Diversity of Galaxy Dust Attenuation Curves Drives the Scatter in the IRX–β Relation

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Received 2018 September 19; revised 2018 December 6; accepted 2018 December 13; published 2019 February 7

Abstract

We study the drivers of the scatter in the IR excess (IRX–β) relation using 23,000 low-redshift galaxies from the GALEX–SDSS–WISE Legacy Catalog 2 (GSWLGC-2). For each galaxy, we derive, using CIGALE and the spectral energy distribution+LIR fitting technique, the slope of the dust attenuation curve and the strength of the UV bump, plus many other galaxy parameters. We find that the IRX–β scatter is driven entirely by a wide range of attenuation curves—primarily by their slopes. Once the slope and the UV bump are fixed, the scatter in the IRX–β relation vanishes. The question of the IRX–β scatter is a direct manifestation of the more fundamental question of the diversity of the attenuation curves. The predominant role of the attenuation curve is the consequence of a narrow range of intrinsic UV slopes of star-forming (SF) galaxies. Galaxies with different specific star formation rates (sSFRs) or population ages do not show strong trends in the IRX–β diagram because their attenuation curves are, on average, similar. Similarly, there is no shift in the IRX–β locus between starbursts and normal SF galaxies, both types having, on average, steep attenuation curves. Optical opacity is identified as the strongest determinant of the attenuation curve slope and consequently of the IRX–β diversity. Despite the scatter, the use of an average IRX–β relation is justified to correct SFRs, adding a random error of ≤0.15 dex. The form of the local correspondence between IRX–β and attenuation curves is maintained at high redshifts as long as the evolution of the intrinsic UV slopes stays within a few tenths.

Key words: dust, extinction – galaxies: fundamental parameters

1. Introduction

Determination of a galaxy’s star formation rate (SFR) is a critical task for the study of galaxy evolution. Many SFR indicators have been proposed and utilized over the years (Kennicutt 1998; Kennicutt & Evans 2012), but two classes of methods stand out as the most practical over a wide range of redshifts: (1) SFRs based on the nebular line emission (Kennicutt 1983) and (2) SFRs based on the stellar continuum emission (Larson & Tinsley 1978). However, both classes of methods are critically limited by our ability to correct for the effects of dust, which requires both knowledge of the dust attenuation law and knowledge of the intrinsic unattenuated spectral energy distribution (SED). These limitations have already been recognized in Pettini et al. (1998) and have not yet been fully overcome.

The line emission method typically utilizes the Hα luminosity (less frequently [O II]3727) of very young stars (≲10 Myr) still embedded in molecular clouds and H II regions. The Hα luminosity must be corrected for dust emission, usually accomplished by observing Hβ, which gives the correction to Hα luminosity via the Balmer decrement plus an appropriate attenuation or extinction curve. Many studies use the Milky Way extinction curve (e.g., Cardelli et al. 1989) to correct for dust affecting emission lines. The correction depends on the relative attenuation curve between the Hβ and Hα wavelengths, i.e., it is not sensitive to the shape of the assumed curve at shorter wavelengths. Getting both Hα and Hβ requires spectroscopic observations, which limits available samples data. Pα, an emission line in the near-IR, is much less affected by dust and represents a better alternative to Hα (e.g., Calzetti et al. 2007), but the observed samples are relatively small. Furthermore, emission-line fluxes need to be corrected for aperture (fiber) or slit losses.

There are several closely related methods that use continuum emission to derive SFRs, either arising from direct stellar emission or arising from the emission of dust heated by relatively young (≲100 Myr) stars. Traditionally, the continuum methods are implemented as (a) the ultraviolet (UV) method, (b) the infrared (IR) method, (c) the UV+IR method, (d) SED fitting (stellar emission), or (e) energy-balance SED fitting (stellar plus dust emission). The UV method obtains the SFR from the far-UV (FUV) luminosity and the UV color, from which the dust correction in the FUV is derived by assuming some correlation between FUV attenuation (A_{FUV}) and the UV color. For star-forming (SF) galaxies, the FUV attenuation is directly related to the ratio of IR luminosity to FUV luminosity, i.e., the IR excess (IRX; Meurer et al. 1999; Gordon et al. 2000). Thus the accuracy of the UV method is predicated on there being a relatively tight and universal relation between IRX and UV color or, alternatively, between IRX and the UV spectral slope (β; f_{\lambda}(\lambda) \propto \lambda^{-\beta}) the so-called IRX–β relation (Meurer et al. 1995, 1999). Correction of the rest-frame UV luminosities with the UV method is employed at high redshifts, where IR information is very limited or nonexistent (e.g., Bouwens et al. 2009; Reddy & Steidel 2009).

Next, in the IR method, the estimate of the SFR is based on the light absorbed by the dust and re-emitted in the thermal IR. It assumes that all emission from young stars is processed by dust and that the contribution of older populations is small (Kennicutt 1998). Its refinement, the UV+IR method (e.g., Daddi et al. 2007; Elbaz et al. 2007; Reddy et al. 2012), combines the observed (attenuated) SFR in the UV with the obscured SFR in the IR but still requires dust heating by older stars to be minimal in order not to bias the answer, or else it needs to be accounted for (Buat et al. 2011; Boquien et al. 2016). Standard SED fitting (Conroy 2013) of just the stellar emission (e.g., Papovich et al. 2001; Shapley et al. 2005; Salim et al. 2007)
is essentially the unabridged version of the plain UV method, but with multiple bands constraining the SFR. SED fitting essentially derives dust-corrected SFRs also via a relation between the UV color and FUV attenuation, but the relation is implicitly present in the models and is typically implemented via a dust attenuation curve(s) and not via an explicit IRX–β relation. Finally, energy-balance SED fitting (Burgarella et al. 2005; da Cunha et al. 2008) directly includes IR in constraining the SFR, which also helps to constrain the parameters of the attenuation curve (assuming it is not fixed in the fitting), while correctly attributing the IR emission to dust heating from both young and old stars (Burgarella et al. 2005; Noll et al. 2009a; Boquien et al. 2012, 2016; Leja et al. 2017; Salim et al. 2018).

In the absence of IR data, many high-redshift studies rely on the UV method and thus need to assume some IRX–β relation or, equivalently, an A_{FUV}–β relation. The relationship between FUV emission (or IRX) and the UV spectral slope was originally studied by Meurer et al. (1999), based on ~60 relatively compact local starbursts (and blue compact dwarfs) drawn from the UV spectral atlas of Kinney et al. (1993), which was produced with International Ultraviolet Explorer (IUE) observations and with IR luminosities derived from Infrared Astronomical Satellite (IRAS) observations. Meurer et al. (1999) found that these starbursts obey a relatively tight IRX–β relation. The existence of a relation lends credence to its application to higher-redshift samples (z ≥ 1), especially because the local starbursts may share many of the characteristics of young galaxies at high redshifts.

The possibility that the IRX–β relation could be universal and relatively tight for non-starbursting galaxies was challenged by Kong et al. (2004), who found that including normal galaxies (observed by IUE and several other early UV satellites) introduces an additional scatter and a possible shift with respect to the starburst relation of Meurer et al. (1999). Moreover, Kong et al. (2004) have suggested that the offset and the additional scatter may be due to a wide range of older stellar populations found in normal SF galaxies, with the offset correlating with the stellar population age.

The possible nonuniversality of the IRX–β relation has been indicated in numerous subsequent studies (e.g., Buat et al. 2005; Seibert et al. 2005; Gil de Paz et al. 2007; Dale et al. 2009; Takeuchi et al. 2010; Grasha et al. 2013), which utilized much larger sets of observations of more normal galaxies acquired by the Galaxy Evolution Explorer (GALEX) in its two UV bands (FUV and NUV), and compared the resulting IRX–β distributions of points to the starburst relations of Meurer et al. (1999) and Kong et al. (2004), finding offsets. However, remeasurements of the Meurer et al. (1999) galaxies using GALEX have revealed that IUE missed a large fraction of FUV emission (Overzier et al. 2011; Takeuchi et al. 2012; Casey et al. 2014), biasing the original starburst relation with respect to the one obtained by GALEX for the same starburst galaxies. Nevertheless, the question of the drivers of the large scatter in the IRX–β relation (the so-called second parameter in that relation) remains.

Following Kong et al. (2004), much attention has been paid to investigating the role of age, or age-related metrics, in the dispersion in the IRX–β relation, both empirically (Burgarella et al. 2005; Seibert et al. 2005; Johnson et al. 2007; Panuzzo et al. 2007; Boquien et al. 2009; Grasha et al. 2013) and using radiative transfer modeling (Popping et al. 2017; Safarzadeh et al. 2017; Narayanan et al. 2018). Factors other than age have been explored as well, such as variations in the intrinsic UV slope (Boquien et al. 2012) and the role of dust type and/or geometry (Witt & Gordon 2000; Bell et al. 2002; Inoue et al. 2006; Thilker et al. 2007; Panuzzo et al. 2007; Popping et al. 2017; Safarzadeh et al. 2017; Narayanan et al. 2018). Both dust type and dust geometry affect the resulting attenuation curve—attenuation as a function of wavelength normalized by attenuation at some wavelength, usually the V band.

The role of the attenuation curve in driving the scatter in the IRX–β plane was explicitly studied in Burgarella et al. (2005), Boquien et al. (2009, 2012), and Buat et al. (2012) and has sometimes been implicitly assumed to be a factor, especially in high-redshift studies (e.g., Meurer et al. 1995; Siana et al. 2009; Bouwens et al. 2016; Salmon et al. 2016; Cullen et al. 2017; Reddy et al. 2018; McLaren et al. 2018). However, its precise role is difficult to establish because measuring the attenuation curve for individual galaxies represents a major challenge (e.g., Kriek & Conroy 2013; Salmon et al. 2016; Leja et al. 2017; Buat et al. 2018; Salim et al. 2018).

IR observations from Spitzer have allowed the study of the IRX–β relation to be carried out to z ≥ 1 for IR-luminous galaxies (Noll et al. 2009b; Reddy et al. 2010; Murphy et al. 2011; Buat et al. 2012) and strongly lensed sources (Siana et al. 2009; Pope et al. 2017), again suggesting a large spread in the IRX–β plane. These redshifts have been subsequently explored at longer wavelengths with Herschel (Nordon et al. 2013). At even higher redshifts (z ≥ 3), some studies using Herschel and ALMA suggest a stronger evolution in the IRX–β relation (Capak et al. 2015; Bouwens et al. 2016; Barisic et al. 2017), but the question of how IR luminosity is measured starts to arise as well (Lee et al. 2012; Cullen et al. 2017; Faisst et al. 2017; Ferrara et al. 2017). Recently, efforts have been made to derive an average IRX–β relation for the general population of high-redshift (z ≥ 2) galaxies using the stacking of Herschel, SCUBA-2, or ALMA observations at longer wavelengths (e.g., Heinis et al. 2013; Pannella et al. 2015; Alvarez-Márquez et al. 2016; Bouwens et al. 2016; Forrest et al. 2016; Bourne et al. 2017; Fudamoto et al. 2017; McLure et al. 2018; Koprivovskii et al. 2018; Reddy et al. 2018), but the question of the drivers of the scatter, which appears to be present at all redshifts, remains a fundamental one.

Our approach in addressing the issue of the IRX–β scatter is that using very large samples of local galaxies with robustly determined galaxy parameters can help inform the underlying mechanisms that may be valid regardless of the redshift. Recently, we constructed the GALEX–Sloan Digital Sky Survey (SDSS)–Wide-field Infrared Survey Explorer (WISE) Legacy Catalog (GSWLC; Salim et al. 2016), a catalog of physical parameters of galaxies obtained using Bayesian SED fitting. GSWLC was drawn from the SDSS spectroscopic survey, with UV observations from GALEX and mid-IR observations from WISE, containing all together 700,000 optically selected galaxies. In a recent update of the catalog (GSWLC-2; Salim et al. 2018), IR luminosity was used to constrain the parameters of the dust attenuation curve for individual galaxies. This important additional information allows us to systematically explore, in the present work, a
range of different galaxy properties as potential drivers of the IRX–β scatter of entire galaxies.

The paper is organized as follows. Section 2 provides a summary of the sample and the data. In Section 3 we describe the derivation of galaxy parameters and the methodology for selecting the fiducial IRX–β relation. In Section 4 we present the results of the systematic investigation of the drivers of the scatter using a nonparametric approach. In Section 5 we introduce new parameterization useful for studying trends in the IRX–β plane. Recipes that include extensions of the IRX–β relation are presented in Section 6. The results are discussed in Section 7 and summarized in Section 8. Throughout this work we assume WMAP7 flat cosmology (\(H_0 = 70.4\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.272\)).

2. Sample and Data

In this work we use the deep UV photometry catalog from GSWLC-2 (GSWLC-D2). GSWLC is a publicly available catalog of SED fitting parameters derived by combining GALEX, SDSS, and WISE photometry. GSWLC-1 (Salim et al. 2016) and GSWLC-2 (Salim et al. 2018) share the sample, but the latter performs energy-balance SED+LIR fitting. The GSWLC sample includes all galaxies from the SDSS Data Release 10 spectroscopic surveys such that 0.01 < \(z\) < 0.30 and \(r_{\text{petro}} < 18.0\) as long as they fall within the GALEX coverage. Because GALEX observations have a very wide range of exposure times, separate samples are defined for shallow (all-sky; GSWLC-A), medium–deep (GSWLC-M), and deep (GSWLC-D) UV observations. Details of the sample construction and matching are given in Salim et al. (2016).

While the GSWLC-D2 catalog is the smallest of the three, covering only 7% of the SDSS footprint, it has the highest quality of UV photometry, with UV exposure time of at least 4000 s, and hence provides the most reliable UV slope (\(\beta\)), which is why we choose it as the sample for this study. GSWLC-D2 contains 48,401 galaxies, which reduces to 47,672 after the exclusion of type I active galactic nuclei (AGNs; QSO-like spectra) and objects with poor (\(\chi^2 > 30\)) SED fits. Next we require that both the FUV and NUV are detected at \(>3\sigma\), which leaves 25,791 objects. This cut mostly removes early-type, passive galaxies, which are not the focus of the study, considering that their FUV attenuation does not follow the tight relation with IRX that the FUV attenuation of SF galaxies does (Cortese et al. 2008; Viaene et al. 2016). Furthermore, we require mid-IR detection in either 12 \(\mu\)m or 22 \(\mu\)m, which results in 23,175 galaxies; we refer to these as “all” the galaxies. In addition, we use the Baldwin et al. (1981: BPT) emission-line diagram to select SF galaxies, as described in Salim et al. (2018). More accurately, we exclude 5501 galaxies on the AGN branch and 5585 galaxies with weak lines (signal-to-noise ratio of H\(_\alpha\) flux <10) to get an “SF” sample of 12,089 galaxies. The SF sample encompasses the main sequence and extends down to log specific SFR (sSFR) \(-11\). Selecting the SF sample based on the SDSS fiber spectroscopy may miss galaxies that have the bulk of their star formation outside of the 3\(''\) fiber (typically early-type galaxies in the green valley; Salim & Rich 2010), but such galaxies are relatively rare (see Figure 8 in Salim et al. 2016). Alternatively, we could have selected galaxies with an sSFR above some threshold, regardless of the BPT class, and this would not have affected the results at all.

We use the GALEX pipeline photometry with application of some corrections, as described in Salim et al. (2018). For optical photometry we use SDSS \(ugriz\) model\(_{\text{mag}}\) measurements. Finally, we use the unWISE forced photometry of Lang et al. (2016) for fluxes at 12 and 22 \(\mu\)m.

3. Methodology

3.1. Derivation of Galaxy Parameters

All galaxy parameters employed in this work are derived using Code Investigating GALaxy Emission (CIGALE; Noll et al. 2009a; Boquien et al. 2018) by applying SED+LIR fitting, a variant of energy-balance SED fitting (Salim et al. 2018). Specifically, we use CIGALE version 0.11, but with custom modifications, some of which were implemented in the 0.12 and 2018.0 versions of the code. Energy-balance SED fitting (da Cunha et al. 2008; Noll et al. 2009a) requires that the energy absorbed by the dust in the UV to the near-IR should match the luminosity emitted by the dust, i.e., the total IR luminosity, \(L_{\text{IR}}\). Energy-balance SED fitting codes typically fit both the stellar and IR SEDs, with a number of parameters required to specify both. In SED+LIR fitting, the IR luminosity is determined separately and is then used as a constraint in the broadband SED fitting, without the need to fit the IR SED. The main advantage of the SED+LIR method compared to UV/ optical+IR SED fitting is that the model library for the SED fitting is not inflated by all of the parameter combinations needed to model the IR SED, allowing for faster fitting and/or allowing for other parameters, e.g., the attenuation curve, to be left free.

The IR luminosities to be used in the SED+LIR fitting are derived in a two-step process. We first use the luminosity-dependent templates of Chary & Elbaz (2001) together with 22 \(\mu\)m flux (or 12 \(\mu\)m, if not detected at 22 \(\mu\)m) to get an estimate of the IR luminosity. With these estimates we apply empirically derived corrections (as a function of \(L_{\text{IR}}\) and \(L_{\text{IR}}/M_\ast\)) constructed to reproduce the IR luminosities of galaxies with far-IR coverage from the Herschel-ATLAS survey (Valiante et al. 2016). This two-step method results in IR luminosities that have a remarkable accuracy of \(\sim\)0.1 dex and show no systematic differences with respect to Herschel luminosities over the entire \(8.8 < \log L_{\text{IR}} < 11.8\) range. The \(L_{\text{IR}}/M_\ast\)-dependent correction eliminates the deviations of Chary & Elbaz (2001) templates reported for starbursting galaxies (Overzier et al. 2011). Details are given in Salim et al. (2018). We also check whether the energy balance assumption is valid for different viewing geometries. We look at the difference between the observed IR luminosity and the dust-absorbed luminosity estimated from the SED fitting without IR constraints, as a function of galaxy inclination, and find no systematic difference greater than 0.04 dex.

The use of the IR luminosity allows the dust attenuation curve to be relatively well constrained when its parameters are left free in the SED fitting. Following Noll et al. (2009a), the attenuation curve is parameterized with a power-law slope deviation from the Calzetti et al. (2000) curve (\(\beta\)), to which the UV bump feature is added having amplitude \(B\). As discussed in Salim et al. (2018), the modification of the slope and the addition of the UV bump is carried out on an \(E(B-V)\) normalized Calzetti et al. (2000) curve. Attenuation curve
slopes are allowed to vary from $\delta = -1.2$, which is steeper than even the SMC extinction curve, to $\delta = 0.4$, which is somewhat shallower than the Calzetti curve. The amplitude of the UV bump, centered at 2175 Å, can vary between $B = -2$ and $B = 6$, twice as strong as that of the Milky Way (MW) bump. Since the amplitude of the bump is not constrained with great accuracy, the inclusion of negative values is meant to offset the posterior bias (Buat et al. 2012; Salmon et al. 2016). The typical error on the curve slope determination is 0.17, and that on the bump amplitude is 1.3 (both for the SF sample).

The attenuation curves described above are not effective curves. The above attenuation curves, of the same slope and the same bump strength, are applied separately to young and old populations, but with the old population suffering a fraction of the attenuation that affects young stars still enshrouded in birth clouds, following the distinction introduced in Charlot & Fall (2000). In the nominal run, using the dust module dustatten_calzlett, this fraction is fixed at the default value of 0.44, which we confirm to be close to the average value when the fraction of attenuation affecting the older population is actually allowed to vary. The split between the young and the old population (i.e., the birth cloud dispersal time) is fixed at 10 Myr, the value that fits the great majority of galaxies. Assuming the same intrinsic shapes for the attenuation curves of both populations is a simplification, driven by the lack of consensus regarding the appropriate curve for the young population (birth clouds) and the difficulty of constraining it from the SED fitting (Lo Faro et al. 2017). Consequently, the results of the study are not sensitive to the details regarding the curve of the young population.

It should be pointed out that applying the same intrinsic attenuation curve (same $A_{\lambda}/A_B$) to young and old populations but with different normalizations, as we do here, changes the effective attenuation curve. Specifically, in our implementation the power-law exponent of the slope of the effective curve is on average ~0.2 steeper than the slope of the intrinsic curve, with some 0.1 scatter around that average. We obtain the above offset by performing SED fitting in which the attenuation curve is treated as an effective curve, without the age-dependent split, and comparing the resulting slopes with the ones from the age-dependent model. In this paper, however, when we refer to the slope of the attenuation curve, we mean the slope deviations from the Calzetti curve implemented as the intrinsic attenuation curves of the two populations. We have found that applying the modified Calzetti curve without the old/young split, so that the input and effective curves are one and the same, results in poorer quality of the fits, presumably because such age-insensitive application is less physical.

The SED fitting is based on the stellar population models of Bruzual & Charlot (2003), with a Chabrier initial mass function (Chabrier 2003) and four stellar metallicities (0.004, 0.008, 0.02, and 0.05). We model star formation histories as two components (a 10 Gyr exponentially declining component and a more recent burst of varying strength and a constant SFR). We include the contribution of nebular emission lines and a nebular continuum. Details on model assumptions and SED fitting are given in Salim et al. (2016, 2018).

3.2. IRX–$\beta$ Parameters and the Fiducial Relation

IRX is defined as the ratio of the total IR luminosity to the rest-frame FUV luminosity in the GALEX bandpass.\(^6\) We determine IRX from the SED fitting, with the typical uncertainty of 0.10 dex. We have verified that the models fully cover the parameter space of observations and that no systematic biases are present between the model and observed values. The UV slope is defined following the original methodology of Calzetti et al. (1994), as the linear fit to rest-frame fluxes from 10 windows spanning the range of 1268 to 2580 Å. The windows are selected to avoid absorption features that may affect the derivation of the slope, as well as to exclude the UV bump, or at least its central portion (1950–2400 Å). The typical error of the UV slope, determined via the SED fitting that includes the nebular continuum contribution, is 0.14. We designate the UV slope determined from the spectral windows as $\beta_{\text{C94}}$ to differentiate it from slopes derived in other ways—for example, those from GALEX FUV and NUV photometry ($\beta_{\text{GLX}} = 2.29(\text{FUV} – \text{NUV}) – 2$), which, in the case of low-redshift studies, are often based on observed (non-rest-frame) magnitudes. From our sample we get the relationship between the two definitions of the slope, depending on the redshift:

\[
\beta_{\text{GLX}} = 0.17 + 1.01\beta_{\text{C94}} \quad (z < 0.3),
\]

\[
\beta_{\text{GLX}} = -0.05 + 0.90\beta_{\text{C94}} \quad (z < 0.05).
\]

For $\beta = -1$, the average for the sample, the difference between the values of two slopes is 0.16 in the case of $z < 0.3$, reducing to 0.05 for $z < 0.05$, in the sense that $\beta_{\text{GLX}}$ is higher. Redshift dependence exists because $\beta_{\text{C94}}$ is measured on a rest-frame spectrum, whereas $\beta_{\text{GLX}}$ in low-redshift studies is often determined from the observed-frame UV color, which differs from the rest-frame UV color due to the $L_{\text{UV}}$ contribution (e.g., Shim & Chary 2013) and to the fact that the UV spectrum is not a perfect power law. The dispersion around the relations is 0.20 and 0.16, respectively, and is driven by galaxies having a range of UV bump strengths, coupled with the fact that the UV bump affects $\beta_{\text{GLX}}$ much more than it does $\beta_{\text{C94}}$.

Some high-redshift studies derive the UV slope based on the FUV region alone (1200–1800 Å). Such $\beta$ will typically be higher (shallower) than the 10-window slope we use here, the difference being ~0.3 at $\beta \sim -1$ (Calzetti 2001; Reddy et al. 2018), but note that the difference is not constant—it increases with $\beta$. A similar significant difference also exists between the slope obtained from a single continuous window covering 1268 $\leq \lambda \leq 2580$ Å ($\beta_{\text{cont}}$; e.g., McLure et al. 2018) and a slope that uses 10 windows in this same range. Using our sample we derive:

\[
\beta_{\text{cont}} = 0.55 + 1.21\beta_{\text{C94}},
\]

\[
\beta_{\text{C94}} = -0.45 + 0.82\beta_{\text{cont}}.
\]

Now the difference at $\beta \sim -1$ is 0.34. This underscores the observation that care must be exercised in comparing the results of studies that measure the UV slope in different ways (Reddy et al. 2018).

For the purposes of describing how different sample cuts lead to different distributions of data points in the IRX–$\beta$ plane,

\(^6\) Furthermore, IRX is defined as just the ratio, following Meurer et al. (1999). Originally, in Meurer et al. (1995), IRX was defined as the logarithm of the ratio. Note, however, that both of these studies define IRX using the far-IR luminosity, unlike most subsequent studies, which use the total IR luminosity.
we will be introducing a fiducial IRX–β relation. Figure 1 displays three previously published relations, all principally based on the local starburst sample of Meurer et al. (1999). The Meurer et al. (1999) relation is based on 57 starburst galaxies whose UV spectra were observed by IUE. They used the Calzetti et al. (1994) methodology to measure UV slopes, but because not all spectra had the near-UV region observed (corresponding to the 10th window), Meurer et al. (1999) determined the UV slopes of all galaxies by using nine FUV windows and then adjusting the result to what would have been determined with all windows using a constant offset. Importantly, the IRX in Meurer et al. (1999) was defined using the far-IR luminosity (40–120 μm), whereas most subsequent studies have defined IRX based on the total IR luminosity (1–1000 μm). The correction factor between them is 1.75 (Calzetti et al. 2000); rather than the 1.4 reported in Meurer et al. 1999, the difference coming from the addition of the submillimeter tail to the far-IR bandpass, i.e., 40–1000 μm) and has been applied throughout. The Meurer et al. (1999) relation adjusted to the total IR luminosity is plotted in Figure 1, and it appears not to coincide with the mean locus of our sample, being too high (or too red).

Kong et al. (2004) re-derived the IRX–β relationship using essentially the same sample as Meurer et al.’s (1999), so it is also located away from the main locus of our data points (Figure 1). Note that Kong et al. (2004) provided their relation in terms of βGLX, which we convert to βC94 using the relation from their Figure A1; this yields a correction similar to our Equation (1). The Kong et al. (2004) and Meurer et al. (1999) relations differ mostly in terms of the βmin asymptote. There are very few points in these samples with log IRX < 0 to allow βmin to be well established. Our more extensive data suggest βmin ≈ −2.2, a value closer to the minimum slope in the Meurer et al. (1999) relation. Studies that perform detailed UV photometry of nearby galaxies, which include many low-metallicity, nearly dust-free dwarfs (Gil de Paz et al. 2007; Dale et al. 2009), never find galaxies with colors bluer than FUV −NUV = −0.05, which corresponds to βGLX = −2.1, or βC94 = −2.3. Note that our models include SEDs with intrinsic UV slopes β0,min = −2.56 (corresponding to 1/20 Z⊙ and young (<100 Myr) bursts), but only 0.2% of SF galaxies are fit by models with β0,C94 < −2.5.

In both the Kong et al. (2004) and Meurer et al. (1999) analyses, the FUV flux comes from IUE measurements in 10″ × 20″ apertures, whereas the IR luminosity comes from IRAS measurements that encompass entire galaxies. This inconsistency was not considered critical by Meurer et al. (1999) because it was assumed that most of the total UV flux was confined to a 10″ × 20″ aperture because starbursts are typically compact and galaxies with large optical diameters (but only if greater than 240″) were explicitly excluded from the sample. However, Overzier et al. (2011) measured the UV fluxes of a large fraction of the Meurer et al. (1999) sample using integrated photometry from GALEX and found that the IUE measurements missed ~1/2 of the UV flux. Similar analysis and results were obtained by Takeuchi et al. (2012) and Casey et al. (2014). The latter study performed new measurements of both starbursts and normal galaxies. The IRX–β relation re-derived by Overzier et al. (2011) is shown in Figure 1 (where their rest-frame βGLX is converted to βC94 using Equation (2)). The bottomline is that the Meurer et al. (1999) and Kong et al. (2004) relations should not be used with modern total UV flux measurements, but rather their updated versions. Our data set is on average well described by the Overzier et al. (2011) relation, and we adopt it as our fiducial relation. Agreement is present despite the fact that our sample is not composed mostly of starbursts, which we will discuss in Section 4.1.

4. Results

In this section we search for parameters that may govern the scatter in the IRX–β plane. The search is first performed in a visual manner and is parameterized afterward. The visual method consists of plotting, on IRX–β diagrams, the slices of data having low, median, and high values of some parameter and looking at the tightness and the shifts/trends in the distribution of points. To determine what constitutes low/median/high values for log sSFR, for example, we construct the distribution of that parameter and find values that correspond to the 5th percentile, the median, and the 95th percentile of the distribution. For log sSFR, the corresponding low/median/high values are −10.61, −10.02, and −9.47 in units of M⊙ yr−1. The slices have a width that we take to be one-ninth of the 90th percentile range of the distribution. In the case of sSFR, each slice is 0.13 dex wide, so, for example, the median slice covers −10.08 < log sSFR < −9.95. In the case of a uniform distribution each bin will contain exactly 10% of all data points. For a normal distribution the median bin will contain 15% of data points, whereas the low/high bins will contain approximately 4%.

A parameter that affects the scatter in the IRX–β plane would yield a much narrower distribution of points when individual slices are plotted, compared to the full distribution of...
points in the IRX–β plane, plus the locus of points would shift considerably when going from the low-percentile to the high-percentile slice. The analysis in subsequent sections pertains to the SF sample. We separately discuss passive galaxies in Section 4.4.

4.1. Galaxy Parameters Related to Star Formation and Population Age

We start the analysis by exploring three parameters (two of which were studied before by Nordon et al. 2013) that are related to stellar population age (Figure 2), following the original hypothesis by Kong et al. (2004). The upper left panel of Figure 2 shows the distribution of the sSFRs in the sample, spanning some 2 dex. SFRs represent averages over 100 Myr. The distribution has a median and a peak at log sSFR ~ −10, with 5th and 95th percentiles some 0.5 dex below and above it. The three panels to the right show where the points selected to have low, median, and high sSFRs lie on the IRX–β plane. Selecting the data by sSFR does not reduce the scatter in the relation appreciably, and there is only a slight shift downward in the locus of points.

Considering that the SF sequence of sSFR versus stellar mass is tilted (e.g., Salim et al. 2007), galaxies with higher sSFRs will also tend to be less massive, and vice versa. Thus, a better way to distinguish galaxies by their level of activity is to look at the relative sSFRs, i.e., the offset of the sSFR with respect to the mean sSFR–\(M_\ast\) relation. A robust linear fit to the relation using the current SF sample gives:

$$\log sSFR = -0.31 \log M_\ast - 6.89.$$  (5)

Selecting galaxies around the 5th and 50th percentiles by the relative sSFR, i.e., galaxies with suppressed and with normal star formation, still does not produce any tightening in the IRX–β distribution or systematic shifts of points (Figure 2, middle row). The 95th percentile selected galaxies lie 0.5 dex above the main sequence, not as high as the IUE starbursts of Calzetti et al. (1994) and Meurer et al. (1999), which lie between 0.5 and 1.5 dex above the main sequence (based on the analysis performed by Salim et al. 2018). Therefore, in this

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**Figure 2.** Age-related parameters and their role in driving the IRX–β scatter in SF galaxies. For each parameter (sSFR, sSFR relative to the SF sequence, and mass-weighted population age) the distribution is shown along with the positions of the median, 5th, and 95th percentiles (dashed lines). Galaxies with values within one histogram bin of these percentiles are plotted in separate IRX–β panels (with the exception of starbursts which cover the entire shaded area). Selecting by these parameters does not reduce the scatter in the IRX–β panels, nor does it produce a notable systematic trend. Most importantly, both the normal SF galaxies and the starbursts are similarly well described with the Overzier et al. (2011) relation (green curve) originally derived based on starbursts alone.
one case we replace the 95th percentile slice with a selection that includes all galaxies with $\Delta \log \text{sSFR} > 0.8$ dex. There are 125 such galaxies in our sample (1% of all star-formers), and their average offset from the main sequence is 1.0 dex, the same as that for the IUE starbursts. Their IRX–$\beta$ distribution is shown in the right panel of the middle row of Figure 2. We do not see that starbursts have an offset in the IRX–$\beta$ distribution with respect to normal or even quiescent star-formers, though the scatter is somewhat smaller, in agreement with the original IUE results of a relatively tight relation. All together, neither the sSFR nor the relative sSFR drives the scatter. The similarity between how normal and starbursting galaxies are distributed in the IRX–$\beta$ plane explains why the IRX–$\beta$ relations derived from local starburst samples (but using total GALEX photometry) describe the average locus of the general population of SF galaxies so well (Figure 1).

Kong et al. (2004), based on their modeling, proposed that galaxies occupy different locations in the IRX–$\beta$ plane according to their birthrate parameter $(b)$, i.e., $b$ governs the scatter. The birthrate parameter is defined as the ratio of the current SFR to the past-averaged one. The latter is the ratio of the total stellar mass produced over the galaxy’s history (the integral of the SFR) divided by the total age of the galaxy. However, the total age of a galaxy, i.e., the time since the commencement of any star formation in a galaxy, is not a particularly meaningful or even measurable quantity, and one may as well assume that all galaxies have the same total age. In that case, the birthrate becomes equivalent to the sSFR. Indeed, the birthrate parameter has been replaced in recent literature by the sSFR, which we have shown not to control the scatter.

Finally, we explore the role of the stellar population age, determined here as the stellar mass–weighted age and spanning the range in our SF sample of 4.5 to 8.5 Gyr, with the peak toward older systems (lower left panel of Figure 2). Selecting subsamples with younger, median, and older ages and showing their IRX–$\beta$ distributions reveals a slight trend where older galaxies tend to shift upward, but again the large scatter remains. In the most favorable case, the stellar population age may only weakly affect the IRX–$\beta$ distribution.

4.2. Galaxy Parameters Related to Dust Attenuation

In Figure 3 we explore the role of dust attenuation parameters in IRX–$\beta$ (still for the SF sample), starting with the slope of the dust attenuation curve, parameterized as a power-law deviation from the Calzetti curve. While the UV slope is calculated over wavelength ranges such that the bulk of the UV bump is excluded, we find that the bump is nevertheless wide enough to affect the UV slope. For this reason we explore the role of the slope and of the bump in the IRX–$\beta$ relation independently of each other, by restricting the other parameter to a small range of values.

The upper row in Figure 3 shows in the first panel the distribution of the slopes (with the bump amplitude restricted to $1 < B < 3$, one-fourth of the full possible range), followed by IRX–$\beta$ panels in which the points are selected to have steep, typical, and shallow slopes. We point out that the range of slopes is quite broad, from shallower than the Calzetti curve to steeper than the SMC curve (Salim et al. 2018). Selecting the subsamples by the steepness of the slope results in a dramatic reduction in scatter, with different attenuation curve slopes occupying distinctly different regions of the IRX–$\beta$ plane. As a matter of fact, the scatter essentially vanishes when selecting galaxies within even narrower ranges of slopes (and UV bump amplitudes). Different attenuation slopes correspond to different tilts in the IRX–$\beta$ point distribution, which we will use as a basis for new parameterization in Section 5. Galaxies with steeper attenuation curve slopes tend to lie below the Overzier et al. (2011) relation, whereas galaxies with shallow slopes (similar to the Calzetti curve slope or MW curve) tend to lie above the Overzier et al. (2011) relation.

In the middle row of panels in Figure 3 we keep the attenuation curve within a restricted range ($-0.5 < \delta < -0.3$) and explore any additional trends due to the varying strength of the UV bump. The distribution in the IRX–$\beta$ plane is tight because of the restricted range of attenuation curve slopes. Plotting the galaxies with weak, median, and strong bumps reveals a moderate shift in the locus. The bump apparently does systematically affect the measurement of the UV slope, even when it was derived over the 10 windows. Specifically, we find that for each unit of amplitude of the bump, the UV slope is shifted by $d\delta_{\text{C94}}/dB = -0.064$.

All together, the conclusion is that the shape of the attenuation curve, primarily its slope, is the principal driver of the scatter in the IRX–$\beta$ diagram. Consequently, the question of what drives the IRX–$\beta$ scatter becomes derivative of the question of what drives the diversity of slopes of the attenuation curve. Salim et al. (2018) focused on the latter question and found that a principal connection exists between the attenuation curve slope and the optical opacity (e.g., $A_V$), with more transparent galaxies having steeper slopes, presumably because the wavelength-dependent scattering dominates over the absorption (Chevallard et al. 2013). Radiative transfer modeling also shows a connection between the attenuation curve slope and optical opacity (Witt & Gordon 2000; Pierini et al. 2004; Seon & Draine 2016). The bottom panels of Figure 3 explicitly explore how selecting galaxies by $A_V$ translates to the IRX–$\beta$ plane. The distribution of points is relatively narrow, though not as narrow as that for the attenuation slope, and the galaxies with different $A_V$ tend to have a similar tilt offset from one another, unlike the changing tilt when varying the attenuation curve slope. Thus, while related, the two factors (the dust attenuation curve slope and $A_V$) are not equivalent. We shall return to the connection between the dust attenuation curves and $A_V$ in Section 7.

Our sample contains very few ultraluminous IR galaxies (ULIRGs) as they are intrinsically rare. Local ULIRGs tend to span $1.5 < \log \text{IRX} < 3$ (Howell et al. 2010), whereas in our sample log IRX does not exceed 2. In light of our results, the special location of ULIRGs in the IRX–$\beta$ plane (Goldader et al. 2002; Buat et al. 2005; Reddy et al. 2010; Penner et al. 2012; Oteo et al. 2013; Casey et al. 2014) may not require a separate explanation. High values of IRX are due to high opacities, but their dispersal along $\beta$ should still be the result of the diversity of attenuation curve slopes (Lo Faro et al. 2017). High optical opacities of ULIRGs imply shallow attenuation curves, which are located mostly to the left of the mean relation, as confirmed in actual data (e.g., Goldader et al. 2002; Howell et al. 2010).

4.3. Other Galaxy Parameters

Other parameters that have been proposed to affect the IRX–$\beta$ relation include (1) the intrinsic UV slope (Boquien et al. 2012), which is sensitive to the star formation history and, as we will see, also to the stellar metallicity; (2) the stellar mass
The intrinsic UV slope $\beta_0$ is the slope that one would observe in the absence of dust. We determine it from the SED fitting with the same 10-window methodology used for $\beta_{C94}$. The upper left panel of Figure 4 shows that the distribution of the intrinsic slopes of SF galaxies is rather narrow, with the 5th and 95th percentile values lying within 0.1 of the median at $\beta_0 = -2.24$. Selecting galaxies that span that range produces only a slight shift in the locus of points, with a scatter that is similar to the scatter of the full sample. The distribution of intrinsic slopes extends to less steep values (up to $\beta_0 \sim -1$) only when passive galaxies ($\log \text{sSFR} < -11$) are included, which will be discussed in Section 4.4.

Following Charlot & fall (2000), our default SED fitting assumes that birth clouds, which suffer higher attenuation than ambient interstellar matter, disperse after 10 Myr. However, Charlot & fall (2000) have shown model tracks with different values of birth cloud dispersal time showing a shift in the IRX--$\beta$ plane. We thus produce a separate run where we allow the split between young and old stars (i.e., the birth cloud dispersal time) to span a range of 3 to 30 Myr. The middle left panel of Figure 4 shows that the distribution is indeed highly peaked at 10 Myr and further that selecting galaxies by shorter and longer dispersal times does not reduce the scatter or produce trends in the IRX--$\beta$ plane.

Similarly, in our nominal SED run we keep the V-band attenuation affecting older stars (those which have left the birth clouds) at some fixed fraction of the attenuation affecting young stars. Again, the modeling of Charlot & Fall (2000) suggests that allowing this fraction to vary may lead to trends in the IRX--$\beta$ plane, so we produce a run where the ratio is not fixed. Selecting galaxies with low ratios necessarily selects galaxies with low $A_V$, which restricts them to low IRX values. Otherwise, there is no clear trend for the different values of the old-to-young attenuation ratio, and we do not present the associated plots.

(e.g., Álvarez-Márquez et al. 2016); (3) the lifetime of the birth clouds; (4) the fraction of dust absorbed in the birth clouds (Charlot & Fall 2000); and (5) the galaxy inclination (Wang et al. 2018).

Figure 3. Dust-related parameters and their role in driving the IRX--$\beta$ scatter in SF galaxies. The distributions of the attenuation curve slopes (for a fixed UV bump), the UV bump amplitude (for a fixed slope), and the optical attenuations are shown. Galaxies with values within one histogram bin of the 5th, 50th, and 95th percentiles are plotted in the the IRX--$\beta$ panels. The attenuation curve slope is strongly correlated with the tilt in the IRX--$\beta$ relation, with some additional changes in the tilt due to the UV bump. The attenuation curve slope itself depends on the optical opacity (Pierini et al. 2004; Chevallard et al. 2013; Seon & Draine 2016; Salim et al. 2018), which is why selecting by $A_V$ also produces a relatively tight distribution of points in the IRX--$\beta$ plots. The green curve represents the Overzier et al. (2011) relation.
We also examine (but do not present) the IRX–β plots for galaxies selected to have different inclinations, measured as $b/a$ axis ratios. Highly inclined edge-on galaxies ($0.2 < b/a < 0.3$) do tend to lie in the IRX–β diagram somewhat above the face-on galaxies ($b/a > 0.9$) and to exhibit a larger scatter in IRX. Similar trends have recently been seen at $z \sim 1.5$ by Wang et al. (2018). Salim et al. (2018) have shown that edge-on galaxies tend to have somewhat shallower attenuation curves than face-on galaxies and that the difference in attenuation curve slopes is entirely due to the higher average dust content, i.e., greater $A_V$, of edge-on galaxies. Once $A_V$ is accounted for by fixing it, the dependence goes away.

Finally, we look at the IRX–β dependence on the stellar mass (bottom row of Figure 4). Selecting the slices of data around the 5th, 50th, and 95th percentiles roughly corresponds to selecting galaxies with masses around $\log M_\odot = 9$, 10, and 11. While the substantial scatter in these mass-selected slices remains, the shift in the locus is more pronounced than for any of the non-dust parameters that we have considered. Mass dependence of similar magnitude was previously reported in a $z \sim 3$ sample, from a stacking analysis of Álvarez-Márquez et al. (2016), which motivated them to suggest that the IRX–$M_\odot$ relation should be combined with IRX–β. The dependence of the slope of the attenuation curves on $M_\odot$ was discussed in Salim et al. (2018), and as in the case of inclination, it was shown that this dependence is entirely due to the more massive galaxies having higher $A_V$, a parameter that most strongly drives the slopes of the attenuation curves. We revisit this analysis in the context of IRX–β in Section 5.

An alternative way of showing the relationship between IRX–β and the various parameters is to color-code the data points according to the value of the parameter (Figure 5). The strongest trend is with respect to the slope of the attenuation curve, followed by the trend with respect to $A_V$. Other trends exist as well (most notably with respect to the stellar mass) but are small compared to the galaxy-to-galaxy scatter.

### 4.4. Passive Galaxies

In Figure 4 we show that the range of intrinsic UV slopes ($\beta_0$) is quite small ($\sim 0.2$) and therefore cannot have a significant role in driving the scatter in the IRX–β relation. This is because in our analysis so far we have focused on SF galaxies, the type of galaxies for which the IRX–β relation is expected to be useful. Our full sample, however, does include passive galaxies ($-13 < \log \text{sSFR} < -11$), with the data needed to place them on the IRX–β plot. We first show, in
Figure 6, the relationship between the sSFR and the intrinsic UV slope for the full sample (SF and passive), which confirms that actively SF galaxies have a small range of $\beta_0$. The range becomes much wider (toward shallower values of $\beta_0$) for passive galaxies, extending all the way to $\beta_0 \approx 0$. In addition to the sSFR, the intrinsic UV slope of passive galaxies depends very strongly on the stellar metallicity, with metal-poor galaxies having shallower intrinsic UV slopes (higher $\beta_0$).

In Figure 7 we use color-coded values to look at the role of several select parameters in driving the IRX–$\beta$ scatter of 5180 passive galaxies. The galaxies are selected to have log sSFR $< -11$, regardless of their BPT diagram classification. First, we notice that the overall distribution of the points is not too dissimilar to that of the actively SF galaxies. Next, it is again the slope of the attenuation curve that presents the strongest trend. Stratification according to $\beta_0$ is present only in the sense that the observed slope must be shallower than the intrinsic slope ($\beta_{C94} > \beta_0$), but for any given intrinsic slope the distribution of points to the right of that value is quite broad.

This empirical result that even passive galaxies strongly segregate in the IRX–$\beta$ plane by the slope of the attenuation curve is surprising, given that the wide range of intrinsic UV slopes should largely smear the correlation. To understand the root causes behind this result we turn to stellar population models. In Figure 8, we show model IRX–$\beta$ values for galaxies spanning a range of passive star formation histories (log sSFR $< -11$) and having various attenuations, but assuming a fixed dust attenuation curve ($\delta = -0.4$, $B = 1$). As expected, the points disperse widely, driven by a wide range in $\beta_0$. The points do not just shift along $\beta$ for older galaxies but also move up, because the IRX includes the increased contribution from the dust heating of older stars. Furthermore, the direction in which the points corresponding to shallower $\beta_0$ disperse is highly dependent on the stellar metallicity. For supersolar metallicity ($Z = 0.05$) the older galaxies even get bluer in the UV, perhaps because of the metal line blanketing of turnoff stars in the NUV. The great majority of passive galaxies in our sample have near-solar metallicity ($Z = 0.02$). For solar metallicity the direction of the spread due to the stellar population being older (red arrow) matches almost exactly the dust attenuation vector. This effectively means that the wide range of $\beta_0$ will not lead to an additional scatter. This fortuitous alignment will preserve the tight correlation between the IRX–$\beta$ point distribution and the slope of the dust attenuation curve.

It should be pointed out that for passive galaxies the relationship between $A_{FUV}$ and IRX becomes strongly dependent on the population age, because of the dust heating from old stars (Cortese et al. 2008), so the derivation of $A_{FUV}$ becomes uncertain from IRX alone, and it is better to base the
SFR corrections on methods that do not involve IR emission or use full SED fitting.

5. New IRX–β Parameterization

Informed by the results presented in the previous section, where the scatter in the IRX–β plane essentially vanishes by fixing the dust attenuation curve, in this section we introduce a new parameterization of IRX–β values, to serve two purposes: allowing the slope of the attenuation curve to be measured directly from IRX and β values and allowing the investigation of more subtle trends in the IRX–β scatter and, consequently, in the dust attenuation curve.

Looking at the upper panels of Figure 3, we see that different attenuation curve slopes select objects having a different tilt with respect to the Overzier et al. (2011) relation. A change in the tilt of an IRX–β relation, without a change in β_{min}, can be accomplished by scaling its exponent. Specifically, we scale the exponent of the Overzier et al. (2011) IRX–β relation (0.78β_{GLX} + 1.54 = 0.4A_{FUV}) by 1/η. Figure 9 shows a family of curves produced by different η parameters. Points above (steeper than) the Overzier et al. (2011) relation have η < 1. Most data points lie within the 0.4 < η < 1.6 range. Thus, we can describe the entire IRX–β distribution using one parameter that informs us how much each galaxy deviates from the fiducial IRX–β relation.

The value of parameter η of any IRX–β data point will be:

$$\eta = \frac{\log \left( \frac{\text{IRX}}{0.78\beta_{GLX} + 1.54} + 1 \right)}{0.70\beta_{C94} + 1.50}.$$  \hspace{1cm} (6)

where β_{GLX} featured in Overzier et al. (2011) was converted to β_{C94} using Equation (1).

Figure 10 shows the dependence of η on the different galaxy parameters discussed in Section 4. As expected, and as desired,
The strongest trend of the tilt $\eta$, with the least amount of scatter, is with respect to the dust attenuation curve $\delta$. The tight correlation means that the slope of the attenuation curve can be determined directly from IRX–$\beta$ using a simple linear relation:

$$\delta = 0.79 - 1.05 \eta,$$

where the coefficients were determined based on a robust bisector fit and without placing any restrictions on the UV bump amplitude. The scatter around the relation is 0.12, driven almost entirely by the effect of varying the UV bump amplitude on $\beta_{C94}$. The scatter is restricted to this value also because of the correlation between the slope and the UV bump amplitude (Kriek & Conroy 2013; Salim et al. 2018). We underscore the fact that the slope $\delta$ corresponds to intrinsic curves in an age-dependent application of the modified Calzetti curve. The slope of an effective attenuation curve will be $\delta_{\text{eff}} = \delta - 0.20$.

Figure 10 also allows us to investigate, in more detail than is possible from Figures 2–5, any subtle effects that different parameters may have on the locus and the scatter of data points in the IRX–$\beta$ plane. The advantage of the new parameterization...
compared to the parameterization using the perpendicular distance from a fiducial relation (Kong et al. 2004) is that the tilt directly informs us about the trends in the dust attenuation curve. The strong trend of $\eta$ versus $A_V$ was already discussed in the context of the optical opacity being a strong driver of the dust attenuation curve and will be discussed more in Section 7. There is a weaker trend of $\eta$ as a function of the sSFR as well as of the average stellar population age and the stellar mass. However, neither of these trends is primary. They go away entirely once $A_V$ is fixed, as shown in Figure 11, where the optical opacity is restricted to values $0.2 < A_V < 0.3$. Thus, the trend of $\eta$ with respect to the stellar mass is entirely the result of the well-known underlying trend between $M_*$ and $A_V$. A similar explanation holds for a relatively weak trend of $\eta$ with inclination (plot not shown), which also disappears when $A_V$ is accounted for.

We conclude that different global galaxy properties may in some cases correspond to somewhat different attenuation curves (albeit with quite large scatter), but what drives the variety of attenuation curves is fundamentally the differences in optical opacity, which itself depends on the amount of dust and dust geometry. This conclusion is further borne out by performing a linear regression of $\eta$ against other parameters and finding that only $A_V$ reduces the scatter substantially and independently of the other parameters.

6. Dust Correction Recipe and the Impact of Scatter on SFR Determination

The relatively large scatter in the IRX–$\beta$ relation may appear to bring into question its utility for deriving dust-corrected SFRs. To determine the impact of the scatter, we compare the SFRs and sSFRs that would have been derived using several popular IRX–$\beta$-related recipes and the accurate SFRs from the SED+LIR fitting. We focus on SF galaxies and specifically look at the Overzier et al. (2011) relation that we have used throughout the paper and two $A_{FUV}$–(FUV–NUV) relations: one from Salim et al. (2007; Equation (5)) and another from Hao et al. (2011). We find that these (s)SFRs have a random scatter between 0.14 and 0.18 dex with respect to the (s)SFRs from the SED+LIR fitting, with little or no zero-point offset and only a mild nonlinearity (tilt). We conclude that the use of a fixed but nevertheless appropriate IRX–$\beta$ or $A_{FUV}$–(FUV–NUV) relation does not render the derived SFRs useless, but just adds a random error of some 0.15 dex. This assessment is based on our sample, which is a mix of galaxies spanning a range of UV slopes $-2 \leq \beta \leq 1$. Beyond $z = 4$, the typical galaxies that one detects in deep surveys have only blue UV slopes, $\beta \leq -1$ (Overzier et al. 2008; Bouwens et al. 2009), which is the combined effect of lower UV luminosities and lower dust content for galaxies of fixed luminosity. The joint effect of this evolution is that derivations of the SFR will be less affected by the dispersion in the IRX–$\beta$. Restricting the above exercise to $\beta < -1.5$, the added uncertainty due to scatter becomes 0.12 dex.

Our results show that truly accurate SFR correction is only possible if the dust attenuation curve is known. If it is not, i.e., when IR data are not available, the IRX–$\beta$ or $A_{FUV}$–$\beta$ relation could potentially be expanded to include a dependence on some observable parameter(s) that can hopefully serve as a proxy for the attenuation curve. Of the various observable parameters that we have considered, the one with the strongest correlation with the dust attenuation curve is the stellar mass (Figure 10), because of its correlation with $A_V$, which in turn drives the slope of the curve. Including the stellar mass in the dust correction recipe, as suggested by Álvarez-Márquez et al. (2016), can make the correction somewhat more accurate. We perform a linear regression and find the following relation:

$$A_{FUV} = 1.117 \beta_{94} + 0.262 (\log M_\ast - 10) + 2.92.$$  (8)

The scatter about the relation is 0.39 mag, somewhat better than when the mass term is ignored (0.41 mag). The exact benefit will depend on the mass distribution of the sample. It should be pointed out that the $A_{FUV}$–$M_\ast$ relation (i.e., IRX–$M_\ast$) alone is considerably inferior to the $A_{FUV}$–$\beta$ relation, with 0.67 mag of scatter. Another possibility to refine the estimate of SFR dust correction is to try to use the nebular attenuation, e.g., the Balmer decrement, even though it is a rather rough proxy for the stellar continuum attenuation (see Figure 12 in Salim et al. 2018). Including the Balmer optical depth (based on SDSS spectroscopy) provides a somewhat tighter correlation than including the stellar mass:

$$A_{FUV} = 1.006 \beta_{94} + 1.111 \tau_{H\alpha} + 2.47,$$  (9)
where $\tau_{\text{Bal}}$ is the Balmer optical depth ($\tau_{\text{Bal}} = \ln(\text{BD}/2.86)$) and the scatter around the relation is 0.36 mag, a 20% reduction in variance with respect to a relation that depends on $\beta$ alone. As in the case of the stellar mass, the Balmer optical depth alone is only poorly correlated with $\beta_{\text{SF}}$, with a scatter of 0.59 mag. A relation that includes both the stellar mass and the Balmer optical depth (in addition to $\beta$) has almost no additional benefit because of the mutual correlations.

The above recipes should be largely redshift-independent out to $z \sim 3$, given that there does not appear to be much evolution in the average IRX−$\beta$ relation out to that redshift (Álvarez-Márquez et al. 2016), assuming an unbiased sample selection. If SFRs are being determined from the SED fitting, which is preferable to the above recipes because it takes into account all of the available information, the diversity of attenuation curves can be taken into account by applying in the SED fitting code the mass-dependent attenuation curves provided in Salim et al. (2018).

7. Discussion

7.1. Do Normal Galaxies Follow a Different IRX−$\beta$ Relation from Starbursts?

Kong et al. (2004) originally suggested that starbursts and normal star-formers follow different IRX−$\beta$ relations, based both on observations and on IRX−$\beta$ modeling. Empirically, they showed that normal SF galaxies tend to be to the right of starbursts (redder UV color at a fixed IRX) and that the offset may correlate with the age-sensitive D4000 index. We do not find any such trend, which, in the context of our results, means that the two populations have on average similar attenuation curves, as was also shown directly in Salim et al. (2018).

In Kong et al. (2004), UV observations of starbursts come entirely from the IUE sample without aperture corrections, whereas their SF sample consists of IUE observations that have been aperture-corrected or of observations from UV facilities with larger apertures. Discrepant UV measurements could systematically offset the IRX value because the IR luminosity in all cases comes from integrated IRAS measurements. However, the possibility that the age may lead to trends in IRX−$\beta$ has additionally been supported by Kong et al.’s (2004) modeling, showing that the offset from the starburst relation is correlated with the birthrate parameter (akin to the sSFR; see Section 4.1). In light of the result from the current study, that it is the attenuation curve that ultimately matters, it could be that the trend with the birthrate parameter is a consequence of the assumed attenuation model in Kong et al. (2004), the two-component young/old-population model of Charlot & Fall (2000), where the attenuation slope is strongly dependent on the population age. Dependence on age is strong in Charlot & Fall (2000) type models because the underlying extinction curve is fixed. Once it is allowed to vary, as is likely the case in reality, age becomes a minor factor (Popping et al. 2017). Indeed, like the current study, many other studies that tried to find the dependence on the birthrate parameter or other age indicator did not meet with success (e.g., Burgarella et al. 2005; Seibert et al. 2005; Johnson et al. 2007; Panuzzo et al. 2007).

Despite not finding dependence on the birthrate parameter within their sample, Panuzzo et al. (2007) show a large offset between their entire sample (with UV measurements from GALEX) and the Meurer et al. (1999) starburst relation derived from IUE-observed starbursts. A similar offset between normal star-formers and the line describing starbursts has been presented in many other studies (Buat et al. 2005; Seibert et al. 2005; Gil de Paz et al. 2007; Takeuchi et al. 2010). At face value these results indicate that starbursts are somehow different, despite the lack of a trend involving the birthrate parameter (the value of which should be much higher in starbursts than in normal galaxies). The resolution to this issue has been found by Overzier et al. (2011) and Takeuchi et al. (2012) (and confirmed later by Casey et al. 2014), who have remeasured the UV fluxes of the original IUE starburst sample but now using GALEX images and have found that the total FUV (and NUV) flux is $2-3 \times$ greater than what has been measured in the small aperture of IUE. The flux loss makes IRX lower, shifting the starburst relation upward. The possibility of a systematic aperture bias was already suggested by Cortese et al. (2006), Gil de Paz et al. (2007), and Boissier et al. (2007). The re-derived starburst relations of Overzier et al. (2011) and Takeuchi et al. (2012) are shifted downward with respect to the IUE-based relations (IRX decreases because $L_{\text{FUV}}$ increases) and essentially eliminate the offset between starbursting and normal SF galaxies (e.g., gray squares compared to cyan triangles in the left panel of Figure 3 of Overzier et al. 2011). The IUE flux loss does not affect much the measurement of the UV slope or the UV color. According to Takeuchi et al. (2012), the change in $\beta$ measured in a small aperture versus a large aperture is $\sim 0.1$. In summary, measuring starbursts and normal SF galaxies in a consistent way removes the offset, which we confirm here (Figure 2, middle row). The use of relations based on IUE measurements, primarily the Meurer et al. (1999) and Kong et al. (2004) relations, with modern UV measurements should be avoided.

Is it nevertheless possible that just the central starbursts follow a different relation from the one based on integrated UV measurements? To answer this question one would have to measure the IR luminosity in the same small aperture as the UV flux, which IRAS could not do. This was made possible to some extent by Takeuchi et al. (2012), using the AKARI IR data. The results (their Figures 10 and 11) demonstrate that there is not much difference in the IRX−$\beta$ locus of the central starbursts and the integrated measurements of the starbursts, thus preserving the similarity of starbursts and normal galaxies in terms of their IRX−$\beta$ and, consequently, of their attenuation curves.

7.2. Dust Attenuation Curve as the Driver of the IRX−$\beta$ Scatter, which Itself Depends on Other Factors

The result that the scatter in the IRX−$\beta$ relation is driven entirely by the diversity of attenuation curves may seem at odds with numerous studies that have discussed or have identified other factors or a combination of factors that may or may not include the attenuation curve. This difference is only apparent. Our analysis shows that those “other” factors may have their effect on the IRX−$\beta$ relation, but only fundamentally through their effect on the attenuation curve. Therefore, the IRX−$\beta$ scatter is simply a manifestation of the differences in attenuation curves, facilitated by the fact that the intrinsic UV slopes ($\beta_0$) of SF galaxies span a small range, much smaller than the range of observed UV slopes (upper left panel of Figures 4 and 6). The narrow range of intrinsic UV slopes is expected in relatively continuous star formation histories (Leitherer et al. 1999; Calzetti 2001) that characterize integrated galaxy light. Indeed, we find that the models predict
that the range of $\beta_0$ remains narrow even if there is a strong, quickly decaying recent burst, as long as it lies on top of a non-negligible continuous SFR, which, in the local universe and for the integrated light of galaxies, is always present. We have redone the entire analysis with an expanded model grid that includes young, quickly decaying bursts, and the results remain unchanged: the scatter in the IRX–$\beta$ plane vanishes once the attenuation curve is fixed, because the range of $\beta_0$ stays narrow.

Our results may not hold for individual SF regions within galaxies (e.g., Gordon et al. 2004; Calzetti et al. 2005; Thilker et al. 2007; Boquien et al. 2009, 2012; Muñoz-Mateos et al. 2009), where the star formation histories may be more similar to an instantaneous burst that plummets to zero SFR. How similar the star formation history of an SF region may be to an instantaneous burst probably also depends on how small the measured region is. In cases where the star formation ceases completely after a brief burst, the effects of aging will lead to a significant reddening of both the intrinsic UV slopes (Leitherer et al. 1999; Calzetti 2001) and the UV–optical colors. Furthermore, the effects of dust–star geometry may be different for SF regions than when considering entire galaxies, complicating the interpretation.

Returning to the integrated light of galaxies, we illustrate the ultimate role of the attenuation curves by the following example. Several studies have pointed out the principal role of dust grain distribution (i.e., the dust type) in driving the IRX–$\beta$ scatter (e.g., Panuzzo et al. 2007; Popping et al. 2017; Safarzadeh et al. 2017). The attenuation curve is the end result of the intrinsic extinction curve, which depends on the dust properties (Weingartner & Draine 2001), and of the relative distribution of dust and stars of one or multiple populations (the geometry). We do not know much about the extinction curves (dust types) of galaxies other than the ones where we can probe the line of sight to individual reddened stars (i.e., the MW, LMC, and SMC), and even in these galaxies there is much variation along different lines of sight. Furthermore, even a fixed extinction curve will result in very different attenuation curves depending on the dust–star geometry (e.g., Panuzzo et al. 2007; Popping et al. 2017; Narayanan et al. 2018).

However, the point we wish to make is that how the resulting attenuation curve arose (different dust type or geometry) does not change the fact that there is a very close connection between the resulting attenuation curve and the IRX–$\beta$ locus. Conceptually speaking, the role of the geometry and the dust types is the questions that pertain directly to the attenuation curve and only by extension to IRX–$\beta$. The question of the diversity of attenuation curves is more fundamental than its manifestation in IRX–$\beta$, both because the former is more general, as it pertains to a broader wavelength range, and because in the UV region the effect of changing the attenuation curve slope and changing the UV bump strength will be somewhat degenerate (see also Mao et al. 2014). Thus it is preferable to investigate the questions relating to the diversity of attenuation curves directly, rather than via IRX–$\beta$, which should primarily be used as a tool to estimate FUV dust correction.

What can we say about the drivers of the variation in attenuation curves that manifests as IRX–$\beta$ scatter? Of the parameters that we study here, it is the optical opacity ($A_V$) that matters the most. Other, weaker trends (with age, sSFR, or stellar mass) vanish once $A_V$ is fixed, demonstrating that these trends are not primary but operate via their correlation with $A_V$.

That the optical opacity is strongly related to the dust attenuation slope has been shown using the GSWL-M2 data set in Salim et al. (2018) and has also been obtained as a result in radiative transfer models (Witt & Gordon 2000; Pierini et al. 2004; Chevallard et al. 2013; Seon & Draine 2016; Narayanan et al. 2018). It appears to be the consequence of the changing contributions of scattering (which is strongly wavelength-dependent) and absorption (which is not), the former being dominant in low-opacity galaxies. The relationship between the dust attenuation curve and $A_V$ does have an intrinsic scatter, given that at the minimum there must be galaxy-to-galaxy differences in dust type. It appears that for a given dust mass the geometry, including the turbulence (Seon & Draine 2016) and the covering fraction of dust, just changes $A_V$ (Popping et al. 2017), so they again may not represent independent factors that determine the shape of the attenuation curve. Similarly, galaxy inclination may increase the observed $A_V$ from its intrinsic (face-on) value, but the resulting relationship between the observed $A_V$ and the attenuation curve will be the same as that for a face-on galaxy with that higher value as its intrinsic $A_V$ (Chevallard et al. 2013; Salim et al. 2018). In other words, the different ages and varying amounts of turbulence, inclination, etc., of galaxies affect the attenuation curve and IRX–$\beta$ scatter through $A_V$ and not independently of it.

7.3. IRX–$\beta$ Relation at Higher Redshifts

Most low-redshift studies that explore the role of the attenuation curve in driving the IRX–$\beta$ scatter consider it as one of the possible factors whose significance with respect to other factors needs to be established (e.g., Burgarella et al. 2005; Boquien et al. 2012; Mao et al. 2014). We started by following such an approach in this study, but after establishing that the IRX–$\beta$ scatter is simply a manifestation of the diversity of attenuation curves, we switched to considering what other factors affect both the IRX–$\beta$ relation and the attenuation curve. Interestingly, in many high-redshift studies the close connection between the attenuation law and IRX–$\beta$ relation is taken for granted, and the IRX–$\beta$ relation is then naturally considered as a tool to learn about the dust attenuation curve (Siana et al. 2009 as an early example of such an approach). For example, Salmon et al. (2016) present relatively narrow loci of model points in the IRX–$\beta$ plane corresponding to different attenuation and extinction curves. Different tracks clearly cover a wide range in the IRX–$\beta$ plane, in itself suggesting the dominant role of attenuation curves in driving the scatter. Indeed, the authors consider these tracks to be the “observational basis” for constraining the attenuation curves. Similar views are present in other high-redshift studies (e.g., Lo Faro et al. 2017; McLure et al. 2018; Reddy et al. 2018). Cullen et al. (2017) explicitly state that for a constant $\beta_0$ there exists a simple mapping between the effective attenuation curve and the $A_{\text{FUV}}$–$\beta$ relation.

When high-redshift studies have concerns regarding the close connection between the IRX–$\beta$ plot and the attenuation curve, they are primarily due to the possible uncertainty regarding the values of the intrinsic UV slopes of young galaxies (Buat et al. 2012), given that the form of the correspondence between the IRX–$\beta$ point distribution and the attenuation curves relies on knowing the intrinsic UV slope. Reddy et al. (2018) argue that the typical intrinsic UV slope at $z \sim 2$ is $\beta_0 = -2.62$, in line with the predictions of BPASS models (Stanway et al. 2016) but in contrast to what is assumed...
SMC extinction curves are treated as attenuation curves. The average galaxy (as an intrinsic attenuation curve in an age-dependent ways, treating each curve as an effective attenuation curve and dust module. We implemented the attenuation curves in two SED the location of the tracks by forcing the above curves in our relation with respect to the Calzetti curve. We have determined bump in the MW curve results in a different locus in the IRX − β relation. For this reason, the SMC track is sometimes shown to lie below our SMC track. The observed IRX − β values in the local universe span the range of these fiducial curves, in broad agreement with the analysis of attenuation curves in Salim et al. (2018). It is worth noting that the inferences from interpreting IRX − β in terms of canonical extinction curves are limited, given that we do not expect attenuation curves to look like the MW’s or SMC’s extinction curve, except by chance. Indeed, the results from Salim et al. (2018) suggest that attenuation curves that look like the MW (shallow strong bump) or SMC (steep, no bump) curve are not typical. In Salim et al. (2018) we showed that a typical curve of a low-redshift galaxy has a slope almost as steep as the SMC slope but also featuring a modest bump. Indeed, if we were to add a bump to the SMC curve (with strength B = 2.5), the SMC’s locus would shift toward the Overzier et al. (2011) relation and closer to the middle of the observed points. This shift due to the bump, albeit small, emphasizes the point that direct determination of an attenuation curve from multiband photometry that straddles the bump will be more powerful than deriving the attenuation curve from the IRX − β relation. The latter is subject to the degeneracy introduced by the presence of the UV bump, which affects even the β_{C94} slope designed to minimize the influence of the bump region.

The tracks shown in Figure 12 are calculated for our local sample. Any evolution toward bluer intrinsic UV slopes at higher redshifts will be reflected in the shift of these curves to the left, by Δβ_0, the level of which is currently uncertain but is probably no more than a few tenths. In such a case, the form of the correspondence between the IRX − β relation and the attenuation curves will mostly stay similar.

8. Summary

We summarize our findings as follows:

1. The general population of low-redshift galaxies exhibits a relatively large scatter in the IRX − β plane.
2. The scatter in the IRX − β diagram of SF galaxies is driven entirely by the diversity of dust attenuation curves (primarily by their slopes and to a lesser degree by the varying strength of their UV bumps).
3. Consequently, the question of the IRX − β scatter of SF galaxies becomes derivative of the question of the variations in the shapes of dust attenuation curves. The latter appears to primarily depend on the optical opacity (A_V; Seon & Draine 2016; Salim et al. 2018) and presumably on the intrinsic variations in dust type, i.e., the grain size distribution (Weingartner & Draine 2001).
4. The fundamental reason why the dust attenuation curve is the driver of the scatter in the IRX − β diagram is that SF galaxies (log sSFR > −10.5) have a relatively small range of intrinsic (dust-free) UV slopes (90% are within 0.1 of β = −2.24).
5. The position of an SF galaxy on the IRX − β diagram is the result only of the shape of the dust attenuation curve and the dust opacity, all other factors being indirect, i.e., affecting just these two.
6. Galaxies of different population ages or different sSFRs (whether absolute sSFRs, or relative to the main sequence) have, on average, very similar dust attenuation curves and, consequently, similar IRX − β distributions.
7. Similarly, the starbursting galaxies and normal SF galaxies exhibit no significant shift in average IRX − β relations and are both well described by the Overzier
et al. (2011) relation. The previously reported shift can be explained by the known, factor of 2–3 aperture loss of the FUV flux that affects the commonly used local starburst relations derived from IUE data.

8. Passive galaxies (log sSFR < −11) have much redder intrinsic UV slopes (−2 < β0 < 0) than SF galaxies, which are strongly dependent on the stellar metallicity. Nevertheless, the IRX–β scatter for passive galaxies of fixed dust attenuation curve slopes is not substantially increased with respect to that of the SF galaxies due to the fortuitous fact that for solar-like metallicities the star formation history vector and the attenuation vector are parallel. Therefore, the dust attenuation curve effectively remains the principal driver of the IRX–β scatter for passive galaxies.

9. As a consequence of the above points, the IRX–β diagram can be used as a direct tool to determine the slope of the attenuation curve for SF galaxies in the UV region (e.g., using Equation (7)). However, the UV slope β suffers from some degeneracy between the attenuation curve slope and UV bump strength, so it is preferable and more comprehensive to base attenuation curve determinations on the full SED fitting, especially one that includes the IR SED or IR luminosity as a constraint.

10. The placement of attenuation curve tracks on the IRX–β diagram will shift to the left for galaxies at high redshifts (1 < z < 5), to account for their bluer intrinsic UV slopes, by a value that is currently uncertain but may be as low as Δβ = −0.1 (a negligible change) or as high as −0.4 (a moderate change).

While many studies have explored the role of the attenuation curve in the IRX–β relation, our principal contribution is in showing that the two aspects, when considering entire galaxies, are fundamentally connected owing to the very small range of intrinsic UV slopes in SF galaxies. This result should help the field more efficiently focus on the more fundamental question of what shapes the dust attenuation curve, for which significant advances, both observational and theoretical, are being made.

To that end, the new IRX–β parameterization that we introduce in this paper, which can be used to directly estimate the slope of the attenuation curve, can also be useful.

We are grateful to Véronique Buat and the reviewer for their many helpful and thought-provoking comments. The construction of GSWLC was funded through NASA ADAP award NNX12AE06G. M.B. acknowledges support from FONDECYT regular grant 1170618. Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III website is located at http://www.sdss3.org/. The study is based on observations made with the NASA GALEX. GALEX is operated for NASA by the California Institute of Technology under NASA contract NAS5-98034. This publication makes use of data products from WISE, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by NASA.

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