-Caballero et al. (2013). Their sample comprises objects at $z \sim 0.9$. Thanks to the resolution of the survey, they were able to measure the strength of the 4000 Å spectral break ($D_n(4000)$) in galaxies with stellar mass $\geq 10^9 M_\odot$. SHARDS data showed an improvement compared to broad-band photometry and optical spectroscopic surveys because these surveys are constrained to galaxies 10 times more massive. They stacked SEDs by their stellar mass and found that more massive objects have a lower emission with a larger 4000 Å break and red continua. The authors suggest that this outcome implies stellar age is the main driver of the observed trend between optical colours and stellar mass.

Star-forming galaxies at $z \sim 0.84$ and $z \sim 1.23$ are studied in Cava et al. (2015) with SHARDS. The galaxies were chosen by taking into account different SFR trac-
ers, namely \([\text{O} \text{II}]\), the UV emission and MIR/FIR emission. They selected objects according to their \([\text{O} \text{II}]\) emission and were contrasted with mass-selected objects at the same redshift. They obtained sSFR, UVJ colours and dust emission, using Spitzer and Herschel. In this way, they were capable of identifying emission line galaxies up to 26-27 AB mag. By comparing them to stellar population synthesis models, they estimate the rest-frame equivalent width for the emission lines, finding that its evolution compares to the general SFR density evolution of the universe: it is proportional to \((1+z)^3\) for \(z \simeq 1\). Besides, they employ the UVJ diagram to separate star forming galaxies and quiescent galaxies, which proved to be an effective tool (see, e.g. Labbé et al., 2005). Finally, the dust attenuation shows correlations with SFR and stellar mass: higher dust attenuation is related to larger stellar mass, which is associated with stronger star formation as well.

Along the same lines, Lumbreras-Calle et al. (2018) analyse 160 low mass galaxies at \(0 \leq z \leq 0.5\) with low SFR. They use an algorithm to simultaneously detect \([\text{O} \text{III}]\) and \(\text{H}_\alpha\), by fitting the SED with two simple stellar populations. They determined equivalent widths and absolute fluxes. In accordance with previous studies, they found that low extinction and metallicities are associated with low masses. They found the position of these objects in the UVJ diagram is associated with emission line galaxies which have bluer colours, compared to the median colour obtained from the general population of SHARDS galaxies.

### 3.2 Methodology

Even though the analysis of the SHARDS sample will be based on a similar methodology with respect to UVOT and SDSS photometry, there are some key differences. First, we analyse how to incorporate redshift and the offsets of the SHARDS passbands. Then, we look at whether different grid model sizes or the use of an MCMC method may improve the results. Another important matter to consider when using SED modelling is the star formation history (SFH) adopted for the synthetic models. We look upon five different SFH parametrisations and test the results. Finally, these results are used to define corrections to the output.
3.2. Methodology

3.2.1 Redshift and passband offsets

The offsets of the SHARDS passbands —as explained in Section 3.1— and the redshift are the two main differences between the methodology used in Chapter 2. First, let us consider redshift. This parameter adds complexity to the problem because the photometry of the corresponding stellar populations also depend on this new free parameter. Thus, the number of models substantially increase when redshift is brought into the analysis. The second difference relates to the offsets of the central wavelength of the SHARDS filters to the pipeline. As mentioned before, the offset is different for each galaxy and each passband. So, offsets are different for each object and passband combinations: the same object may have different offset values for each one of the different filters. Therefore, one will need a unique set of photometric values (grid) for each one of the measurements. This constitutes an important problem because it would be highly impractical to build a specific grid not only for each galaxy, but a specific grid for each of the SHARDS passbands (offsets). To solve this issue, we decided to proceed as follows:

1. Instead of dealing with offsets for each galaxy, we assume a mean or average central wavelength shift for each of the 25 filters of $\pm 100$ Å in general. We chose this number because it is comparable to the mean value of the offsets of our SHARDS measurements.

2. Now that we have a mean offset, we build two sets of photometric model grids employing different sets of passbands, each one corresponding to a different offset: $+100$ Å and $-100$ Å.

3. We now have two different magnitude values corresponding to each offset, so we can easily obtain the slope of the line that passes through these two different points. By doing this interpolation, we assume that this line describes the behaviour of the offsets.

4. This process will allow us to compute a linear interpolation of the model grids and obtain a mean magnitude value corresponding to the specific passband. We assume the offsets of the passbands to be linear, so by obtaining the slope
of the line which describes this behaviour, we can model it. Because we know the offset for each passband beforehand, we can interpolate with this value and obtain the corresponding magnitude. It is important to note that this same procedure has to be done for each different redshift value.

**Table 3.1:** List of SHARDS + WFC3 + CFHT passbands

<table>
<thead>
<tr>
<th>Filter</th>
<th>CWL (nm)</th>
<th>Passband Width (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f500w17</td>
<td>500</td>
<td>15</td>
</tr>
<tr>
<td>f517w17</td>
<td>517</td>
<td>16.5</td>
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<tr>
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<td>534</td>
<td>17.7</td>
</tr>
<tr>
<td>f551w17</td>
<td>551</td>
<td>13.8</td>
</tr>
<tr>
<td>f568w17</td>
<td>568</td>
<td>14.4</td>
</tr>
<tr>
<td>f585w17</td>
<td>585</td>
<td>15.1</td>
</tr>
<tr>
<td>f602w17</td>
<td>602</td>
<td>15.5</td>
</tr>
<tr>
<td>f619w17</td>
<td>619</td>
<td>15.8</td>
</tr>
<tr>
<td>f636w17</td>
<td>636</td>
<td>16.2</td>
</tr>
<tr>
<td>f653w17</td>
<td>653</td>
<td>15.4</td>
</tr>
<tr>
<td>f670w17</td>
<td>670</td>
<td>16</td>
</tr>
<tr>
<td>f687w17</td>
<td>687</td>
<td>17.2</td>
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<tr>
<td>f704w17</td>
<td>704</td>
<td>17.9</td>
</tr>
<tr>
<td>f721w17</td>
<td>721</td>
<td>18.5</td>
</tr>
<tr>
<td>f738w17</td>
<td>738</td>
<td>14.9</td>
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<td>755</td>
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<td>15.6</td>
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<tr>
<td>f857w17</td>
<td>857</td>
<td>15.9</td>
</tr>
<tr>
<td>f883w35</td>
<td>883</td>
<td>33.6</td>
</tr>
<tr>
<td>f941w33</td>
<td>941</td>
<td>27.8</td>
</tr>
<tr>
<td>f105w</td>
<td>1053.08</td>
<td>264.86</td>
</tr>
<tr>
<td>f125w</td>
<td>1248.6</td>
<td>284.5</td>
</tr>
<tr>
<td>f160w</td>
<td>1536.9</td>
<td>268.3</td>
</tr>
<tr>
<td>K</td>
<td>2149.7</td>
<td>320.8</td>
</tr>
</tbody>
</table>

We similarly deal with redshift. As explained above, it is unfeasible to have a grid of models for each one of the different redshift corresponding to each one of the mock (or real) galaxies. Consequently, we do the following:
3.2. Methodology

Table 3.2: Redshift range

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redshift</td>
<td>$z$</td>
<td>[1.5, 3.5]</td>
</tr>
</tbody>
</table>

(i) Given redshift $z$, we consider the two nearest values $z_{n-1}$ and $z_{n+1}$, such that $z_{n-1} < z < z_{n+1}$.

(ii) Then, we make a linear interpolation between $z_{n-1}$ and $z_{n+1}$.

(iii) We approximate all the possible values for the redshift range shown in Table 3.2.

(iv) In conclusion, we follow an approach similar to that of the passband offset. We assume that the function describing the filter response is linear and consequently we use the slope of this line to compute a magnitude obtained for each one of the grid models. Again, this is done because we cannot build a grid for each observation.

To summarise, in order to overcome the main two issues and perform the analysis, we need to make two different linear interpolations: one for the redshift and the other for the offsets of the passbands.

3.2.2 Grid models

For the analysis of this chapter, we use the SHARDS passbands as given before in Table 3.1. The first 24 filters correspond to the aforementioned SHARDS narrowband survey. The next four are HST broadband WFC3 filters — f105w, f125w & f160w — and the K filter from CFHT (Koekemoer et al., 2011, McCracken et al., 2010).

Now that we have established which passbands we will consider for this exercise, the next step is to determine the region on the parameter space which we will use for the BC03 models. The parametrisation of the dust attenuation law is given by CSB10. The grid of BC03 models will probe a wide range of stellar and dust parameters (See Table 3.3). Namely: age, metallicity, colour excess $E(B - V)$,
3.2. Methodology

total-to-selective ratio $R_V$ and NUV bump strength $B$, with dust being described as a single foreground screen. We note the range of dust attenuation parameters includes the case of the Milky Way dust extinction law. For the case of redshift, it varies from 1.5 to 3.5, in steps of 0.1 —See Table 3.2. The range of dust parameters chosen for this exercise corresponds to the possible values we could obtain. For example, $R_V$ ranges from around 2.7 for the LMC, up to 5 for dense molecular clouds (Glassgold, 2008, Pogge, 2011, Tielens, 2005). For the case of the NUV bump, it varies from 0, which corresponds to the Calzetti law, and up to 1.5 which is 50% stronger than the MW (Conroy et al., 2010, Galliano et al., 2018).

Now, we explore two different possible grids that could be used in our methodology. The main difference between these two is the number of models that comprises them. We have a “low-resolution” and a “high-resolution” grid. The first approach is to build the “low-resolution” grid, because it is easier to construct and deal with, due to time and memory limitations. It is important to note that the name is an indicative label, as it still consists of an acceptable number of models.

Low-resolution grid

For this analysis, we compare our low-resolution grid with a set of 278 mock simulations with the previous specified photometry. The error in magnitude for the simulations is assumed to be the same as in a SHARDS sample of 278 galaxies. For the low-resolution grid, the range for the stellar and dust parameters appears in Table 3.3. This interval gives us a total of 1,048,576 models for each redshift: i.e. 22,020,096 models in total. Although, this number does not take into account the extra models built to obtain the slope which describes the CWL offset of the passbands for each one of the redshifts, which in this case, would double that number.

We will follow the same method of SED modelling discussed in Chapter 2. Namely, we compare our simulated data to a set of BC03 models and retrieve their stellar and dust-related parameters by finding the best-fit with a $\chi^2$ statistic.

On Figure 3.2, we have depicted the results from the simulated data. This analysis produces dust constraints on $R_V$, $B$ and $E(B - V)$. At this point, it is important to recall that, the first two are related to the dust attenuation, and $E(B - V)$ is a nor-
Table 3.3: Parameter range of low-res grids

<table>
<thead>
<tr>
<th>Observable</th>
<th>Parameter</th>
<th>Range</th>
<th>Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>log(t₀/Gyr)</td>
<td>[-2, +0.9]</td>
<td>16</td>
</tr>
<tr>
<td>Metallicity</td>
<td>log Z/Z⊙</td>
<td>[-2, 0.3]</td>
<td>16</td>
</tr>
<tr>
<td>Colour Excess</td>
<td>E(B−V)</td>
<td>[0, 1.5]</td>
<td>16</td>
</tr>
<tr>
<td>Total to selective extinction ratio</td>
<td>Rᵥ</td>
<td>[0.5, 5]</td>
<td>16</td>
</tr>
<tr>
<td>NUV Bump strength</td>
<td>B</td>
<td>[0, 1.5]</td>
<td>16</td>
</tr>
</tbody>
</table>

Number of models 1,048,576

normalisation factor accounting for the amount of dust present. On this plot, the input and output values are directly compared. The input value refers to the simulated data, and the output corresponds to the retrieved value obtained from the methodology. On this figure, the black line is associated to a 1:1 correspondence between the output and input. Ideally, one expects the results to lie close to this line. With this plot, we can conclude that the strength of the NUV bump and the colour excess are well-constrained, using SHARDS photometry plus other passbands previously mentioned. On the other hand, when we look at Rᵥ we notice some outliers and scattering. There are possible solutions to this issue. We explore some of them later on. The reason why we do not analyse the retrieved ages and metallicity is because, as discussed in the previous chapter, these parameters are treated as nuisance parameters and we marginalise them in the methodology.

Figure 3.2: Results from simulated data. Input vs output. Grey dots are the individual results. Red circles and error bars are median and RMS values, binned at fixed number of data points per bin. The red line shows an interpolating line between these two. Note that this curve is close to the 1:1 line that has been added as reference.
Higher-resolution grid

The next natural step to improve our previous results by expanding the grid of models summarised in Table 3.3. However, we encounter computer memory problems while using our grids of models. What we did first was to expand the number of steps for the dust parameters to 32. We extended these parameters as they represent the most relevant physical properties for our analysis. The other parameters (age and metallicity), remained the same and a larger grid of models was built. This grid encodes 8,388,608 models for each one of the 22 different redshifts. In addition, we also have the offset issue. Unfortunately, after taking all of this into account, this was proved not to be a suitable approach because, when these higher resolution grids are used, the size of them introduces a particular problem with computer memory. To illustrate this issue, we can consider the case of a grid at $z = 2.4$ with 3.3 GB of size. The code has to make use of more than one of these grids, leading to a failure due to memory management. An alternative solution was implemented as it will be discussed in the next section.

### 3.2.3 Markov Chain Monte Carlo (MCMC)

In order to overcome the memory management issues, a Markov Chain Monte Carlo (MCMC) algorithm was implemented. In particular, the Metropolis-Hastings algorithm was adopted. MCMC is a random sampling method which does not sample the multidimensional region of parameters uniformly. The main objective is to visit a point $x$ with a probability proportional to a given distribution function (Andrieu et al., 2003, Foreman-Mackey et al., 2013, Goodman and Weare, 2010).

The algorithm used consists of the following steps:

1. A new random value for each one of the parameters is proposed. The starting point for this new values is taken from the best-fit results from the analysis presented in Section 3.2.2.

2. Obtain $\chi^2$ and likelihood $\mathcal{L}$ of the new set of parameters.

3. Compare the likelihood $\mathcal{L}$ with a random number $r \in [0,1]$. If $\mathcal{L} \geq r$, this
3.2. Methodology

new set of parameters is accepted. If it is not \( \mathcal{L} \leq r \), the set of new parameters is rejected and the process starts again.

4. If the new \( \chi^2 \) found with the random parameters happens to be smaller than the previous minimum \( \chi^2 \), this \( \chi^2 \) is assigned as the new minimum.

5. In the end, we will end up with a distribution of accepted parameters, which will be used to build a probability distribution function for each one of the dust parameters.

Figure 3.3: MCMC results. Input vs output for dust-related parameters. Same notation of Figure 3.2 is used.

Figure 3.3 shows the results from implementing the algorithm. Unfortunately, we observe that even though an MCMC algorithm may seem at first glance to be a potentially better approach, the direct application of the above algorithm to our analysis does not lead to a large improvement of our previous result. This situation rises because the parameters are correlated to each other. In other words, there is a degeneracy in the system. In contrast to our previous approach, which explores a wide range of parameters, our MCMC algorithm only probes the parameter space along the Markov chain. This may be solved if one uses more than a Markov chain, which is not included in our MCMC algorithm and may provide an explanation for the discrete behaviour seen in Figure 3.3. An example of this problem is illustrated in Figure 3.4. This figure shows the area of higher probability for any two arbitrary parameters \( \pi_1 \) and \( \pi_2 \). The \( X \) denotes the input or actual value we are tracking and our Markov chain is represented by the wavy line. As it is exemplified in this
3.2. Methodology

![Figure 3.4: Cartoon of the contours of the probability density of any two parameters $\pi_1$ and $\pi_2$. $X$ is the input value and the wavy line represents a Markov Chain.](image)

The cartoon, the Markov chain converges in an area of high probability, but not at the true input value. This led us to conclude that the implementation of an MCMC sampling does not yield better results than our previous methodology. The aforementioned approach is a “brute-force” method, nevertheless, it proves to be more straightforward and robust enough.

After the two previous tests, we decided to increase the number of models used in our grid by expanding to 24 steps grid for each one of the dust parameters —See Table 3.4. We make a compromise between a grid with no memory issues and one with a superior accuracy than our previous “low-resolution” grid. Therefore, we make use of a larger grid without any particular memory management problem. In total, we have 1 769 472 of possible models for each redshift. We address redshift as explained in Section 3.2.1 and its range is given in Table 3.2. In total, the model grid comprises more than 38 900 000 of possible models to choose from. The amount of computing time needed to build all the possible models is a reflection of the aforementioned vastness of the number of models. We made use of the computer cluster at UCL Department of Space and Climate Physics for this undertaking. The average computing time for each grid model was 5 hours for each redshift step (22 steps). Furthermore, to obtain the slope for the interpolation needed to solve the offset issue, we need to obtain the SED and photometry for two different set of SHARDS passbands —see Section 3.2.1.
3.2.4 Testing against different SFHs

The next step is to test the effect of having different Star Formation Histories (SFH) in our set of simulated data. The reason for this exercise is that galaxies are more complicated objects than an SFH of an SSP which is the SFH of the model grid. We test how well the methodology can render the dust parameters despite these differences. For this analysis, we compare five sets of 278 mock simulations to the SSP model grid with the previous specified photometry (SHARDS, plus WFC3 and CFHT). Therefore, we build five sets of mock data corresponding to five types of SFH: a simple stellar population (SSP), two-burst history (2SSP), an exponentially decaying star formation (EXP), and increasing rate (EXPP) and a constant star formation followed by a truncation (CST). In this respect, a 2SSP has two SSP, superimposing a young and an old component, so to account for the older population. An EXP model is the most commonly used, although because it is hard to model rising SFHs, they may be less suitable at higher redshifts (e.g. Carnall et al., 2019, Reddy et al., 2012). For this reason, we also consider an exponentially increasing rate (EXPP).

Nevertheless, we acknowledge that the more realistic SFH may correspond to a combination of these or more SFH. This observation would be relevant when we deal with corrections to the methodology. We could apply this test to more and different sets of synthetic data, however, these simulations show the typical range of potential formation histories seen in the literature (e.g. Domínguez Sánchez et al., 2016, Ferreras et al., 2012, Papovich et al., 2011, Reddy et al., 2012). Furthermore, we acknowledge that we could perform any variety of tests with different SFH, nevertheless, the true SFH for each galaxy would be different to the one we model, because the SFH of galaxies would be a blend. We perform this test in order to explore how the retrieved values are affected with these different histories due to diverse galactic scenarios. It is important to note that these simulations provide a blind test to our methodology, because the pipeline used to build the mock data are different to the one analysing them.

One can assume that the analysis with SSP modelling would be trivial because
### 3.2. Methodology

<table>
<thead>
<tr>
<th>Observable</th>
<th>Parameter</th>
<th>Range</th>
<th>Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>log($t_0$/Gyr)</td>
<td>[-2, +0.9]</td>
<td>16</td>
</tr>
<tr>
<td>Metallicity</td>
<td>log $Z/Z_\odot$</td>
<td>[-2, 0.3]</td>
<td>8</td>
</tr>
<tr>
<td>Colour Excess</td>
<td>$E(B-V)$</td>
<td>[0, 1.5]</td>
<td>24</td>
</tr>
<tr>
<td>Total to selective extinction ratio</td>
<td>$R_V$</td>
<td>[0.5, 5]</td>
<td>24</td>
</tr>
<tr>
<td>NUV Bump strength</td>
<td>B</td>
<td>[0, 1.5]</td>
<td>24</td>
</tr>
</tbody>
</table>

Number of models 1 769 472

the templates of the model grid are BC03 SSP models. Nevertheless, it is important to bear in mind that the mock data is constructed with random estimates for stellar and dust parameters, along with redshift. The latter raises a pivotal difference because the methodology has to interpolate the model grid values of the closest redshift steps. Furthermore, the interpolation due to the offset of the passbands is also necessary and it does affect the outcome.

Given that we already compare different SFH, a logical step would have been to do a similar test to contrast the impact of different population synthesis models. We could opt to perform this test, however, we will not because this analysis has already been done in Hutton et al. (2014), where the authors compare the models from Maraston (2005) with a grid using BC03 models. They concluded that their derivation of the dust parameters is robust, regardless of the population synthesis models used.

Every set of simulated data was constructed with random estimates for stellar, dust parameters and redshift. Those values provide the necessary information to build an SSP, which is attenuated following the CSB10 parametrisation. Then, we obtain the simulated photometry using the transmission curves named in Table 3.1 with the range shown in Table 3.5. In order to produce a more realistic simulation, we take the flux uncertainties and passband offsets from a set of observed galaxies in SHARDS, with the same redshift and flux distribution as the working sample presented in the next chapter.

We apply the same method to compare the mock values of our simulated data with the output values. As our grid of BC03 models use a simple stellar popula-
### Table 3.5: Parameter range for the simulated photometry

<table>
<thead>
<tr>
<th>Observable</th>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>$\log(t_0/\text{Gyr})$</td>
<td>[-2, +0.9]</td>
</tr>
<tr>
<td>Metallicity</td>
<td>$\log(Z/Z_\odot)$</td>
<td>[-2, 0.3]</td>
</tr>
<tr>
<td>Colour Excess</td>
<td>$E(B-V)$</td>
<td>[0, 0.6]</td>
</tr>
<tr>
<td>Total to selective extinction ratio</td>
<td>$R_V$</td>
<td>[0.5, 5]</td>
</tr>
<tr>
<td>NUV Bump strength</td>
<td>$B$</td>
<td>[0, 1.5]</td>
</tr>
</tbody>
</table>

**Figure 3.5:** Results from mock data using SSP SFH. We have the input vs output comparison. The black line is associated with a 1:1 correspondence. Grey dots are the individual results. RMS and median are the error bars and red circles binned at a fixed number of data points per bin.

The second SFH we test is 2SSP, i.e. a star formation history described by the superposition of two SSPs. As with the SSP simulated data, we have a range of ages, metallicity and dust properties in our set of mock photometry. We emphasise that the grid of models is still the same as before, i.e. SSP models. Figure 3.6 a) shows the results for dust parameters. Likewise, we observe a better fit with $E(B-V)$ or colour excess and the strength of the bump $B$, even though that our grid models use SSPs. Figure 3.6 b) has the input and output values for age and metallicity and Figure 3.6 c) shows $\Delta(\text{In} - \text{out})$ which is the difference between the simulated data and retrieved age and metallicity. From both figures we can observe the behaviour of the marginalised parameters, age and ZH, is similar to the one observed in the
3.2. Methodology

Figure 3.6: Results for age and metallicity from mock data using 2SSP models. Grey dots are the individual results. Same labels as Figure 3.5. Black line corresponds to a 1:1 reference line and the black dashed line is the expected value for $\Delta \ln - \text{out}$. 
3.2. Methodology

Figure 3.7: Results from mock data using EXP models. The black line is associated with a 1:1 correspondence. Grey dots are the individual results. RMS and median are the error bars and red circles binned at fixed number of data points per bin. In this case, the 1:1 correspondence is not as clear as in Figure 3.5 or 3.6.

Figure 3.8: Results from mock data using CST models. Same labels as Figure 3.7. This case presents an improvement compared to the EXP models.

We applied our methodology to a set of data with a composite of stellar populations that follow an exponentially decaying star formation rate (EXP). The results are shown in Figure 3.7, where the mock and retrieved values are compared. On this case, the 1:1 correspondence is less clear for this star formation history. Similar plots were obtained (Figure 3.8 and 3.9) for the two remaining SFH, EXPP and CST, which gives comparable results to the plots of the other SFHs we already presented. For the CST case, the results improve in relation to other SFH. The opposite scenario occurs for the EXPP SFHs simulations.
3.3 Corrections to the data

After assessing the impact of different SFH parametrisations on our methodology, we decided to account for these diverse galactic scenarios. The next step would be
3.3. Corrections to the data

Figure 3.10: Histograms showing the accuracy of the retrieved dust parameters by comparing the input and output values $\Delta R_V$, $\Delta B$ and $\Delta E(B-V)$. In this exercise, five different SFHs are considered: constant star formation rate (CST); exponentially increasing star formation rate (EXPP); exponentially decaying star formation rate (EXP); a superposition of two simple stellar populations (2SSP) and a simple stellar population (SSP). An estimate of the uncertainties from this analysis is given by the width of the distributions.
3.3. Corrections to the data

to obtain a linear mean correction between the input and output parameters. These corrections are derived from a comparison with the simulated data from the previous section. The corrections make use of the five different star formation histories because we cannot determine which is the one corresponding to the real data. The linear mean corrections are obtained by adjusting the mock data using the method of least squares. Thus, the correction is defined as:

$$\pi_{\text{corr}} = \alpha \pi_{\text{ret}} + \beta,$$  \hspace{1cm} (3.1)

where $\pi_{\text{corr}}$ is the corrected value. $\pi_{\text{ret}}$ is the retrieved value, obtained from the analysis described above and $(\alpha, \beta)$ are the linear fit parameters showing in Table 3.6. We see the results of the applied corrections in Figure 3.11 with a 1:1 reference line. These corrections were implemented to a joint set comprising all mock data with different SFHs. Likewise, the corrections that will be applied to our SHARDS sample in Chapter 4 are shown in Table 3.6. Furthermore, clipping the sample at the 3$\sigma$ level is done before the fits are obtained.

It is computationally expensive to use a set of different SFH for different model grids. This is why we did not use grids of models with different SFHs. The SSP-only grid already requires a computing time of $\sim 7$ hours for the set, due to the sizes of the grid of models ($\sim 3\text{GB}$), and the two interpolations which means handling 4 model grids ($3\text{GB} \times 4$ model grids $= 12\text{GB}$) for each galaxy.

Table 3.6: Corrections to the dust parameters

<table>
<thead>
<tr>
<th>$\pi$</th>
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<th>$\beta$</th>
<th>RMS($\Delta\pi$)</th>
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<td>$R_V$</td>
<td>1.0329</td>
<td>$-0.337$</td>
<td>0.72</td>
</tr>
<tr>
<td>$B$</td>
<td>0.9772</td>
<td>$+0.073$</td>
<td>0.18</td>
</tr>
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<td>$E(B-V)$</td>
<td>0.7738</td>
<td>$+0.032$</td>
<td>0.07</td>
</tr>
</tbody>
</table>

To check for degeneracies we present a contour plot showing the probability for both $R_V$ and the NUV bump strength. In Figure 3.12 we can observe the areas with higher probability for the parameter. In this case, the input choice is $R_V = 0.95$ and $B = 0.17$.

It is important to note that, by construction, our simulated data are not corre-
3.3. Corrections to the data

Figure 3.11: Input vs Output of the simulated data after corrections were applied. The grey dots are the whole set of simulated data, considering the five different SFH scenarios. The black line is associated with a 1:1 correspondence. Grey dots are the individual results. RMS and median are the error bars and red circles binned at a fixed number of data points per bin.

Figure 3.12: Colour map showing the probability for $R_V$ and $B$ values. The simulations are from SSP models. The input value for $R_V$ is 0.95 and $B$ is 0.17, which corresponds to the area of more probability.

lated. To illustrate this, we present Figure 3.13 and Figure 3.14. The former shows the SSP simulated input parameters, and the latter depicts the retrieved or “output” dust parameters. In both figures, we can observe all the possible correlations between the dust parameters $R_V, B, E(B-V)$. A quick inspection shows that there are no apparent trends. Note that this is important as Hutton et al. (2015) and Kriek and
Conroy (2013) found significant trends in the M82 and galaxies at $z > 0.5$, respectively. This comparison confirms that such trends cannot be caused by a bias in the derivation of the dust attenuation parameters.

![Figure 3.13: SSP simulated dust parameters showing no correlations between our input SSP simulated dust parameters.](image)

Finally, recalling the aim of the analysis made in this chapter, we wanted to test the methodology with simulated photometry comparable to SHARDS data. We extended the methodology to include redshift, the offsets of the passbands and to include different SFH to account for different galactic scenarios. This test leads us to obtain corrections that will be applied later on. Furthermore, we can conclude that the pipeline was verified, and it is prepared to be applied to real galaxies from the SHARDS survey.
Figure 3.14: SSP retrieved dust parameters. $E(B-V)$, $R_V$ and $B$ show no correlations between our resulting dust parameters from SSP models.
Chapter 4

Constraining the dust attenuation law: The SHARDS sample

In this chapter, we apply the methodology previously discussed and tested, to our SHARDS sample of star-forming galaxies at $z \lesssim 2$. We analyse 1753 galaxies by constraining the following dust-related parameters: total-to-selective ratio ($R_V$), NUV bump strength ($B$) and colour excess ($E(B - V)$). We examine correlations between these parameters and other observables. We investigate whether the NUV slope ($\beta$) is affected by the presence of the NUV bump. This chapter is based on the results published in Tress et al. (2018).

4.1 SHARDS sample definition

In this chapter, we analyse a sample selected from the SHARDS survey (Chapter 3). To begin with, the sample comprises photometry of 1,807 star-forming galaxies (Pérez-González et al., 2013). In addition to the 25 narrow-band filters used by the SHARDS survey —See Table 4.1, we will use optical photometry with ACS F435W (Giavalisco et al., 2004). In addition, we use NIR fluxes from CANDELS (Koekemoer et al., 2011) in the HST/WFC3 F105W, F125W, F140W and F160W passbands, and deep K$_s$ photometry from CFHT (McCracken et al., 2010) and IRAC 3.6$\mu$m (Fazio et al., 2004). Figure 4.1 shows the transmission curves of the full set of 32 filters used in this study. From the Figure, it is clear how appropriate SHARDS data is to probe the region of the NUV bump within the redshift range $1.5 < z < 3.0$. 
### 4.1. SHARDS sample definition

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</tr>
</tbody>
</table>
4.1. SHARDS sample definition

Figure 4.1: On the top panel, we observe different dust attenuation laws which are parametrised by Conroy et al. (2010). This is an example given for a galaxy at $z = 1.7$, with different values for the total-to-selective ratio $R_V$ and NUV bump strength $B$. The curves are normalised to the V-band. The Milky Way dust attenuation law corresponds to the thick solid line ($B = 1$, $R_V = 3.1$), while the Calzetti law is shown by the thin black line ($R_V = 4.05$, $B = 0$). The bottom panel shows the normalised transmission profile of the filters used in the analysis. It is important to note the SHARDS medium band filters cover the region around the NUV 2175Å bump at $1.5 < z < 3$.

The data was extracted from the Rainbow database (http://rainbowx.fis.ucm.es), using version 14.5 (Barro et al., 2011, Pérez-González et al., 2008). The sources were retrieved with a median S/N per filter of at least 5 and the GALFIT models in the CANDELS WFC3/F160W images are acceptable in all the SHARDS passbands (no error flags). Photometric redshifts are available in all sources.

The sample is biased in favour of NUV bright sources, due to the S/N constraint in the NUV rest-frame given by SHARDS. Therefore, it is important to check if the photo-spectra are contaminated by AGN light. To do this, the sample was cross-matched with the 2Ms Chandra Deep Field North (Alexander et al., 2003), then we used Trouille et al. (2008) to convert fluxes in the 2-8keV band into luminosities. From this, 33 sources were found to have an X-ray detection, with an average $\langle L_X \rangle = 2.9 \times 10^{43}$, erg s$^{-1}$. We removed the 33 galaxies from the sample. Likewise,
using flux ratios from Spitzer/IRAC, we applied the criterion of Donley et al. (2012) to discard objects with an obscured AGN. In this way, we end up with 1,753 sources for our sample.

![Histogram of the redshift range from SHARDS sample, with an average of 2.10.](image)

**Figure 4.2:** Histogram of the redshift range from SHARDS sample, with an average of 2.10.

The redshift of our sample ranges from 1.5 to 3.0 — See Figure 4.2. The aim is to explore the dust attenuation law in the rest-frame NUV and optical region, so the objects covering this particular redshift window have the NUV bump encompassed within the SHARDS passbands.

## 4.2 Retrieved dust parameters

Following our standard methodology, we assume that dust acts as a foreground screen, and therefore we do not probe the distribution of dust within galaxies. The difference between this foreground screen scenario and a homogeneous mixing of stars and dust is the apparent optical depth. Unfortunately, this means we cannot distinguish between dust properties and dust-star geometry in the interpretation of the results. So, to retrieve the dust properties, we will use the observed fluxes and marginalise over the stellar parameters related to controlling the illumination source. A standard ΛCDM cosmology is assumed, with Ω_m = 0.27, H_0 = 72 km s^{-1} Mpc^{-1} and stellar masses correspond to a Chabrier (2003) IMF.
Figure 4.3: Examples of the SED fits obtained for three galaxies. The red dots are the observed fluxes along with their corresponding redshift and $K_s$ AB magnitude. The fluxes uncertainties are depicted. The FWHM of the NIR passbands corresponds to horizontal error bars. Best fits for $R_V$ and $B$ are also shown. The best fit to the models is the solid black line using Conroy et al. (2010). On the other hand, the dotted blue line is associated with the Calzetti dust attenuation law. The source SH09310 presents a prominent NUV bump. The figure is divided in the observed frame optical (left) and NIR (right). The spectra is cut in two parts to help with visualisation by having the SHARDS passbands exclusively in the left panel.
An example of the results of our methodology is illustrated in Figure 4.3. It shows the observed fluxes and best-fit models of three galaxies at $K_s \sim 22 - 23$ AB. The best fit is displayed at a higher spectral resolution compared to the photometric data, for reference. Our analysis produces SSP-equivalent ages from 10 Myr to 1 Gyr. The sample produces an average reduced $\langle \chi_r^2 \rangle = 1.54$, with 32 fluxes and 5 parameters. Furthermore, Figure 4.3 includes the best-fit attenuated with a dust law provided by the Calzetti parametrisation, which provides a worse fit to the data. This is not the scenario for all galaxies because it depends on the strength of the NUV bump in each galaxy. Note in this case the Calzetti law does not model this feature. In fact, the lack of the NUV bump is one of its main characteristics.

### 4.2.1 Comparison between different observables

We compare the three retrieved dust parameters to different observables in Figure 4.4. From left to right, we show redshift, the Sérsic index of the CANDELS surface brightness radius in kpc, axis ratio, stellar mass in solar units ($M_\odot$), star formation rate in $M_\odot$ yr$^{-1}$ and specific star formation rate in yr$^{-1}$. The red dashed line depicts the oldest tercile (oldest third of galaxies), while the blue dashed line is the younger population. We do not observe a strong correlation with the dust-related parameters, in general. With stellar mass, as expected, we observe that the amount of reddening increases for more massive objects. sSFR also presents a trend, with higher log(sSFR) corresponding to a smaller reddening. Likewise, massive galaxies are associated with a weaker NUV bump and a smaller sSFR. In contrast, Buat et al. (2012) found that the amplitude of the NUV bump is lower in galaxies with higher specific star formation rates.

From Figure 4.4, we observe there are significant trends related to the stellar age. Older populations (red) are related to a flatter attenuation curve compared to the younger objects (blue). This trend may be related to a possible homogenisation of the birth clouds and ISM in older galaxies, and provides evidence of dust processes occurring. In this case, a steeper curve indicates that the attenuation, and therefore the presence of dust, is affecting the UV/optical wavelength, which is associated to SF regions. This relation can also be linked to the grain size distribution; thus, the
4.2. Retrieved dust parameters

Figure 4.4: Dust-related parameters, NUV bump strength ($B$), total-to-selective ratio ($RV$) and colour excess ($E(B-V)$) related to different observables: spectroscopic redshift, Sérsic index, semi-major axis in physical units (kpc) – measured in the WFC3/F160W band, axis ratio, stellar mass (in $M_{\odot}$), star formation rate (in $M_{\odot}$ yr$^{-1}$) and specific star formation rate (in yr$^{-1}$). The lines follow a running median, and the shade is a 1σ error. The red dashed line depicts the old tercile (oldest third of the population), while the blue dashed line the young tercile (youngest third of the population). The median stellar age of the distribution is 5.2 Myr. We observe that sSFR increases as reddening decreases. Likewise, an increment in sSFR is also associated with a stronger NUV bump.

older populations would have a larger grain size distribution.

Similarly, a weak trend is seen with older stellar age corresponding to a weaker NUV bump (e.g. Kriek and Conroy, 2013, Wild et al., 2011). This trend may be a consequence of dust evolution suppressing the NUV bump carrier. Another relation we observe from Figure 4.4 is that younger objects tend to have larger values of colour excess. This behaviour is expected because the younger populations are still embedded in their birth clouds, and this is associated with the presence of dust, i.e. more reddening.
4.2. Retrieved dust parameters

4.2.2 Relation between Noll et al. (2009) and CSB10 parametrisation

To compare the dust parameters from CSB10 to Noll et al. (2009) parametrisation, a translation between the dust slope $\delta$ and $E_b$ into the NUV bump strength $B$ and $R_V$ is needed. A Python script was written to fit one parametrisation into the other, within the spectral window 1,700 – 6,000 Å.

Figure 4.5 and 4.6 illustrate the relationship between these two pairs of dust parameters. These figures were made using the definitions of the different quantities from the parametrisations CSB10 and Noll et al. (2009). The first plot shows the NUV bump relation with $E_b$ and $B$. The former parameter presents an additional dependence on $\delta$, because the dust slope acts as a “modulator” of the general wavelength dependence of the dust curve. Three different $\delta$ values are shown, and the linear fit is given by:
4.2. Retrieved dust parameters

Figure 4.6: Relationship between $R_V$ and $\delta$ dust parameters. Three choices of the NUV bump strength parameter $E_b$ and it shows no dependency. Thus, the quadratic fit to this trend is shown in Equation 4.2

$$
\begin{align*}
B &= 0.2255E_b + 0.2091 & \delta &= +0.2 \\
B &= 0.2038E_b + 0.1856 & \delta &= 0 \\
B &= 0.1802E_b + 0.1861 & \delta &= -0.4
\end{align*}
\right\} \quad (4.1)
$$

On the other hand, $\delta$ and $R_V$ do not present the same dependency on the NUV bump, so the final fitting results are shown in Figure 4.6, regardless of the $E_b$ value. The fit required is a polynomial described by:

$$R_V = 1.747\delta^2 + 3.503\delta + 3.271. \quad (4.2)$$

For the Milky Way extinction, the CSB10 parametrisation corresponds to $R_V = 3.1$ and $B = 1$, which are mapped into $\delta \simeq -0.05$, $E_b \simeq 4.0$, respectively.

We emphasise that it is important to obtain a relation between CSB10 dust parametrisation and the Noll dust attenuation curve because these are two of the dust parametrisations preferred. Therefore, the relations obtained are pivotal in
4.2. Retrieved dust parameters

4.2.3 Correlations of dust parameters

The next step includes looking for correlations between the dust parameters analysed, $R_V$, $B$ and $E(B-V)$. To illustrate this, we present Figure 4.7. The grey dots represent the individual data points and the red line and shaded region correspond to the running median and the RMS scatter, respectively. We should remember that the simulations tested in the previous chapter were, by construction, random selected with no correlation between the input parameters and returned uncorrelated parameters. Using the simulations mentioned before, we conclude there is no potential systematic trend. The Spearman rank correlation for the output parameters of the mock data is $\rho_{SYS} = -0.07$. This implies a small systematic but not strong enough to explain the observed trend.

On Figure 4.7, we observe different trends. There is a clear trend between $R_V$ and the NUV bump strength. This relation is qualitatively in agreement with previous studies as Kriek and Conroy (2013), as shown in Figure 1.13. Between $B$ and the colour excess, we also identified a trend. Likewise, we found a slight relation between colour excess and the total-to-selective ratio, similar to the one observed in Salmon et al. (2016). Now, we follow with a more detailed description of each one of these relations.

A decreasing trend between $R_V$ and $B$ is observed in Figure 4.7. The Spearman rank correlation between $B$ and $R_V$ is $\rho = -0.27$, in contrast with the null hypothesis of no correlation, obtained from $10^4$ randomised realisations of the same set, $\rho_{STAT} = 0.00 \pm 0.02$. The green dashed line is the least-squares linear fit, given by:

$$R_V = -1.27B + 3.53 \quad (RMS = 0.89). \quad (4.3)$$

From Eq. 4.3, it follows that if $B \to 0$, i.e. the Calzetti law scenario, we get $R_V = 3.53$, which is comparable to the Calzetti value $R_V = 4.05 \pm 0.80$ and only slightly larger than the standard Milky Way. Kriek and Conroy (2013) present a qualitatively similar trend, as seen in Equation 1.14, but they used the parametrisa-
4.2. Retrieved dust parameters

Figure 4.7: Correlations between dust attenuation parameters. Grey dots represent individual data. The solid line and shading are a moving median and RMS scatter. The Milky Way values for $R_V$ and $B$ is depicted as a star in the top-left panel. Eq. 1.14 is given by the blue hatched region, accounting for the scatter in the relation with $\Delta E_b = \pm 0.5$ (Kriek and Conroy, 2013). Likewise, the top-right panel illustrates the relation from Eq. 1.15 (Salmon et al., 2016). It is important to note that both of these relations are given originally by Noll et al. (2009) parametrisations with $\delta$ and $E_b$, which are related to $R_V$ and $B$, respectively. A linear fit is shown by the green dashed lines, which are described by 4.3 and 4.4. There is not a fit between $R_V$ and $E(B-V)$ because there is a large scatter of the data points.

The trend we observe between $R_V$ and $B$ may be explained by two different scenarios. First, if we assume that the total-to-selective ratio is associated with the grain size distribution, we can relate this behaviour to variations in the composition of the dust. So, it would fit with the common notion that small dust particles are accountable for the NUV bump (Draine, 1989), i.e. small grains produce a steeper
4.2. Retrieved dust parameters

attenuation law, which consequently gives lower values for $R_V$ and a stronger NUV bump. The second scenario is related to different dust geometries existing within the different stellar populations, due to the fact that the attenuation law may be dependent on the age of the stellar populations. On this line, radiative transfer models show that a clumpy distribution of dust alone may be able to account for a shallower dust attenuation law and a weaker NUV bump (e.g. Charlot and Fall, 2000, Panuzzo et al., 2007, Witt and Gordon, 2000). Consequently, this trend — Equation 4.4— could be explained by the clumpiness of the dust distribution.

Another correlation that we observe in Figure 4.7 is related to the colour excess. In our case, a decreasing colour excess is associated with a stronger NUV bump. The Spearman rank correlation between $B$ and $E(B-V)$ is $\rho = -0.58$ for the correlation, $\rho_{STAT} = 0.00 \pm 0.02$ for the statistical expectation with a random sample, and for potential systematic from the methodology $\rho_{SYS} = -0.04$. The trend between colour excess and NUV bump strength is described by:

$$E(B-V) = -0.24B + 0.27 \quad (RMS = 0.08). \quad (4.4)$$

The retrieved colour excess in our sample stays below 0.5 mag, possibly due to a selection bias, meaning that dustier galaxies would be fainter than the flux limit of the SHARDS survey.

Following the total-to-selective ratio v. colour excess panel from Figure 4.7, we can observe that the running median implies that $R_V$ increases along with $E(B-V)$. In this case, no linear fit is given due to the large scatter observed. Nevertheless, in Equation 1.15 from Salmon et al. (2016) we see a similar relation but with equivalent parameters $\delta$ and $E_b$. The equation is depicted in Figure 4.7 by the blue hatched region using Section 4.2.2. This relation produces a higher dust content given by $E(B-V)$, along with a flatter dust attenuation curve. The aforementioned trend is predicted by Chevallard et al. (2013). They obtained a trend of lower $R_V$ along with lower $E(B-V)$, meaning they had a steeper attenuation laws at lower opacities.

If we compare Figure 4.7 to a similar plot for galaxy M82, given in Figure 1.10, we do observe different trends. To begin with, we observe that in Figure 1.10
for galaxy M82, a higher $R_V$ is associated with a stronger NUV bump, which suggests a larger dust grain sizes are related with the NUV bump carrier. Furthermore, M82 presents a stronger reddening in regions with a strong NUV bump. These two correlations are in the opposite direction of the trends we found in SHARDS sample. The discrepancies may be explained by different reasons. First, we have to take into account that M82 is the closest starburst, and in contrast, the SHARDS sample consists of galaxies out to $z \sim 2$. In fact, for galaxies at high-$z$, we observe a similar behaviour to Figure 4.7 (e.g. Kriek and Conroy, 2013, Salmon et al., 2016). Furthermore, the results from Hutton et al. (2015) corresponds to values of dust properties within the same galaxy, while we have statistics on several non-resolved galaxies. This last point refers to the spatial resolution, which tell us about the importance of spatially-resolved studies on the dust properties within the same galaxy.

Finally, we acknowledge a possible degeneracy between $R_V$ and age. In this instance, we refer to true age, and not only the SSP-age which is the measured stellar population parameter. This degeneracy rises in view that a lower $R_V$ means a steeper attenuation law which eliminates more UV/blue photons, i.e. UV/blue are more attenuated than photons at a longer wavelength. This scenario can be explained by two different reasons. First, this shape of the dust attenuation law may be observed in younger populations. In this case, the reason behind the steep curve lies on the fact that younger galaxies produce more UV photons in their SF regions which are embedded in dust. Then, this dust attenuates the corresponding UV light, giving a steeper attenuation law. In contrast, an older population can also mimic this effect, because older populations generate less UV photons, producing a similar scenario of having attenuated UV photons. Note the possible systematic in our observed trend goes in the opposite direction, so it would give more evidence that the result is, in fact, an inherent trend.
4.3 Variations in the dust attenuation law and the NUV slope

As analysed above, the dust-related parameters show a wide range of values among our sample. Thus, it is relevant to consider how potential variations in the dust attenuation law affects the UV power-law index $\beta$. This slope is used as a proxy for dust content in galaxies. We discussed in Chapter 1 that the standard Calzetti et al. (1994) definition of $\beta$ mostly avoids the NUV bump region. We are trying to test if a systematic bias may occur as the strength of the NUV bump is correlated with other galaxy parameters.

We built a set of BC03-based synthetic populations as a way to test the effect that different dust properties may have on the NUV slope. We chose fixed stellar parameters, with a diverse range of attenuation laws. We obtained the $\beta$ slope with an attenuation given by Calzetti et al. (2000) or a Fitzpatrick (1999) dust parametrisation. Then, we compared it to a generic $\beta$ using instead the parametrisation of the dust attenuation law given by Conroy et al. (2010), constrained by our analysis.

We obtained the slope $\beta$ following the standard procedure: fitting a power law to the flux in the NUV region $F(\lambda) \propto \lambda^\beta$, over the 1,300–2,600 Å spectral window defined in Calzetti et al. (1994). The UV slopes are compared by defining $\Delta\beta$ as the difference between the value from the standard choice of dust attenuation law and the CSB10 parametrisation given the same stellar population parameters, and same colour excess.

Before addressing the two dust parametrisation tests, we highlight the importance of this type of exercise for dust studies. It is essential to test if the observed variety of dust attenuation properties affect probing tools of dust obscuration, in this case the UV slope, and how the variation affects them, in order to account for any systematic or biases.

4.3.1 Fitzpatrick law

For the first exercise, we use the standard Fitzpatrick dust law (Fitzpatrick, 1999). We employed synthetic populations at solar metallicity with two different values of
Figure 4.8: Estimate from a synthetic population of the difference ($\Delta \beta$) on the UV slope using a CSB10 or a Fitzpatrick dust attenuation law. We assume two different ages 0.05 and 0.15 Gyr. The distribution of the NUV bump from our SHARDS sample is shown on the panel below. $\Delta \beta = 0$ is depicted by the dotted line. Shaded areas correspond to a varying colour excess from 0.1 to 0.5 mag. Three different values of the total-to-selective ratio were used.
age: 0.05 and 0.15 Gyr, to probe different stellar models. Furthermore, the UV slope is determined more robustly when taking into account young populations ($\lesssim 200$ Myr) because the spectrum in this region is well fit by a power law. For the dust parameters, we consider a colour excess from 0.1 to 0.5 mag, as it is depicted by the shaded areas in Figure 4.8. We included three different values of the total-to-selective ratio: $R_V = 0.5, 3.1, 5.0$. The strength of the bump $B$ varies from 0 to 1.5.

We derived two different UV slopes $\beta$: one considering the standard galactic extinction with Fitzpatrick (1999) law, and the other one using the CSB10 attenuation law. Both stellar populations have the same stellar parameters. Then, we define $\Delta \beta$ as:

$$\Delta \beta = \beta - \beta_{\text{Fitzpatrick}}$$ (4.5)

From Figure 4.8, we can observe differences in the UV slope $\beta$ when using the two different dust attenuation laws, i.e. $\Delta \beta \neq 0$. A non-zero $\Delta \beta$ is found regardless of the age of the stellar populations. The possible slope corrections, in this case, are in the range $\Delta \beta \in [-2, 4]$ depending on the chosen dust parameters. In particular, the stellar population with the smallest $R_V$ presents more variation as the colour excess changes.

### 4.3.2 Calzetti law

The second dust attenuation curve we used as a standard was the Calzetti et al. (2000) law. This is the most used dust curve for starburst galaxies. As in the Fitzpatrick case discussed above, the ages of the synthetic BC03 populations are 0.05 and 0.15 Gyr SSP at solar metallicity. Concerning the dust parameters, we follow the same course of action: we chose three different values for $R_V = 0.5, 3.1, 5.0$, along with a NUV bump strength varying from 0 to 1.5 and a colour excess from 0.1 to 0.5 mag.

We defined the difference between the UV slope $\beta$, first by obtaining CSB10 attenuation curve and the second, considering the Calzetti law. Therefore, $\Delta \beta$ is
4.3. Variations in the dust attenuation law and the NUV slope

Figure 4.9: $\Delta \beta$ for UV slopes taking into account a CSB10 and a Calzetti dust law. As in Figure 4.8, the three values for $R_V$ correspond to different colours. A histogram of the NUV bump strength rendered from the SHARDS sample is also shown. No difference from the two calculated $\beta$ is represented by the dotted line. We observe that the choice of dust parametrisation affects the calculation of $\beta$. 
4.3. Variations in the dust attenuation law and the NUV slope

defined by:

\[ \Delta \beta = \beta - \beta_{\text{Calzetti}} \] (4.6)

Figure 4.9 shows the results from this test. We observe that differences in the slope \( \beta \) exists, even though the definition of \( \beta \) avoids the area of the NUV bump. In this case, the difference \( \Delta \beta \in [-1,4] \). However, we emphasise that the stellar parameters for both of the stellar populations are the same. Thus, we observe \( \Delta \beta \neq 0 \) due to the use of a different dust parametrisation. It is worth mentioning that the observed UV continuum slope is, in principle, independent from the stellar population from the object: an older galaxy can have the same slope as a galaxy with larger quantity of dust (Reddy et al., 2015).

After these two tests, we conclude that the wide range of dust parameters, in particular the presence of the NUV bump, does affect the computation of the UV slope. Moreover, our choice of the dust parametrisation also has an impact on the results. We found that the use of a dust attenuation curve which does not model the NUV bump, like the Calzetti law, produces different NUV slopes compared to other dust parametrisations, even though the definition of the UV slope avoids the NUV bump.

4.3.3 Corrected NUV slope

To evaluate how the value of \( \beta \) would vary considering different dust attenuation parameters, we derived the UV slope for our sample of star-forming galaxies from SHARDS (\( \beta_{\text{obs}} \)). This observed UV slope is calculated using the standard \( \beta \) definition, with the Calzetti et al. (1994) window range but using the SHARDS photometry which falls in that interval. We compared this value with a UV slope obtained using the Calzetti parametrisation, by correcting it based on the \( \Delta \beta \) between the Calzetti law and the CSB10. We consider the same constraints on the dust attenuation parameters on a galaxy-by-galaxy basis. Therefore, we define a corrected UV slope:

\[ \beta_c \equiv \beta_{\text{obs}} - \Delta \beta. \] (4.7)

The UV slope \( \beta_{\text{obs}} \) was obtained using the SHARDS photometric measure-
4.3. Variations in the dust attenuation law and the NUV slope

Figure 4.10: Histogram showing the distribution of the UV slope $\beta$ from the SHARDS data given by the orange dashed line, and the corrected slope $\beta_c$ (red solid line). The arrows mark out the median of both distributions.

ments. In particular, the data corresponding to filters that fall within the window used in the definition of the slope given in Calzetti et al. (1994). The $\Delta\beta$ correction is the difference for each one for the galaxies with matching synthetic data equivalent to Figure 4.9 using the best-fit values of the stellar and dust parameters for Calzetti and CSB10 parametrisations. In this way, we obtained a corrected $\beta_c$. We consider this UV slope to represent a $\beta$ obtained only with a Calzetti parametrisation, or a Calzetti-equivalent.

Figure 4.10 illustrates both obtained slopes, the original $\beta$ and the corrected slope $\beta_c$. This distribution shows the differences between the slopes. Even though the changes were expected to be high, as shown in Figure 4.9, the actual stellar and dust parameters from our SHARDS sample gives differences $\Delta\beta \sim 0.4$.

4.3.4 Dust parameters compared to UV slope $\beta$

Finally, we compared our new corrected $\beta_c$ to different parameters to find any possible correlations. Figure 4.11 illustrates the corrected slope for our SHARDS sample along with the corresponding stellar mass. The observed trend is a weak positive
4.3. Variations in the dust attenuation law and the NUV slope

The corrected UV slope $\beta_c$ is shown against stellar mass. The blue solid line illustrates objects with ages in the first tercile of the age distribution. Thus, blue describe younger populations. On the other hand, the red dashed line represents the third tercile, therefore red depicts the older populations. Solid lines are the mean and shaded regions show the uncertainty. Furthermore, histograms for these two parameters are located in the top/right panels. In the same manner, blue (red) is associated with young (old) ages.

Figure 4.11: The corrected UV slope $\beta_c$ is shown against stellar mass. The blue solid line illustrates objects with ages in the first tercile of the age distribution. Thus, blue describe younger populations. On the other hand, the red dashed line represents the third tercile, therefore red depicts the older populations. Solid lines are the mean and shaded regions show the uncertainty. Furthermore, histograms for these two parameters are located in the top/right panels. In the same manner, blue (red) is associated with young (old) ages.

correlation, even after the sample was divided with respect to age. Furthermore, we identified a trend regarding mass and age as shown in the top histogram. This type of behaviour is not unexpected, as stellar metallicity and age may be correlated with stellar mass (e.g. Gallazzi et al., 2005). The other histogram shows a wider scatter in the UV slope for the youngest sample. This subset presents the flattest UV slope, associated to a higher contribution from dust.

Figure 4.12 relates $\beta_c$ to the dust-related parameters mentioned above, along with the SFR. We chose this last specific quantity because we wanted to test if SFR was a function of $\beta_c$, as the UV slope is used as a tracer of dust obscuration which is sensitive to SF. From the Figure, we observe a correlation between the corrected slope and, both the colour excess and NUV bump strength: objects with shallower UV slope are associated with weaker NUV bumps but are dustier. In the case of the colour excess, this behaviour is observed in local starburst galaxies (Calzetti
4.4 Implications for high redshift studies

Considering a general view of dust studies at high redshift, we can mention that this work fits in the non-universality of the dust attenuation law scenario because we observe a wide variety of possible dust values for the whole SHARDS sample. In particular, this study agrees with the most common conclusion regarding the

Figure 4.12: The corrected NUV slope, $\beta_c$, is shown as a function of dust parameters and the star formation rate. From the top, downwards: star formation rate (log scale in $M_\odot$ yr$^{-1}$) colour excess, total-to-selective extinction and NUV bump strength. The labels for colour and line follow the same notation of dividing the sample as in Figure 4.11, with red-dashed (blue-solid) representing old (young) populations. Likewise, panels on the right show the distribution of the best-fit parameters.

et al., 1994). Because the sample is also split by age, we noticed that at fixed $\beta_c$, older galaxies correspond to a higher $R_V$ or a greyer law, as it can be seen from the histograms also displayed in Figure 4.12.
4.4. Implications for high redshift studies

presence of the NUV bump in galaxies at high redshift. Most of our sample presents a NUV bump; in contrast with the most used attenuation law, the Calzetti law, which is employed to correct for dust and lacks this feature. Nevertheless, we emphasise we obtained a wide range of values. We do observe galaxies which do not have a NUV bump in our sample, but we also found galaxies having a NUV bump at least as strong as the one we see in the Milky Way. This result calls into question the implementation of an specific dust attenuation law to different types of galaxies; thus, also correcting for dust attenuation with the Calzetti law, in particular. The generalisation of the dust attenuation law is used because of its practicality and the difficulty of obtaining an individual dust attenuation curve for each case studied. Nevertheless, the variation of the dust attenuation curve for each case should be acknowledged and considered.

Subsequent high redshift studies need to focus on the possible trends in dust parameters that may appear and compare it with the existent relations. This point highlights why equivalence relations similar to what we calculated in Section 4.2.2, are important for dust studies to assure the comparisons are correct. In this context, an interesting comparison of dust model simulations with the SHARDS sample (Tress et al., 2018) and other dust studies, is given by Narayanan et al. (2018). They contrasted the results from Kriek and Conroy (2013), Salmon et al. (2016) and Salim et al. (2018). The first two studies match our redshift range, but Salim et al. (2018) focuses on galaxies at \( z \sim 0 \). From these studies, a distinct relation is found between the extinction in the V-band \( A_V \) and the slope of the attenuation curve \( \delta \) (Noll et al. (2009) parametrisation). This relation is shown in the left panel of Figure 4.13. A key difference between the observations and the simulations is that the former individually select from a specific redshift range. In contrast, Narayanan et al. (2018) make use of every galaxy in their sample of zoomed-in simulations. Nevertheless, Figure 4.13 shows a good agreement between the observations derived from SED fitting at different redshift, and the increase of \( A_V \) with \( \delta \), observed from the simulations.

Regarding the NUV bump and the dust slope (similar to \( R_V \) as in Section 4.2.2),
4.4. Implications for high redshift studies

Figure 4.13: This figure from Narayanan et al. (2018, figure 12) compares observations from Salim et al. (2018), Salmon et al. (2016) and our SHARDS sample (Tress et al., 2018), to their models (blue points). On the left panel, it shows the power-law index of the curve and the extinction on the V-band. The mean results from Salim et al. (2018) are the blue region while Salmon et al. (2016) are the orange area. Purple points correspond to the SHARDS sample, in agreement with other studies. The right panel illustrates the NUV bump and dust slope given by the Noll et al. (2009) parametrisation. Blue points are Narayanan et al. (2018) study, orange data is given by Kriek and Conroy (2013). We emphasise that both orange and purple points correspond to real data while blue points are simulations, which may explain the differences observed.

Figure 4.13 shows the trends between their equivalent parameters from Noll et al. (2009) parametrisation. Both Narayanan et al. (2018) and Kriek and Conroy (2013) works present a trend, depicted as a blue and orange line respectively. This correlation shows that flatter attenuation curves are associated to a weaker NUV bump strength. The simulations have this correspondence due to unobscured young stars reducing the effect of the NUV bump (Narayanan et al., 2018). The Kriek and Conroy (2013) and Tress et al. (2018) data do not follow exactly the trends found in Narayanan et al. (2018), even if qualitatively they have a similar behaviour. An important difference is that Narayanan et al. (2018) are simulations, while the results of Tress et al. (2018) and Kriek and Conroy (2013) represent real data. This last point may explain the disparity between them. Furthermore, we point out that the trends observed in the two studies with real data are comparable.

Studies analysing dust may also need to consider how the wide range of dust parameters may or not impact their diagnostic tools and, thus, their results. We identified that standard dust probes as the UV slope are affected, although in our
SHARDS sample we do not observe a large effect. Nevertheless, we cannot
generalise that this will always be the case so further research is needed. Moreover,
studies at different redshift could also show how dust parameters may change with
time.

An interesting issue to tackle for future studies is to modify the range for analysis of $R_V$ and $B$ and match the extent of the dust attenuation parameters used in Figure 4.7. From this figure, we observe that past studies consider a smaller interval of the parameters, especially for $R_V$, so a different range could be useful for a better comparison. In addition to the previous, Figure 1.13 from Kriek and Conroy (2013) shows how low-redshift studies—in particular, Milky Way sightlines, LMC, SMC and Calzetti values—have a different range compared to their stack of galaxies. These examples show how a wider range may be of benefit.

To summarise this chapter, we probed the dust attenuation properties of galaxies at $z \lesssim 2$ using a CSB10 dust parametrisation and a SSP-model grids. Our findings were consistent with a non-universal dust attenuation scenario, as we identified a wide range of dust parameters. In particular, we observed the presence of the NUV bump in the majority of our sample. This result disagrees with the most usual dust parametrisation which does not model the NUV bump, the Calzetti law. We detected correlations between the dust properties. As discussed before, because we are considering dust as a foreground screen, this does not allow us to disentangle the main reason behind the observed trends between $R_V$ and NUV bump strength $B$. This correlation may be attributed to a change in dust composition or the geometric distribution of dust. The fact that older stars seem to have differences in the dust distribution compared to younger stars, may suggest that dust clumpiness plays a bigger role. The next chapter adopts simple dust attenuation models while having the same underlying extinction curve in order to probe the effects on the aforementioned trend and break this degeneracy. We found that the variety of dust parameters can affect dust-probing tools as the UV slope. Specifically, we noticed the choice of dust attenuation law affects the calculation of the UV slope. Even though the differences were expected to be high, the retrieved SHARDS properties
lead to smaller changes. The next chapter explores more on this topic, examining the possible effects on different diagnostic tools.
Chapter 5

A further insight into SHARDS: dust models

Previously, we analysed the dust attenuation law of the SHARDS star-forming galaxies, finding a correlation between the total-to-selective ratio $R_V$, and the NUV bump strength $B$. In particular, we found that larger values of $R_V$ correspond to a weaker NUV bump. The reason behind this correlation may be explained in two different ways. First, if we associate $R_V$ with the grain size distribution, we would expect that smaller dust grains are related to stronger NUV bump. Alternatively, we could also attribute $R_V$ to the geometric distribution of dust. To break this degeneracy, this chapter probes simple dust models describing different dust attenuation curves with an age-dependent extinction but at fixed dust composition. We explore different dust models from the literature and revise the SHARDS sample by locating the objects in the UVJ diagram, which is used to distinguish quiescent and star-forming galaxies. This analysis is done to test if the diverse range of attenuation laws affects their location in the bi-colour plot. Finally, the distribution of the sample on the main sequence of star-forming galaxies is also analysed. This chapter is based on the results of Tress et al. (2019).

5.1 Introduction

Recalling the analysis from Chapter 4, the SHARDS survey is an ultra-deep galaxy survey taken at the GTC. The optical photo-spectra has resolution $R \sim 50$ with
5.2. UVJ

Besides the SHARDS passbands, optical and NIR fluxes were used to constrain the dust attenuation law. The data-set comprises of 1,753 star-forming galaxies at $1.5 < z < 3$. This sample is compared to a set of population synthesis models, following a Bayesian approach. The adopted parametric dust attenuation law is given by Conroy et al. (2010, CSB10), which uses $R_V$ and NUV bump strength $B$, along with colour excess $E(B - V)$ to characterise the dust properties. Our first approach to further characterise our SHARDS sample is to explore the UVJ diagram. As we observed in Chapter 4, there is a wide range of dust parameters, and we want to explore the effect of that variation on the UVJ plot. Secondly, we analyse the SHARDS sample location relative to the main sequence of star formation of galaxies. Then, we compare Draine and Li (2007), and Witt and Gordon (2000) models to our SHARDS dust parameters, along with a simple dust model with a colour excess as a function of age. The last point seeks to explore the age-dependent extinction acting as a proxy for dust geometry.

5.2 UVJ

We use the UVJ bi-colour plot to distinguish between quiescent and star-forming galaxies within our sample. $R_V$ and the NUV bump strength showed a correlation in Chapter 4, so this exercise explores how dust attenuation may introduce a systematic in this classification scheme. The first step was to obtain the $U - V$ and $V - J$ colours. We recover them using the stellar population synthesis models of Bruzual and Charlot (2003). Even if they are not observed quantities, both the stellar population and dust-related parameters adopted are the same as those retrieved from SHARDS —presented previously in Chapter 4.

The UVJ diagram of the SHARDS sample is depicted in Figure 5.1. The plot is arranged in different redshift windows (increasing left to right) and three dust parameters $E(B - V)$, $R_V$ and $B$ (top to bottom). The limits for star-forming galaxies is given by Whitaker et al. (2011, See Eq. 1.18). From this figure, we notice most galaxies are defined as star-forming as expected in a sample that selected bright NUV sources (See Chapter 4). Most galaxies fall on a diagonal strip (bottom-left
Figure 5.1: Rest-frame UVJ diagram for each of the dust-related parameters from SHARDS. Red (blue) points correspond to higher(lower) values for $E(B-V)$, $R_V$ and $B$ (top-downwards). The sample is divided by three redshift bins with the lines showing the limits for star-forming galaxies as defined by (Whitaker et al., 2011). The arrows show how an object is affected by an increase in $A_V$ of 1, with three different values for $R_V = [1.0, 3.1, 4.0]$ with Milky Way NUV bump strength. The typical error bars are also shown.
Nevertheless, the NUV bump seems not to have an impact on the location of the galaxies on the UVJ plane.

Other correlations with dust parameters may be observed. On the top panel, colour excess $E(B - V)$ is shown, with redder objects appearing higher up in the diagram, at every redshift. This behaviour is expected given the direction of the dust vector (arrows in Figure 5.1), which shows the position redder objects take. Within the highest redshift panel, we observe fewer red objects. This may be explained by an observation bias, i.e. we do not observe dustier objects at high redshift because they are intrinsically fainter. Regarding $R_V$, we observe a weak sign of objects with greyer (i.e. flatter) attenuation located in the top-right region. Again, the fact that fewer galaxies are observed in the highest redshift window may be explained due to the flux and SNR limit of the sample. To quantify the trends, the Kolmogorov-Smirnov (KS) statistic, as given by Peacock (1983), for two-dimensional data set, was used. We split the sample at the median value of the distribution for each dust parameter to compare the resulting samples with the KS test. Accordingly, a KS statistic $D_{KS} = 0.54$ was found when splitting the sample regarding $E(B - V)$, $D_{KS} = 0.32$ for a $R_V$ split and a $D_{KS} = 0.30$ for a B split. This agrees with the fact that the most significant trend is found in the colour excess. In order to evaluate the significance of these values, we performed 1000 random splits of the sample, by creating subsets with the same number of galaxies. This analysis renders a Monte Carlo distribution, giving $D_{KS} = 0.06 \pm 0.01$. Figure 5.2 shows the distribution of the KS statistic. This discussion confirms the observed trends as a function of the dust parameters are statistically significant.

Figure 5.1 shows three different vectors representing how an object would be affected by an increase in $A_V$ of 1 (bottom to top). We take into account three different values of $R_V = 1.0, 3.1, 4.0$, along with Milky Way NUV bump strength. As expected, a steeper dust attenuation law renders a higher reddening at the same $A_V$. This outcome results from the definition of $R_V$ in terms of $E(B - V)$ (Equation 1.6), so if $A_V$ is fixed to 1, a steeper dust curve (smaller $R_V$) is a consequence of a stronger $E(B - V)$, compared to a flatter curve scenario (i.e. higher $R_V$). In
5.3. Main Sequence of star-formation

The goal for this section is to seek potential trends of the parameters regarding the main sequence of star-forming galaxies and to determine whether the observed dust variety impacts the analysis. We look to further characterise our galaxy sample by exploring the correlation between derived SFR and stellar mass.

We analyse our sample and their position on the main sequence of star-formation. The subset of the SHARDS sample used here corresponds to 1,722 objects with a well-defined SFRs given by Wuyts et al. (2011), covering from the $U$ band to 8$\mu$m fluxes. This sub-sample has a comparable stellar mass distribution as the full set (1,753 galaxies) which has a median and standard deviation of $\log M_*/M_\odot = 10.35 \pm 0.46$. Likewise, they present practically an identical redshift
distribution. Figure 5.3 shows the Main Sequence for this sub-sample. The definition of the main sequence is given by Equation 1.18 (Speagle et al., 2014). The expected relation for galaxies at $z = 2$ from that equation is shown for comparison. Most of the objects fall within the expected value, i.e. close to the MS relation, as can also be seen in Figure 5.4.

In order to parametrise the location of our sub-sample relative to the SFR and stellar mass relation, we define a dimensionless coefficient $\Delta SF_z$ as:

$$\Delta SF_z = \frac{SFR - SFR_{MSz}}{SFR_{MSz}}.$$

$SFR_{MSz}$ is the SFR expected from the Main Sequence at a given redshift as in Equation 1.18. This coefficient represents the fractional offset in the SFR, or distance between our galaxies and the star formation value of the Main Sequence. The inset in Figure 5.4 exemplifies this definition. A positive (negative) coefficient implies that the galaxy has a SFR higher (lower) than the expected SFR value on the Main Sequence. The distribution of $\Delta SF_z$ considers the redshift for each SHARDS object. From Figure 5.4, we observe that our sample is slightly biased to stronger SF galaxies. Most of our sub-sample falls into the expected MS relation, thus the median for the coefficient is $\Delta SF_z = 0.11$. Accordingly, more than $77\%$ has $|\Delta SF| \leq$
In a second case, we employ the MS defined at the median redshift $z = 2$ to test for a possible variance of the MS location with redshift. We plot Figure 5.5, which is the same plot as Figure 5.4, and we found a median $\Delta SF_{z=2} = 0.14$, thus the differences between considering the median redshift and a variable redshift for the definition of the MS are negligible.

A comparison between the dust parameters, $R_V$, $E(B-V)$ and $B$, and $\Delta SF$ is given by Figure 5.6. The sample is split with respect to the median age, where the red (blue) line corresponds to older (younger) objects. The lines and shade show the median and $1\sigma$ scatter, respectively. The median age is 5.2 Myr. No apparent trend is observed between $\Delta SF$ and any of the dust-related parameters. Nevertheless, this figure implies there is a small decrease in the strength of the NUV bump as $\Delta SF$ increases (higher SF than expected). This result is observed in the younger population and it is a marginal trend given the error bars from $B$. Consequently,
the variations of the dust parameters do not strongly affect the strength of the star formation activity. We note that younger galaxies show a slightly greater offset on $\Delta S F_z$, as the median for this subset is $+0.17$. Finally, we also observe the same behaviour as in the previous chapter, with older galaxies being associated with a flatter attenuation curve, as well as younger galaxies being redder.

5.4 Comparison with standard dust attenuation models

In this section, we compare our SHARDS results with two of the standard dust attenuation models: Draine and Li (2007) and Witt and Gordon (2000).

5.4.1 Draine and Li models

As previously discussed, the model presented by Draine and Li (2007) provides a framework for the infrared emission from dust. This model derives fundamental
Figure 5.6: Comparison of the $\Delta SF$ coefficient and the dust-related SHARDS parameters. The blue (dashed red) line corresponds to younger (older) objects. The sample is split at the SSP-equivalent age median of 5.2 Myr. $\Delta SF = 0$ is the position of the main sequence for star-forming galaxies.
Comparison with standard dust attenuation models

5.4. Comparison with standard dust attenuation models

properties using infrared observations with Spitzer’s IRAC and MIPS cameras. The model comprises a mixture of PAHs, carbonaceous grains, and amorphous silicate grains, heated by starlight, which reproduce the Milky Way extinction law. The Draine and Li (2007) model is parametrised by $q_{\text{PAH}}$ which is the fraction of the total dust mass that is in PAH, by the lower cutoff $U_{\text{min}}$ of the starlight intensity distribution, with $U$ being the distribution of the starlight intensity. It is a dimensionless scaling factor considered in the definition of heating grains by radiation (energy density per unit frequency, Draine and Li, 2007). Finally, the parameter $\gamma$ corresponds to the dust mass fraction heated by starlight.

SHARDS fluxes, plus Spitzer and Herschel were used to derive the Draine and Li (2007) parameters. 24 $\mu$m fluxes (from Spitzer/MIPS) and at least one flux data point from Herschel (Pérez-González et al., 2013) were used to lift the degeneracy between the model parameters. For both $q_{\text{PAH}}$ and $\gamma$, an interpolation of the original model was done to produce a finer grid. The parameters are obtained using infrared fluxes, and are mostly independent of the dust parameters constrained in the previous chapter, which used the rest-frame NUV and optical. The fitting is done by comparing the model grid of the observed fluxes with a standard $\chi^2$ statistic. The best-fit follows the minimum value for $\chi^2$. Next, a Monte Carlo method was used, so the fitting is done 10 times per galaxy. In each time, a Gaussian random deviate is added to the fluxes, with a zero mean and variance equivalent to the flux uncertainties. The uncertainty is obtained with the distribution of the best-fit. An important point to bear in mind is that compared to our previous analysis, this test has the new element of infrared fluxes. This model fitting was presented in Tress et al. (2019).

In the end, 71 galaxies in total had good fits to these models. The redshift distribution of the sub-sample is comparable to the original data. The median and standard deviation of the stellar mass of the original sample is $\log M_s/M_\odot = 9.59 \pm 0.56$, in contrast with $10.28 \pm 0.58$ for the smaller sample. So, this subset is biased towards the massive end. Even if this is a smaller sample, we decided to compare it with their best-fit dust parameters from SHARDS.

Figure 5.7 shows the results compared to the dust-related parameters $R_V$, $B$
5.4. Comparison with standard dust attenuation models

Figure 5.7: Distribution of best-fit dust parameters and Draine and Li (2007) models. From top to bottom: fraction of dust associated with PAHs \( q_{\text{PAH}} \), fraction of the dust heated by starlight \( \gamma \), dust mass \( \log M_d \) and starlight intensity \( U_{\text{min}} \). The solid line in each panel shows the running median and the error bars represent the RMS scatter within each bin. The error bars for each parameter are the 1\( \sigma \) uncertainty from a Monte Carlo run.
and $E(B-V)$. The solid lines trace the median of binned data at a fixed number of data points per bin and the grey dots are the data points. The median value of the $1\sigma$ uncertainty is shown as an error bar for each parameter. We observe that higher values of $q_{PAH}$ relate to a higher value of $R_V$. There is a weak trend in which a flatter attenuation is associated with a lower fraction of dust heated by starlight ($\gamma$). For the dust mass, an increment with $R_V$ is seen: the larger the dust mass, the flatter the attenuation law. The NUV bump strength also shows an increase in the median trend of $q_{PAH}$. This relation aligns with the accepted view that small graphite-like dust particles, are the carrier of the NUV bump (e.g., Draine, 1989). We observe that as $E(B-V)$ increases, so does $q_{PAH}$, along with a decline of the total fraction of dust heated by starlight ($\gamma$). The total dust mass is also correlated to the colour excess. We observed a comparable trend in the SHARDS analysis but regarding the total stellar mass. This correlation can be seen in Figure 4.4 where the dust parameters are compared with different observables. In the case of starlight intensity ($U_{min}$), it seems to be related with colour excess, with a lower threshold in dustier galaxies. Nevertheless, we emphasise that the trends observed are weak and should be considered semi-quantitative because of the large variation and uncertainty. Moreover, this is a smaller subset than the original SHARDS sample. Nonetheless, these results are shown in Figure 5.7, as a precursor of larger datasets comprising medium/narrow band photometry, such as J-PAS (Benitez et al., 2014).

### 5.4.2 W&G models

A standard reference in the analysis of the attenuation law in galaxies is the dust models given by WG00. They employ multiple-scattering radiative transfer calculations to represent three types of galactic environment and two different types of dust corresponding to the Milky Way and SMC. In general, they found that flatter dust curves (i.e. higher $R_V$) correspond to more clumpy dust distributions with a weaker bump and present more reddening.

The WG00 models explore three different galactic environments: CLOUDY, DUSTY and SHELL. The distinguishing characteristics between these models consist of a different range of star/dust distributions: SHELL is a star region surrounded
by a dust shell, DUSTY has an uniform mixture of stars and dust, and CLOUDY a mixed dust-star region surrounded by a dust-free region (See Figure 1.6).

Another aspect to consider is the structure and WG00 models take into account two different types: homogeneous and clumpy. The former attenuates more than their corresponding clumpy case. Therefore, the NUV bump strength is reduced, because a clumpy structure has a flatter wavelength dependence for the attenuation. The opposite happens within a homogeneous distribution (Witt and Gordon, 2000). The intrinsic opacity function adopted by WG00 corresponds to the Milky Way and the bar of the Small Magellanic Cloud. The contrast between different scenarios accounts for the diverse return of scattered radiation, resulting in a range of effective attenuation laws. For instance, the homogeneous SHELL is comparable to a spherical homogeneous screen with flux scattered back into the beam (Witt and Gordon, 2000).

The equivalence between WG00 models and the CSB10 dust parameters (normalised by optical depth $\tau_V$) was obtained to have a better comparison with the SHARDS results which are attenuated by the CSB10 parametrisation. The WG00 models correspond to three different optical depths $\tau_V = [0.05, 1.5, 4.5]$, as in Figure 5.8. The similar parameters $E_b$ and $\delta$ from Noll et al. (2009) were also analysed — See Table 5.1. This parametrisation has slightly different wavelength dependence, so it is not fully equivalent to CSB10, as discussed in the previous chapter.

The comparison between WG00 and the two dust parametrisations was done with a PYTHON script which fits the WG00 dust curves. WG00 attenuation curves are publicly available and the spectral window considered was $\lambda \in [1300, 7500]$ Å. The script consists of two stages. First, it starts with a Sequential Least Squares Programming fit, calling SciPy function minimize with method SLSQP with a large error bar, so considering 20% of the value of the opacity at each wavelength. Next, an MCMC search is performed, starting with the best-fit value using the EMCEE sampler (Foreman-Mackey et al., 2013). Thus, reducing the error bars to a 5% level. Extracting the first 100 burn-in steps, the output after 400 steps gives a distribution from which the median and RMS for each parameter is attained (Table
5.4. Comparison with standard dust attenuation models

5.1). The best fit is taken from the median of the distribution for each parameter, which is plotted and visually inspected to assure the convergence of the fitting procedure. A translation of this type, from one dust model to the other, is needed to review if the results are comparable.

Table 5.1 shows the results. Generally, we observe that a steeper dust attenuation curve is associated with the homogeneous case. As the optical depth increases, the NUV bump strength decreases for both CLOUDY and DUSTY geometry and both the homogeneous and clumpy scenarios. As the environment shifts from a moderate optically thick to a very optically thick case, this results on the NUV bump strength being halved for the CLOUDY and clumpy SHELL case. The same trend is observed at lower redshifts, where the NUV bump is stronger with a lower optical opacity (Salim et al., 2018). Looking at both the total-to-selective ratio and NUV bump strength, the former increases for every case, although for the SHELL homogeneous scenario this increase is less clear. In general, the optical depth increase along with a flatter attenuation is a trend seen in other works (Narayanan et al., 2018, Salim et al., 2018, Salmon et al., 2016) and in this thesis (Section 4.2.3, Figure 4.7).

Figure 5.8 shows the results of the WG00 models fitted to the CSB10 parametrisation. On the left panels, it illustrates the fits corresponding to three different WG models for the Milky Way case with CLOUDY geometry. As we observe, CSB10 provides a good fit. Nevertheless, the mismatch increases at shorter wavelengths. On the right panel, the same models are shown but taking into account an SMC-like extinction law. The reason the models are better fitted to an extinction similar to Milky Way, instead of SMC-type, is because by definition CSB10 is parametrised considering the Milky Way as a reference —See Figure 5.8. Furthermore, the SMC does not present the NUV bump, so the parameter would be $B = 0$ in all cases.

Figure 5.9 and Figure 5.10 show the comparison of WG00 models and the dust properties of the SHARDS sample. The grey dots are the individual galaxies, and the solid red line is the best fit. As seen from Figure 5.9, WG00 models do
5.4. Comparison with standard dust attenuation models

Figure 5.8: CSB10 fits (dashed lines) for each one of the WG00 dust models at three different values of $\tau_V$, corresponding to two different structures: homogeneous (h) and clumpy (c) in a CLOUDY, DUSTY and SHELL geometry. The left column corresponds to a Milky Way (MW) extinction. The right column follows an SMC extinction law.
5.4. Comparison with standard dust attenuation models

Figure 5.9: Comparison of dust-related parameters $R_V$ and $B$. WG00 models are also shown as black lines. Grey dots are individual measurements from SHARDS sample and the solid red line is the best fit. Milky Way extinction values are represented by a star.

Figure 5.10: Colour excess and NUV bump plane. Labels as in Figure 5.9.
Table 5.1: Fit of the Witt and Gordon (2000) models (Milky Way extinction) to the generic attenuation function of Conroy et al. (2010) (errors quoted at the 1σ level).

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5.5 Age-dependent extinction: a phenomenological model

not provide an appropriate match, since their $R_V$ values are too high, meaning they exhibit a greyer (flatter) attenuation, plus stronger bump strengths. Nevertheless, the models have similar slopes: steeper law (i.e. small $R_V$) with a strong bump towards a greyer attenuation (i.e. higher $R_V$) along with a weaker bump. Figure 5.10 renders a comparable scenario where WG00 NUV bump strengths are greater, so they do not provide a good fit for the SHARDS sample. Nevertheless, they follow the same trends observed for galaxies at $z \sim 2$ (Kriek and Conroy, 2013, Tress et al., 2018): a greyer attenuation associated with a smaller bump, along with a more mixed dust geometry, when light is dominated by young stars as seen in previous models (See Narayanan et al., 2018, Seon and Draine, 2016).

5.5 Age-dependent extinction: a phenomenological model

In this section, we do a test to disentangle the two possible causes for the dust correlation between $R_V$ and $B$, as observed in the previous chapter. The first explanation is that the observed trend results from changes in the grain size distribution. The second cause implies variations in dust geometry among galaxies, meaning changes in the distribution of dust regarding the underlying stellar populations.

The standard method to analyse the attenuation law and its relationship to both, dust composition and distribution within the stellar populations, is to study it through radiative transfer modelling (see, e.g., Groves et al., 2004, Panuzzo et al., 2007, Popescu et al., 2011, Seon and Draine, 2016, Witt and Gordon, 2000). Nevertheless, the use of a simple phenomenological model is also a valid course of action, therefore our model still encompasses the fundamental aspect of dealing with the consequences of the distribution of dust. An important assumption we make is to consider a constant extinction law in all galaxies. In other words, the wavelength dependence of dust scattering and absorption will depend on a fixed dust composition. Thus, we assume that the differences in the attenuation law arise from variations of the geometry of dust among the galaxies. We highlight that this is an analysis that encapsulates the dust distribution testing we wanted to explore. This study involves
changes in the geometry of the dust; namely, variations in the location of dust in the stellar population as a function of time. With this hypothesis, we are trying to model changes in the dust distribution of dust by emulating different dust processes that have as an outcome, a variation in the total amount of dust present, similar to dust evolution/dust destruction processes. In this way, our modelling does not seek to describe the physical processes in single star-forming clouds, where dust dispersion and destruction takes place, albeit in shorter timescales. What we look for is to define a phenomenological model which accounts for the global dust evolution over galaxy scales, including complex scenarios from the SFH and the evolution of dust geometry.

The geometry scenario we look to model is the following. The youngest populations are expected to be most affected by dust, because they are usually found in gas-rich and also, dust-rich regions. As these populations age, they disperse along with the gas and dust which result in a fainter attenuation. In this fashion, Silva et al. (1998) provided a galaxy model with an extinction which is both age-selective and geometry-dependent. In turn, Charlot and Fall (2000) designed a model in which older populations are affected by a diffuse dust law and younger stars experience a higher opacity. Within this context, we explore these two simple models that describe these age-dependent scenarios. Therefore, we add a smooth dependence on the level of extinction; so, $E(B - V)$ decreases monotonically with time, given a single age population. To summarise, the analysis models different geometries that are time-dependent. The models are simple, so qualitative tests are performed aiming just to observe whether correlations between the retrieved dust parameters are found.

The first step in our analysis is to build a set of mock data with fixed dust properties. We use the same redshifts, SHARDS passbands offsets, and flux uncertainties as in the SHARDS sample, because the aim is to review potential trends on the dust-related parameters, even after considering the same dust composition, i.e. the same underlying extinction. The new element that we add to our model is a smooth time dependence on extinction. Therefore, the colour excess $E(B - V)$ decreases
monotonically with time for a given, single-age population. In our model, the star formation rate is constant, and the composition is fixed to the standard Milky Way law, $R_V = 3.1$ and $B = 1$ at solar metallicity. This assumption looks to uncover if a fixed composition still produces a trend qualitatively similar to the observations, presented in the previous chapter.

We consider two different functions for the colour excess to assess whether the functional form influences the effective attenuation. First, we will explore a linear dependency with (log) time and second, an exponentially decreasing function. Two parameters quantify the timescale in which the effect of dust decrease: $\mu$ and $\tau$. Both scenarios are comparable with the “birth cloud” model, i.e. younger stars suffer more dust attenuation compared to older stars. In both cases, we use the BC03 synthetic models at a fixed Milky Way extinction law with the same distribution of stellar parameters, redshift, flux uncertainties and SHARDS offsets as with our previous SHARDS sample.

We emphasise that the working hypothesis we use for these two tests is that the extinction law, namely the wavelength dependency of dust, which relies on the dust composition, is the same in all galaxies. In contrast, the observed variations in the attenuation curve result from the different “geometry”.

### 5.5.1 Linear decrease of reddening ($\mu$)

The equation describing the linear decrease of reddening for the first test is defined by:

$$E(B-V)(t) = \max \left[ \epsilon_M - \mu \log \left( \frac{t}{0.01 \text{Gyr}} \right), 0 \right]. \quad (5.2)$$

The normalisation is given by $\epsilon_M$, which is the maximum reddening suffered by the population. $\epsilon_M$ is a uniform random deviate between 0.1 and 0.6. This range is comparable to the variation observed in the SHARDS sample. The composite stellar population has a constant star formation rate between 0.01 and 1 Gyr. Furthermore, $\mu$ is chosen so the amount of reddening when $t=1$ Gyr is zero. Thus, a greater value of $\mu$ is associated with a rapidly changing extinction, mimicking dust being
What we want to achieve with this simple model is to assess whether any correlation found between the dust parameters could be associated to an age-dependent dust extinction model. So, the next step is to apply the same pipeline as in the previous chapter, using the same SSP model grids. The retrieved values for $R_V$ and $B$ are shown in Figure 5.11. The sample is colour-coded based on the value of $\mu$. From the plot, we can observe that the Milky Way extinction values are covered within our sample, represented by a white star symbol in the plot. It is important to note that, by construction, all data have the same extinction. Thus, the values we would expect for $R_V$ and $B$ would be the Milky Way values. From Figure 5.11 we see this is not the case. Moreover, a correlation between the dust parameters of the effective dust attenuation law is found. We observe this correspondence instead of having all the retrieved parameters with values close to $R_V = 3.1$ and $B = 1$. This occurs dispersed efficiently.

Figure 5.11: $R_V$ and B relationship considering an age-dependent reddening. In particular, a linear variation with (log)time, parametrised by a slope $\mu$. The sample is colour-coded according to the $\mu$ parameter. The best-fit result is given by the blue solid line. The correlation coefficient is given along with a 1 $\sigma$ error bar. The star symbol represents the Milky Way extinction values. The dotted line is the trend observed in the previous chapter (See Equation 4.3). The dashed line and shaded area shows this observed slope and scatter but with a constraint of the Milky Way value for the NUV bump $B = 1$. Dotted line is the same relation given in Section 4.2.3.
due to the introduction of an age-dependent extinction, which we use as a proxy for the dust geometry. In particular, the trend seems to qualitatively agree with the results from Chapter 4 (dotted line). Accordingly, when the attenuation law is greyer, i.e. higher $R_V$, a weaker bump is observed. In Figure 5.11, the observed SHARDS trend is shifted by imposing the Milky Way values, so the dashed line is $R_V = 3.1$ at $B = 1$, and the shaded area corresponds to the observed scatter in the trend. We do not observe a clear trend as in Equation 4.3, which may suggest that a more intricate description of the attenuation or variations in dust composition — among other factors — are elements that can be expected to play a role. Another aspect to consider is that the uncertainty expected for our methodology is $\Delta R_V \sim 0.7$ and $\Delta B \sim 0.2$.

Figure 5.11 shows that objects associated with a slower time variation, i.e. galaxies with a lower value of $\mu$, have a flatter (greyer) attenuation with a smaller NUV bump. Galaxies with a stronger NUV bump have an attenuation curve comparable to the Milky Way, albeit scatter is present. The linear correlation coefficient was obtained to quantify the observed trend, with $\rho_{xy} = -0.18 \pm 0.01$. A Monte Carlo analysis was used to compute the error bar ($1\sigma$). It includes 100 realisations produced by adding noise to the data points that correspond to the error bars of the individual parameter estimates.

We emphasise that the aim of this analysis is not to decipher the observed trends, but to test if a time-dependent reddening at a fixed composition may create the observed correlations. Variations in the dust composition modify the intrinsic dust extinction law which may produce changes that could describe the discrepancy between the observational trends and this phenomenological model. Nevertheless, this test is not aimed to completely explain the observational trends.

The model presented in this section describes younger stars that are more attenuated since they are still embedded in their birth clouds. In the case of older populations, since the dust has been dispersed or destroyed, the stars are progressively less attenuated. This is qualitatively similar to the Charlot and Fall (2000) “birth model”, although the timescales between the two are quite different. Illustrating
this, the “birth model” considers that the clouds dissipate after \( \sim 10\,\text{Myr} \), but our model encompasses more process from the evolution of dust in its timescale. Regarding the NUV bump, Panuzzo et al. (2007) also describes young obscured stars having a weaker bump. Following this exercise, since the underlying extinction remains the same, we may argue that geometry alone can be a plausible explanation for the observed trends found in star-forming galaxies.

### 5.5.2 Exponential decrease of reddening (\( \tau \))

To explore if the functional form has any effect on the attenuation, the next set of BC03 models follows an exponential decrease of reddening given by:

\[
E(B - V)(t) = \epsilon_M e^{-t/\tau}.
\]  

(5.3)

If compared to our previous linear test, the rate of change with time is slower in this case. \( \tau \) introduces a timescale which depicts the efficiency of the disintegration/dispersal of dust. So, dust surrounds the youngest phases of star formation, as \( \tau \to 0 \). On the other hand, when \( \tau \to \infty \) all populations are affected in the same manner by extinction, representing a foreground dust screen.

The simulated data are created in the same fashion, with a constant star formation rate between 0.1 and 1 Gyr, plus the same distribution of redshift, flux uncertainty and passband offsets from SHARDS. The two free parameters (\( \tau \) and \( \epsilon_M \)) are taken from a uniform random deviate, from \( \tau = 0.1 \) and 1 Gyr, and \( \epsilon_M = 0.1 \) and 0.6 mag, respectively. The mock data are analysed as described in Chapter 4 with Figure 5.12 showing the retrieved \( R_V \) and \( B \) parameters. In this case, we also observe that the dust parameters do not correspond to \( R_V = 3.1 \) and \( B = 1 \), but there is a correlation between the bump strength and \( R_V \) (blue line), which qualitatively agrees with the observational SHARDS trend (dotted line). The trend is shifted by a constant value, taking into account the Milky Way constraint of \( B = 1 \) (dashed line and shaded area), to illustrate the dust composition of the dust model. In Figure 5.12, we observe a weaker age-dependent extinction is associated with higher values of \( \tau \) and that objects with this characteristic feature a greyer or flatter attenuation
5.5. Age-dependent extinction: a phenomenological model

Figure 5.12: $R_V$ and $B$ with reddening changing exponentially with time, given by the $\tau$ parameter. Same colour coding, as in Figure 5.11, with the star illustrating the Milky Way extinction. The blue solid line is the simple linear best-fit result of the data. The correlation coefficient is shown along with a 1 $\sigma$ error bar. The dotted line depicts the trend observed in the previous chapter. The dashed line and shaded area show the slope and scatter but with a constraint of the Milky Way value for the NUV bump $B = 1$. Dotted line is the same relation given in Section 4.2.3.

law. This would imply that as the dust geometry approaches a foreground screen scenario, it produces a dust curve which is not as strongly wavelength-dependent.

As in the previous test, we quantify the observed trend with the linear correlation coefficient, which is $\rho_{xy} = -0.15 \pm 0.01$. Following the linear correlation coefficient, this simple test suggests that an appropriate explanation for the dust trends involves the destruction and dispersion of dust in star-forming galaxies and an age-dependent extinction. As we mentioned before, we have two different options to explain these observed trends between $R_V$ and NUV bump strength. One explanation is that the ISM has a wide variation within different stellar populations, but the geometry of dust stays the same. The second description requires the same dust composition, but with a different associated geometry of dust. This last scenario was the one explored in this Chapter. Thus, in conclusion, the results from this study lead us to argue that variations in geometry can, at least in part, explain the correlation between $R_V$ and NUV bump strength and may be responsible for the ob-
served scatter in different attenuation laws. Finally, we emphasise that even if these two models describe a variation in dust geometry in a simple way, the outcome still produces dust values that differ from the assumed Milky Way composition plus it generates correlations or trends between the dust parameters.

5.6 Implications

We aimed to expand the analysis initiated in the previous chapter of the SHARDS sample. We examined an eclectic set of tests to search for possible consequences of the range observed in the dust-related parameters, focusing on diagnostics of star formation and quiescence, along with the interpretation of the variety considering different dust attenuation models.

The analysis on the UVJ diagram aimed at characterising our SHARDS sample in terms of the star formation. What we conclude is that, despite the range of observed parameters, this type of standard classification was not affected by it, as the loci used to define the quiescent galaxies remained unaffected. A degeneracy is added along a diagonal in the plot, with varying stellar and dust parameters. A weak correlation with the NUV bump and the location of galaxies is observed, which may affect the fluxes through the $U$ passband.

Along the same lines, we wanted to explore if the location of these galaxies relative to the main sequence of star formation is affected by the dust characteristics. The deviations from the main sequence involve less than 25% of the sample and we do not observe strong correlations with the retrieved dust parameters.

By comparing the models of WG00 and Draine and Li (2007) to our SHARDS sample, we wanted to explore how well-established models match our results and conclusions. Even though the Draine and Li (2007) models did not yield strong correlations, we found a weak trend that suggests a possible contribution of PAH molecules in environments with a stronger NUV bump. This result conforms with the standard view that these molecules are expected to be the carrier of the feature. WG00 models have analogous results to the SHARDS retrieved parameters, albeit with flatter attenuation curves.
The correlations observed in the SHARDS sample and their interpretations entail important aspects of dust in galaxies. First, it deals with the intrinsic composition relating to the dust extinction law. Second, the geometry of dust or the distribution of dust with the underlying stellar components. With synthetic BC03 models accounting for the efficiency of dust destruction and dispersal, we explored this hypothesis in a “birth cloud” model with a linear and an exponential decrease of reddening. The result was a trend comparable to the SHARDS relation with $R_V$ and $B$. We observed an anti-correlation, so a stronger NUV bump is associated with a steeper attenuation curve. This behaviour is also observed in the literature and at different redshifts (Buat et al., 2011, Narayanan et al., 2018, Noll et al., 2007, Panuzzo et al., 2007, Salim et al., 2018).

Within this context, we obtained flatter attenuation curves than the expected Milky Way value. The important result is that in general, we observe $R_V \neq 3.1$. Moreover, Figure 5.11 and 5.12 show that a smaller $\mu$ and a larger $\tau$ correspond with the stronger $R_V$ values. Higher $R_V$ values are associated with a foreground screen, because this type of geometry have all populations equally affected, producing a weak wavelength dependence on dust, i.e. a flatter curve. This agrees with our simple dust model, as small $\tau$ values mimic a less efficient dust dispersion and $\tau \to \infty$ models a foreground dust screen.

However, timescales for the birth cloud model are different, as Charlot and Fall (2000) adopt shorter timescales. In order to compare these results to our longer timescales-scenarios, a more detailed radiative transfer models would be needed. Regardless, future work on this subject should not overlook the implications that dust geometry may produce, as different dust properties are used. This conclusion follows the tests performed, where the distribution of dust is potentially the major driver on these trends.
Chapter 6

General Conclusions and Outlook

The description of galaxies can be reduced to four fundamental components, namely dark matter, gas, stellar populations and dust. As we discussed in Chapter 1, dust produces three main effects on light: it absorbs and scatters light at shorter wavelengths, and re-emits it in the infrared. The first two effects are encoded in the term dust extinction. In this case, the stellar population acts as an illuminating source with a distribution of dust being a foreground screen, so all the stellar populations are equally affected. Galaxies are, however, more complicated objects than that. This leads to the definition of dust attenuation, which also takes into account the “geometry” of dust, i.e. its distribution, so the light not only is affected by absorption and scattering of light out of the line of sight, but also into it.

Both extinction and attenuation are described by a wavelength-dependent function, usually a parametric dust curve. As we have revisited, this function could describe the Milky Way extinction, like the Cardelli et al. (1989), or Fitzpatrick (1999) law, or starburst systems like the Calzetti et al. (1994) attenuation law. In this way, the focal point of this thesis can be summarised by saying that it aims to analyse the effects of dust on interpreting galaxy observations on a scenario with a non-universal dust attenuation law. For this, we use the Conroy et al. (2010) parametrisation of the dust attenuation law, which adopts three parameters to describe the dust properties: the total-to-selective ratio $R_V$, the strength of the absorption feature at 2175 Å $B$, and the colour excess $E(B-V)$. The first two parameters relate to the shape of the dust curve. $R_V$ refers to the steepness of the dust attenuation law, with
a higher (lower) value being associated with a flatter (steeper) attenuation function. 

$B$ is the strength of the absorption feature whose carrier is not well known. It is believed to have a benzene-type of structure and PAHs are possible carriers. Finally, the colour excess describes the net amount of dust present, representing a normalisation form.

Our methodology involves a comparison between real data and a set of simulations retrieved from Bruzual and Charlot (2003) simple stellar population (SSP) models. We used a $\chi^2$ statistic to obtain the best fit. Then, we apply a Bayesian approach to compute the likelihood for each one of the dust parameters by marginalising over the rest of the parameters.

As a first approach and to test our methodology, we built a set of simulated data to assess how well we can retrieve the stellar and dust parameters. In this first case, we made use of Swift/UVOT and SDSS passbands as discussed in Chapter 2. UVOT NUV filters are especially helpful to probe the 2175 Å bump (See, e.g. Figure 2.2). We constrained the stellar parameters, plus the amount of reddening given by the colour excess $E(B-V)$, the total-to-selective ratio $R_V$ and NUV bump strength $B$ as seen in Figure 2.5.

Our next objective was to analyse the observations from the SHARDS survey (See Chapter 3). This is an ultra-deep galaxy survey taken at the 10.4m GTC with medium band filters, which effectively produces low-resolution spectra. Following a similar methodology as with UVOT and SDSS passbands, we then built a set of simulations using SHARDS data complemented with ancillary optical and NIR broadband photometry from HST, covering a wide spectral range. An important difference in this new set of simulations was to take into consideration redshift and the wavelength offsets that the SHARDS passbands present. Furthermore, we confirmed that we did not need the implementation of an MCMC sampling, because the methodology is robust enough for our purposes. An important highlight from these simulations is the fact that our simulated data are not correlated by construction, allowing us to robustly detect potential trends in the observed data.

Since we built a grid of SSP models to compare to SHARDS observations, a
possible caveat is that galaxies have a more complex SFH than an SSP. To mitigate this problem, we built a set of simulated data including different SFHs from SSP to exponentially decaying star-formation. Therefore, we assessed the impact of an SSP-model grid in our comparison with the observations. Chapter 3 confirms that we retrieved the dust parameters well, and the methodology is robust. Moreover, we used these simulations as a calibration to the final observations.

In Chapter 4, we constrained $R_V$, $B$ and $E(B-V)$, along with stellar age and metallicity. The retrieved dust parameters exhibit a wide range of properties, confirming the non-universality of the dust attenuation curve in the SHARDS sample. In particular, we found a correlation between the total-to-selective-ratio ($R_V$) and the NUV bump strength ($B$). We observe a weaker bump is associated with a flatter attenuation curve. This trend is qualitatively similar to the relation found in Kriek and Conroy (2013).

Due to the diversity detected on dust properties, we analyse the effect of this possible issue on the UV slope $\beta$, which is the slope of the UV continuum. With a set of simulated data, we found that differences ($\Delta \beta$) existed between slopes obtained using different attenuation curves, namely Conroy et al. (2010) and Calzetti et al. (1994) parametrisations. When we applied these corrections to our SHARDS sample, we found that even if the differences were larger within the mock data, the resulting differences on the UV slope for the SHARDS data were around $\Delta \beta \sim 0.4$. Nevertheless, this test highlights the importance of considering different dust properties in studies involving the NUV bump region.

The dust results of Chapter 4 have been compared with other dust studies for local and high redshift galaxies, along with simulations. Narayanan et al. (2018) contrasted Kriek and Conroy (2013) study and Salmon et al. (2016) analysis, with a local study from Salim et al. (2018). The authors concluded that a relation between the extinction in the V-band $A_V$, and the slope of the attenuation curve $\delta$, is observed in the aforementioned works, including the SHARDS sample. This correspondence shows an increase of $A_V$ along with $\delta$. Nevertheless, when Narayanan et al. (2018) compared the NUV bump and the dust slope, they found that Kriek and Conroy
(2013) results and the SHARDS correlations do not exactly match Narayanan et al. (2018) simulations. Although, qualitatively they follow a similar behaviour as seen in Figure 4.13.

The UVJ diagram is a bi-colour plot of the U-V and V-J colours typically used to separate star-forming and quiescent galaxies. We determined in Chapter 5 that despite the wide range of dust properties, the UVJ diagnostic remained unaffected. Nevertheless, a new degeneracy is added along the diagonal strip observed from bottom-left to top-right on the UVJ plot (Figure 5.1), which spans a range of age, metallicity and dust properties. In Chapter 5, a comparison between Witt and Gordon (2000) and Draine and Li (2007) models with the SHARDS observations was explored, finding an agreement between our results and WG00 models. However, the latter showed flatter attenuation curves in their modelling. The main sequence of star formation in galaxies was studied where we found that dust properties do not correlate with the position of galaxies relative to their stellar mass and SFR. Finally, we analysed the dust attenuation and its geometric distribution within the stellar populations through a simple phenomenological model. We consider a time-dependent extinction with a fixed dust composition. We observed that our model agrees with a flatter attenuation curve in a foreground dust screen scenario. Furthermore, we were able to mimic the SHARDS anti-correlation between \( R_V \) and \( B \), despite the constraint of having Milky Way fixed values for \( R_V \) and \( B \). As a result, this leads us to support the scenario where geometry could be invoked to explain the observed trends.

To summarise, this thesis takes on the question of whether assuming a universal dust attenuation law could lead to potential bias on the interpretation of galaxy observations. In a nutshell, the work presented here further proves the non-universality of the attenuation law. At the same time, we confirmed that the observed wide range of dust properties does not affect the UVJ diagnostic; even though dust affects the UV slope, albeit mildly. In addition, a correlation between \( R_V \) and \( B \) was observed. The explanation could be associated with either the intrinsic dust composition or the “geometry” of dust, i.e the dust distribution within the underlying stellar compo-
We explored a time-dependent extinction model with a fixed dust composition which yielded similar trends on the dust properties. Therefore, this thesis suggests that the geometry of dust provides a likely scenario for the correlations.

The next natural step for this work is to extend the analysis applied to nearby galaxies. The simulations from Chapter 2 would work as a first approach to constrain the dust properties of a local sample. In particular, the UVOT passbands provide an excellent tool to assess the presence of the NUV bump in the extinction/attenuation curve, helping to uncover the non-universality of the attenuation law at lower redshift. Moreover, this type of studies would make possible to search for similar trends in galaxies at low redshift, and in turn, provide clues of the evolution of dust properties through time.

Another advantage of having a sample at lower redshift is the fact that it would be possible to spatially resolve the data. This would allow us to explore their dust properties in detail. In other words, dust could be constrained, for instance, by galactocentric distance or galactic morphology. These studies may produce spatial trends with the dust parameters, as observed in studies of galaxy M82 (Hutton et al., 2014). Furthermore, the analysis of resolved galaxies would help shed light on the importance of the distribution of dust within the stellar populations.

More research is needed to fully understand the discrepancies observed in dust parameters based on the differences seen in galaxies, as is the case with the SHARDS sample and resolved local galaxies. For instance, if we consider figures similar to 4.7 (high $z$) and Figure 1.10 (M82), the trends shown are in complete opposite directions, despite using the same dust parametrisations and a similar approach for the analysis. We notice that the SHARDS behaviour of $R_V$ and the NUV bump strength has been found in other high redshift works (e.g. Kriek and Conroy, 2013, Salmon et al., 2016), but also at low redshift (e.g. Salim et al., 2018). Thereby, spatially-resolved studies on local dust properties within the same galaxy must explore this issue.

The future directions that we have explored should emphasise the impact of dust, either the geometry or dust composition, on the different diagnostic tools used
in the analysis of galaxies. In particular, this work highlights the relevance of the NUV bump in studies involving the UV region, and how it should not be overlooked. This result follows the general conclusion of this thesis and it joins the mounting evidence which argue in favour of the non-universality of the dust attenuation law. The resulting dust measurements are publicly available upon request to the author.
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