DUST-INDUCED SYSTEMATIC ERRORS IN ULTRAVIOLET-DERIVED STAR FORMATION RATES

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ABSTRACT

Rest-frame far-ultraviolet (FUV) luminosities form the “backbone” of our understanding of star formation (SF) at all cosmic epochs. These luminosities are typically corrected for dust by assuming that the tight relationship between the UV spectral slopes (β) and the FUV attenuations (AFUV) of starburst galaxies applies to all star-forming galaxies. Data from seven independent UV experiments demonstrate that quiescent, “normal” star-forming galaxies deviate substantially from the starburst galaxy β-AFUV correlation in the sense that normal galaxies are redder than starbursts. Spatially resolved data for the Large Magellanic Cloud suggest that dust geometry and properties, coupled with a small contribution from older stellar populations, cause deviations from the starburst galaxy β-AFUV correlation. Folding in data for starbursts and ultraluminous infrared galaxies, it is clear that neither rest-frame UV/optical colors nor UV/Hα colors help significantly in constraining the UV attenuation. These results argue that the estimation of SF rates from rest-frame UV and optical data alone is subject to large (factors of at least a few) systematic uncertainties because of dust, which cannot be reliably corrected for using only UV/optical diagnostics.

Subject headings: dust, extinction — galaxies: general — galaxies: stellar content — ultraviolet: galaxies

1. INTRODUCTION

Understanding the star formation (SF) rates of galaxies at a variety of cosmic epochs is a topic of intense current interest (e.g., Yan et al. 1999; Blain et al. 1999; Haarsma et al. 2000). Many SF rates are derived from highly dust-sensitive rest-frame far-ultraviolet (FUV) luminosities (e.g., Madau et al. 1996; Steidel et al. 1999). In the local universe, Calzetti, Kinney, & Storchi-Bergmann (1994), Calzetti et al. (1995), and Meurer, Heckman, & Calzetti (1999) found a tight correlation between the ultraviolet (UV) spectral slope β and the attenuation A in the FUV (AFUV) for a sample of inhomogeneously selected starburst galaxies. This correlation’s low scatter requires a constant intrinsic value of β ~ −2.5 for young stellar populations (e.g., Leitherer et al. 1999), coupled with some regularities in the distribution and extinction properties of dust (e.g., Gordon, Calzetti, & Witt 1997). Assuming that this correlation holds for all galaxies at high redshift, this was used to correct the FUV flux for extinction in a statistical sense (see, e.g., Adelberger & Steidel 2000, and references therein).

However, recent work has called the universality of the β-AFUV correlation into question. Radiative transfer models predict a large scatter between β and AFUV (Witt & Gordon 2000). Furthermore, both Large Magellanic Cloud (LMC) H regions (Bell et al. 2002) and ultraluminous infrared galaxies (ULIRGs; Goldader et al. 2002) do not obey the starburst correlation. Tantalizingly, there are indications that “normal,” quiescent star-forming galaxies have less UV extinction than that predicted by the Calzetti et al. (1994) relation (Buat et al. 2002). Taken together, these issues raise serious questions about the applicability of SF rates derived from rest-frame UV light alone for nonstarbursting galaxies.

1 Defined by, F(f) × λ4, where F(f) is the flux per unit wavelength (λ).
2 Attenuation differs from extinction in that attenuation describes the amount of light lost because of dust at a given wavelength in systems with complex star/dust geometries in which many classic methods for determining extinction, such as color excesses, may not apply.

In this paper, I investigate the relationship between β and AFUV for quiescent, “normal” star-forming galaxies for the first time (to date, this correlation has been examined directly for starbursts, ULIRGs, and H regions only). In § 2, I demonstrate that normal galaxies deviate substantially from the starburst galaxy β-AFUV correlation. In § 3, I use spatially resolved data for the LMC to investigate the origin of this effect. In § 4, I explore potential alternatives to β and briefly discuss the conclusions in § 5. In the following, all UV and optical data are corrected for galactic foreground reddening following Schlegel, Finkbeiner, & Davis (1998), unless stated otherwise.

2. THE β-AFUV CORRELATION FOR NORMAL GALAXIES

Sections 2.1 and 2.2 describe the detailed derivation and uncertainties of β and AFUV estimates for normal galaxies; casual readers can skip ahead to § 2.3.

2.1. Calculation of β and AFUV

Because most of the well-studied quiescent, normal star-forming galaxies greatly exceed the 10″ × 20″ aperture size of the IUE, values of β are calculated from multi-passband—integrated and large-aperture photometry, taking into account galactic foreground extinction. The UV spectral slope β is estimated at between 1500 and 2500 Å for most galaxies (except for the LMC, where it is estimated at between 1500 and 1900 Å). Exploration of both models (Leitherer et al. 1999) and of the IUE spectra of the central parts of seven normal galaxies (Kinney et al. 1993) indicates that there are no significant offsets between values of β determined between 1500 and 2500 Å for normal galaxies and those determined in other ways (e.g., between 1200 and 1900 Å; Meurer et al. 1999; Adelberger & Steidel 2000).

The FUV attenuation, AFUV, is estimated by balancing the total, integrated FUV light (at wavelengths between 1474 and 1650 Å, depending on experiment) against the far-
infrared (FIR) luminosity. I use the flux ratio method of Gordon et al. (2000) to estimate $A_{\text{FUV}}$, which accounts for different dust geometries and stellar populations (assuming a young, $\sim 100$ Myr constant SF rate population for starbursts and an older, $\sim 10$ Gyr constant SF rate population for normal galaxies). A simple estimate that assumes that young FUV-emitting stars completely dominate the heating, $A_{\text{simple}} = -2.5 \log_{10} \frac{L_{\text{FUV}}}{(L_{\text{FUV}} + L_{\text{FIR}})}$, where $L_{\text{FUV}} = \nu f_{\nu}$ is evaluated near 1500 Å and $L_{\text{FIR}}$ is an estimate of the total FIR luminosity, overestimates flux ratio method-derived attenuations $A_{\text{FUV}}$ by $\lesssim 10\%$ (because $A_{\text{simple}}$ does not account for the fact that some FIR is reprocessed light from older stars). If, for normal galaxies, reprocessed light from older stars dominates the FIR luminosity, their $A_{\text{FUV}}$ should be interpreted as upper limits (strengthening these conclusions). The total FIR luminosity for all of the sample galaxies is estimated at between 8 and 1000 $\mu$m by extrapolating the observed 8–100 $\mu$m flux to longer wavelengths using a modified blackbody with an emissivity $\propto \lambda^{-1}$. Comparison of this algorithm for estimating $L_{\text{FIR}}$ with 150–205 $\mu$m Infrared Space Observatory measurements suggests that the $L_{\text{FIR}}$ are accurate for early-type spirals but may underestimate the true $L_{\text{FIR}}$ for starbursts and late-type spirals by $\sim 25\%$ (Calzetti et al. 2000; Popescu et al. 2002). Including the $L_{\text{FIR}}$ from cold dust will (somewhat counterintuitively) move the starbursts by $\sim 0.2$ mag to higher $A_{\text{FUV}}$ but will affect the normal galaxies less (again, strengthening these conclusions). These $A_{\text{FUV}}$ are directly comparable to the “IR excess” of, e.g., Meurer et al. (1999) and the UV extinctions estimated at 2000 Å by, e.g., Buat & Xu (1996) and Buat et al. (2002).

2.2. The Data

Accurate $A_1(\lambda_{\text{eff}} \sim 2488 \text{ Å})$–$B_1(\lambda_{\text{eff}} \sim 1521 \text{ Å})$ colors for seven galaxies with the Ultraviolet Imaging Telescope (UIT; Stecher et al. 1997) data were derived using circular apertures with sizes designed to optimize S/N while encompassing the majority of the galaxian light (Table 1). These colors were corrected to the effective wavebands following the method of Bell et al. (2002), and $\beta$ is then derived using the color-corrected and galactic foreground extinction-corrected $A_1$–$B_1$ assuming $\beta = 0.4(A_1 - B_1)/\log_{10}(\lambda_{\text{eff}}/\lambda_{\text{eff}, A_1})$. To derive $A_{\text{FUV}}$, FUV $B_1$ magnitudes and total FIR fluxes were taken from Bell & Kennicutt (2001), except for M33 (NGC 598); I have measured $B_1 = 5.6 \pm 0.1$ and adopted FIR fluxes from Rice et al. (1988). M81 $A_1$–$B_1$ colors are for the star-forming outer regions only. The colors and magnitudes are consistent to $\lesssim 0.2$ mag with data from other UV satellites (Bell & Kennicutt 2001) and with different analyses of these data (e.g., Marcum et al. 2001).

Galaxies with homogenized 10' aperture Orbiting Astronomical Observatory (OAO) flux measurements at 1550, 1910, and 2460 Å, or homogenized 2/5 square aperture Astronomical Netherlands Satellite (ANS) flux measurements at three or more of 1550, 1800, 2200, and 2500 Å, were taken from the compilation of Rifatto, Longo, & Capaccioli (1995a). Eight (12) galaxies with an observed OAO (ANS) magnitude at 1550 Å of $\lesssim 9.7$ (12.2) were selected to ensure reasonable S/N. Five galaxies are common to both samples. Values of $\beta$ are calculated using a simple linear fit to the foreground extinction-corrected UV magnitudes. The OAO- and ANS-derived $\beta$ values are consistent ($\Delta \beta \lesssim 0.5$) for the five galaxies in common, suggesting errors $\lesssim 0.35$ (as some of the discrepancies could be due to aperture mismatch). Values of $A_{\text{FUV}}$ are calculated using “total” UV magnitudes from Rifatto, Longo, & Capaccioli (1995b) and IRAS fluxes from (in order of preference) Rice et al. (1988), Soifer et al. (1989), or Moshir et al. (1990). Comparison with UIT data showed that “total” UV magnitudes from Rifatto et al. (1995b) derived from large-aperture UV data are good to $\lesssim 0.2$ mag (Bell & Kennicutt 2001).

The properties of the LMC are estimated using the images presented by Bell et al. (2002). Large-aperture photometry of the LMC yields $\beta = -0.2 \pm 0.3$ and $A_{\text{FUV}} = 0.54 \pm 0.21$, whereas totaling the areas detected at greater than 5 $\sigma$ yields $\beta = -0.7 \pm 0.3$ and $A_{\text{FUV}} = 0.48 \pm 0.13$. These are quite consistent with $\beta = -0.7$ from the D2B-Aura satellite (Maucherat-Joubert, Deharveng, & Rocca-Volmerange 1980). A $S'$ aperture around 30 Dor gives $\beta = -1.3 \pm 0.3$ and $A_{\text{FUV}} = 1.4 \pm 0.2$ (consistent with TD1 and ANS values for the area of $\beta = -1.1$; Maucherat-Joubert et al. 1980).

As useful comparison samples, I include (1) 19 starbursts with UV spectra from the IUE in $10^9 \times 20^9$ apertures, with diameters smaller than 1.5 to minimize aperture effects (Calzetti et al. 1994, 1995; Meurer et al. 1999) and (2) seven ULIRGs with total UV fluxes and colors from Hubble Space Telescope STIS data (Goldader et al. 2002).

2.3. Results

Figure 1 demonstrates that normal galaxies (open symbols) have substantially redder UV spectral slopes, by $\Delta \beta \sim 1$, than their starburst counterparts (filled diamonds) at a given $A_{\text{FUV}}$ (derived using FUV/FIR energy balance). Furthermore, normal galaxies exhibit substantially larger scatter than the starbursts.

This result is supported by detailed examination of the distribution of galaxies in the $\beta$–$A_{\text{FUV}}$ plane. Focusing on the UIT galaxies (triangles), three starbursting galaxies (M77, NGC 1317, and NGC 2993) lie on the Calzetti et al. (1994) relation, whereas the normal galaxies, M33, M74, M81, and UGC 6697, do not. The LMC lies redward of the starburst line, whereas 30 Dor, long held as an example of a “mini-starburst,” lies on the Calzetti et al. (1994) relation. All of the OAO and ANS galaxies (stars and circles, respectively) within $\Delta \beta \sim 0.3$ of the starburst relation are intensely forming stars (NGC 4631, M94, and NGC 5248; NGC 4490 is also peculiar). In contrast, OAO and ANS galaxies lying redward of the starbursting relation are typically forming stars somewhat less intensely. It is not, at this time, clear why NGC 4605 and NGC 7331 lie blueward of the Calzetti

### Table 1: Newly Derived UIT $A_1$–$B_1$ Colors

| Galaxy Name   | $A_1$–$B_1$ |
|---------------|------------|
| M33 (NGC 598) | 0.70 ± 0.05 |
| M74 (NGC 628) | 0.33 ± 0.04 |
| M77 (NGC 1068)| 0.37 ± 0.07 |
| NGC 1317      | 0.39 ± 0.02 |
| NGC 2993      | 0.67 ± 0.05 |
| M81 (NGC 3031)| 0.22 ± 0.05 |
| UGC 6697      | 0.4 ± 0.1   |

Note: Colors have not been corrected for foreground galactic extinction.
et al. (1994) relation. IUE data also suggest a $\beta$ offset between normal and starburst galaxies: Kinney et al. (1993) show that spiral galaxies are $\Delta\beta \sim 0.5(1)$ redder than starburst (blue compact and H II) galaxies, even in the $10'' \times 20''$ aperture of the IUE.

The ubiquity of the offset between starbursting and normal galaxies as measured by seven different experiments (UIT, OAO, ANS, and IUE for normal galaxies; a sounding rocket, D2B-Aura, and TD1 for the LMC) argues strongly that the offset is real and is not simply instrumental in origin. This conclusion agrees with Buat et al. (2002), who found that applying the Calzetti et al. (1994) extinction law to normal galaxies overestimated the UV extinction, using an independent sample of galaxies without UV spectral slopes.

3. EXPLORING THE ORIGINS OF THE $\beta$-AFUV CORRELATION

It is reasonable to hypothesize that stellar population and/or dust effects contribute to the difference in behavior between normal and starburst galaxies on the $\beta$-AFUV plane. Stellar population models show that older star-forming stellar populations are somewhat redder ($\Delta\beta \lesssim 0.5$) than younger star-forming populations (e.g., Leitherer et al. 1999). Alternatively, radiative transfer models can easily generate relatively large changes in $\beta$ for only modest AFUV by appealing to different star/dust geometries and/or extinction curves (Gordon et al. 2000; Bell et al. 2002).

In order to test why normal galaxies have redder $\beta$-values than starbursts, independent constraints on a galaxy’s star formation history are required (to allow splitting of age and dust effects). Independent age constraints are available for stellar clusters and associations in the LMC (in the form of $U-B$ optical color). Using $\sim 1''$ resolution multiwavelength images (Bell et al. 2002), I have constructed $5'' (67$ pc) aperture values of $\beta$ and AFUV for a sample of stellar clusters and associations from Bica et al. (1996). I choose 198 clusters and associations with $U < 12$ to maximize the chances that the clusters dominate the aperture FUV flux. Symbol sizes in Figure 2 reflect a cluster’s UV attenuation, as estimated from FUV/FIR. The colors of a single-burst stellar population and dust screen reddening vectors are also shown.

It is clear that only young, unattenuated clusters have “blue” $\beta \sim -2$ values. Redder, $-1 \lesssim \beta \lesssim 1$ clusters tend to be either relatively young but attenuated (the clusters with $U-B \sim -0.8$, but redder $\beta$ values) or older and dust-free (the clusters with $U-B \sim 0$).

The balance between dust and old stellar population effects can be constrained by considering the fraction of the total $U < 12$ LMC cluster UV luminosity that each population represents. The young, unattenuated clusters (defined as having $U-B \lesssim -0.5$ and $\beta \lesssim -1.2$, one-third of the clusters by number) represent 67% of the summed $U < 12$ LMC cluster FUV 1500 Å luminosity. The younger, attenuated clusters (defined as having $U-B \lesssim -0.5$ and $\beta \sim -1.2$, half of the clusters by number) represent 27% of the FUV luminosity. The older, unattenuated clusters (defined as having $U-B > -0.5$, one-sixth of the clusters by number) have only 6% of the FUV luminosity. Noting that the clusters are selected as having $U < 12$ (and therefore are being selected as being reasonably young) and possible differences between the cluster and field SF histories, this result tentatively ascribes much of the observed “redness” of the LMC to dust effects: older stellar populations tend to be UV-faint and do not affect the global $\beta$ estimate as significantly. This
interpretation is consistent with the detailed results of stellar population modeling. Leitherer et al. (1999) show that the maximum possible offset $\Delta \beta$ between young and older star-forming stellar populations is $\sim -0.5$, as, to first order, stars that are bright enough to affect the FUV luminosity of a galaxy with even a small amount of ongoing SF have very blue $\beta$-values.

One intriguing feature of Figure 2 is the population of seemingly unattenuated clusters with $-1 \leq \beta \leq 1$ but blue $U-B$ colors. While the LMC sounding rocket images are photographic and relatively old (Smith, Cornett, & Hill 1987), extensive checks against UIT, IUE, D2B-Aura, TD1, and ANS data have not indicated any significant problems with the calibration and $\beta$-values of the LMC data (see also Bell et al. 2002). This argues that most of these clusters do, in reality, have red $\beta$ but blue $U-B$ color with relatively little associated FIR. Behavior of this kind can be generated by a large dust shell or extended screen geometry. The UV light is attenuated and reddened by the dust shell or screen, but the dust heating is spread out over a much larger area of the sky than that subtended by the UV light from the cluster, and thus the cluster appears to have high FUV/FIR.

This can be explored more quantitatively by inspection of a simple model. Assume that highly extincted clusters ($\sim 1.5$ mag, implying FIR/FUV = 3) are attenuated by a homogeneous shell of dust with a diameter of $5'$, or 67 pc, on the sky (this is a conservative assumption, as the shells could be smaller). Assume that a 0.3 mag attenuated cluster has a similar shell, only larger (so that the FIR/FUV$_{\text{total}} = 3$, but FIR/FUV in the $5'$ aperture is $\frac{1}{4}$). Assuming conservatively that the surface brightness is constant over the face of this dust shell, the area of the dust shell in the 0.3 mag extinction case is 9 times larger than in the 1.5 mag extinction case, so the radius is a factor of 3 larger, at 100 pc. This shell radius is comparable to the H I thickness of the LMC and is not an unreasonable separation between the young, FUV-bright stars and the dust that attenuates them (Elmegreen, Kim, & Staveley-Smith 2001).

While the picture is a little complex, Figure 2 suggests that the LMC has a relatively red $\beta \sim -0.5$ primarily because of dust effects (from radiative transfer and/or extinction curve variations), with a modest contribution from the light of older stellar populations. This lends weight to an interpretation of the redder $\beta$-values of normal galaxies mostly in terms of dust, with a small contribution from SF histories.

4. EXPLORING ALTERNATIVES TO $\beta$

Figure 1 demonstrates that it is difficult to estimate UV attenuations on the basis of UV colors alone. For example, a galaxy with $\beta \sim -1$ could have zero attenuation (if it is a relatively quiescent galaxy), or many magnitudes of attenuation (if it is a ULIRG). In Figure 3, I examine two possible alternatives to $\beta$ that use only rest-frame UV and optical data (and are therefore more easily accessible to researchers wishing to determine SF rates at high redshift).

It is conceivable that FUV $- B$, because of its longer wavelength range, may be more robust to dust radiative transfer effects than the UV spectral slope $\beta$ (but would suffer more acutely from the effects of older stellar populations). Indeed, K. L. Adelberger (2002, private communication) reports that FUV $- B$ tends to be a more robust dust indicator than $\beta$ for high-redshift samples of galaxies. In panel $a$ of Figure 3, I show 1550 Å FUV $- B$ colors against $A_{FUV}$ for the UIT, OAO, ANS, ULIRG, and starburst galaxy samples. Total FUV and $B$ magnitudes were used for the UIT, OAO, ANS, and ULIRG samples, whereas the $B$ magnitudes of the starburst galaxies are roughly corrected to the $IUE$ aperture following Calzetti et al. (1995). It is possible that FUV $- B$ is a slightly more robust indicator than $\beta$, in terms of estimating $A_{FUV}$. However, the scatter is enormous: at a given FUV $- B$ color, the range in $A_{FUV}$ is 3–5 mag, or between 1 and 2 orders of magnitude.

Buat et al. (2002) suggest another potential extinction indicator: H$_{\alpha}$/FUV. This indicator has the virtue of being almost independent of SF history (however, see Sullivan et al. 2000); however, it does depend on the relative distribution of dust around H I regions, compared to the dust around OB associations (see, e.g., Bell et al. 2002). In panel $b$ of Figure 3, I show integrated H$_{\alpha}$/FUV for a sample of normal galaxies from Bell & Kennicutt (2001, open circles), H$_{\alpha}$/FUV for starburst galaxies within the $IUE$ aperture (Calzetti et al. 1994) and 3.5' aperture values for ULIRGs (Goldader et al. 2002; Wu et al. 1998) are also shown. In agreement with Buat et al. (2002), I find that there is a scattered correlation between H$_{\alpha}$/FUV and $A_{FUV}$; however, the scatter is a challenge to its usefulness. For example, at H$_{\alpha}$/FUV $\sim 10$ Å$^{-1}$, 0 mag $\leq A_{FUV}$ $\leq$ 3 mag, and at H$_{\alpha}$/FUV $\sim 100$ Å$^{-1}$, $A_{FUV}$ $\geq$ 3 mag.

Importantly, at a given $A_{FUV}$, starbursts and ULIRGs tend to have bluer $\beta$ values, bluer FUV $- B$ colors, and lower H$_{\alpha}$/FUV than normal galaxies. Thus, SF rates derived from rest-frame UV data, even analyzed in conjunction with rest-frame optical data, suffer from systematic uncertainties of at least factors of a few.

Because of the sample’s inhomogeneous selection, it is difficult to reproduce the UV-bright selection imposed on
distant samples of star-forming galaxies and thus to make
detailed predictions about the degree of systematic error
introduced in the determination of SF rates at high redshift.
However, because the physical nature of distant star-
forming galaxies is still poorly understood, these results
argue that UV-derived SF rates of high-redshift galaxies
should, at best, be viewed with caution.

5. CONCLUSIONS
I have used data from seven independent UV experiments
to show that quiescent, normal star-forming galaxies have
substantially redder UV spectral slopes $\beta$ at a given $A_{FUV}$
than starbursting galaxies. Using spatially resolved data for
the LMC, I suggest that dust geometry and properties,
coupled with a small contribution from older stellar popula-
tions, contribute to deviations from the starburst galaxy
$\beta$-$A_{FUV}$ correlation. Neither rest-frame UV-optical colors
nor UV/H $\lambda_{C11}$ significantly help in constraining the UV
attenuation. These results argue that the estimation of SF
rates from rest-frame UV and optical data alone is subject
to large (factors of at least a few) systematic uncertainties
because of dust, which cannot be reliably corrected for using
only UV/optical diagnostics.

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