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

Eric F. Bell

Steward Observatory, Tucson AZ, USA.

RESUMEN

Las observaciones en el SLR de las luminosidades en el ultravioleta lejano (UVL) son el eje de nuestra comprensión de la formación estelar en todas las épocas cósmicas. Las luminosidades en el UVL típicamente se corrigen por polvo suponiendo que los indicadores de extinción que han sido calibrados para galaxias locales con brotes de formación estelar son válidos para cualquier galaxia. Presento evidencia de que las galaxias con formación estelar 'normal' tienen colores UV/visible sistemáticamente más rojos que las galaxias con brotes, para una extinción en el UVL dada. Esto se atribuye a diferencias en la geometría estrellas/polvo, junto con una contribución pequeña de la población vieja. Incorporando datos para galaxias con brotes y galaxias ultraluminosas infrarrojas, concluyo que las tasas de formación estelar que se infieren de las observaciones UV en el SLR y visible están sujetas a grandes incertidumbres sistemáticas a causa del polvo, que no pueden ser corregidas usando sólo indicadores UV/visible.

ABSTRACT

Rest-frame far-ultraviolet (FUV) luminosities form the 'backbone' of our understanding of star formation at all cosmic epochs. FUV luminosities are typically corrected for dust by assuming that extinction indicators which have been calibrated for local starbursting galaxies apply to all star-forming galaxies. I present evidence that 'normal' star-forming galaxies have systematically redder UV/optical colors than starbursting galaxies at a given FUV extinction. This is attributed to differences in star/dust geometry, coupled with a small contribution from older stellar populations. Folding in data for starbursts and ultra-luminous infrared galaxies, I conclude that SF rates from rest-frame UV and optical data alone are 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.

Key Words: **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 et al. (1994,1995) and Meurer et al. (1999) found a tight correlation between ultraviolet (UV) spectral slope β[1] and the attenuation[2] in the FUV ($A_{\rm FUV}$), for a sample of inhomogeneously-selected starburst galaxies. This correlation's low scatter requires a constant intrinsic value of $\beta \sim -2.5$ 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 et al. 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–$A_{\rm FUV}$ correlation into question. Radiative transfer models predict a large scatter between β and $A_{\rm FUV}$ (Witt & Gordon 2000). Furthermore, both Large Magellanic Cloud (LMC) H II regions (Bell et al. 2002) and ultra-luminous infrared galaxies (ULIRGs; Goldader et al. 2002) do not obey the starburst correlation. Tantalizingly, there are indications that 'normal', quiescent star-forming galax-

[1]Defined by $F_\lambda \propto \lambda^\beta$, where F_λ 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 where many classic methods for determining extinction, such as color excesses, may not apply.

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ies have less UV extinction than predicted by the Calzetti et al. relation (Buat et al. 2002). Taken together, these issues raise serious questions about the applicability of rest-frame UV-derived SF rates for non-starbursting galaxies.

Here, I investigate the relationship between β and $A_{\rm FUV}$ for quiescent, 'normal' star-forming galaxies for the first time (to date, this correlation has been examined directly for starbursts, ULIRGs and H II regions only). For more details, see Bell (2002).

2. THE β–$A_{\rm FUV}$ CORRELATION FOR NORMAL GALAXIES

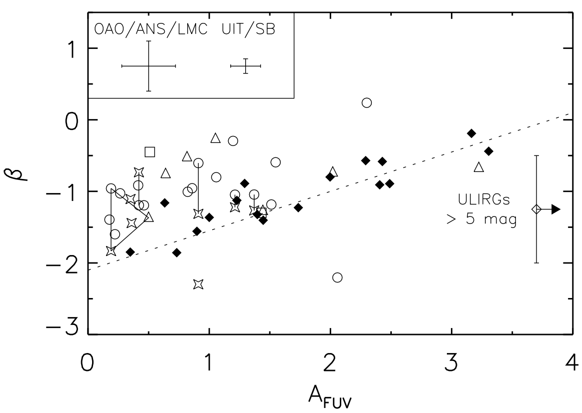

Fig. 1. UV spectral slope β against attenuation at $\sim$ 1500Å, $A_{\rm FUV}$. *UIT* galaxies are plotted as triangles, *OAO* galaxies as stars, *ANS* galaxies as circles, the LMC and 30 Dor are plotted as squares, and starbursts are plotted as filled diamonds. ULIRGs (open diamond) typically have $A_{\rm FUV} \gtrsim 5$ mag, and 'blue' β values (Goldader et al. 2002). The dotted line shows a rough 'by-eye' fit to the starbursts. Different measurements for the same galaxies are connected by solid lines.

In Fig. 1, I show the UV spectral slope β between 1500Å and 2500Å for normal galaxies (calculated using integrated and/or large-aperture photometry) against the FUV attenuation as open symbols. I calculate the FUV attenuation by balancing the FUV and FIR luminosity of my sample galaxies. Gordon et al. (2000) show that this is a robust indicator of FUV attenuation from a modelling perspective. Furthermore, in Bell (2002, in preparation) I argue, by comparing FIR+FUV vs. extinction-corrected Hα SF rates, that FUV/FIR reflects the real FUV attenuation with much better than a factor of two systematic and random error. I show β against $A_{\rm FUV}$ for starbursting galaxies (solid diamonds; Calzetti et al. 1994,1995) and ULIRGs (Goldader et al. 2002) for comparison. Clearly, normal galaxies have substantially redder UV spectral slopes, by $\Delta\beta \sim 1$, than their starburst counterparts at a given $A_{\rm FUV}$ (derived using FUV/FIR energy balance). This offset between starbursting and normal galaxies is seen by 7 different experiments (*UIT*, *OAO*, *ANS*, and *IUE* for normal galaxies; a sounding rocket, *D2B-Aura* and *TD1* for the LMC). Furthermore, normal galaxies exhibit substantially larger scatter than the starbursts. Interestingly, this large scatter is largely intrinsic. The galaxies which are closer to the starburst galaxy relationship tend to be the most vigorously star-forming members of the 'normal' galaxy sample, and the redder ones are more quiescent (but still star-forming).

3. EXPLORING THE ORIGINS OF THE β–$A_{\rm FUV}$ CORRELATION

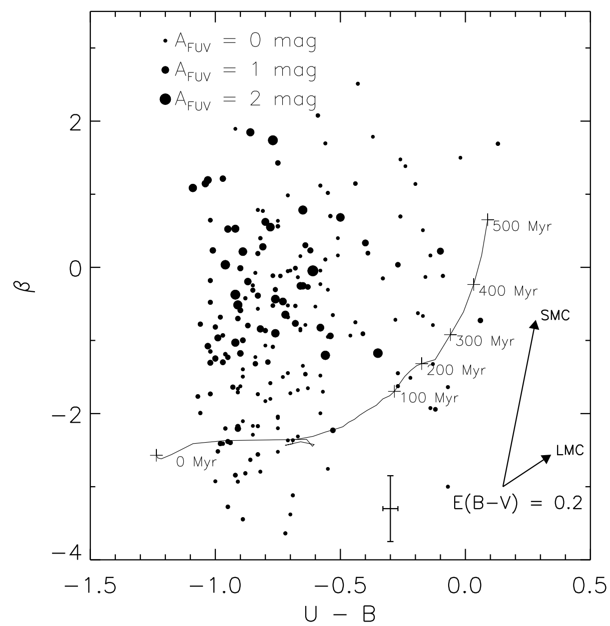

Fig. 2. UV spectral slope β against $U-B$ color (a reasonable age indicator) for a sample of 198 UV-bright stellar clusters and associations in the LMC. Symbols are coded by FUV attenuation: larger symbols depict more highly attenuated clusters. Overplotted are the PÉGASE stellar population model colors for a single burst with ages < 500 Myr (Fioc & Rocca-Volmerange, in preparation). The effect of dust reddening, assuming a SMC bar-type or LMC-type dust screen, is shown. The dust vectors are shown simply to give some intuition about the effects of dust: radiative transfer effects and/or extinction curve variations in the UV make the prediction of the detailed effects of dust on a plot of this type challenging.

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 β–$A_{\rm FUV}$ plane. Stellar population models show that older *star-forming* stellar populations

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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 β for only modest $A_{\rm FUV}$ by appealing to different star/dust geometries and/or extinction curves (e.g., Gordon et al. 2000; Bell et al. 2002).

In order to test why normal galaxies have redder β values than starbursts, independent constraints on a galaxy's SF 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). I construct matched aperture values of β and $A_{\rm FUV}$ for 198 $U < 12$ stellar clusters and associations from Bica et al. (1996) using the images presented by Bell et al. (2002). Symbol sizes in Fig. 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.

Clearly, *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 β values) *or* older and dust free (the clusters with $U-B \sim 0$).

The balance between dust and old stellar population effects on the LMC's overall color can be constrained by considering the fraction of the total $U < 12$ LMC cluster UV luminosity which each population represents. The young, unattenuated clusters represent 67% of the summed $U < 12$ LMC cluster FUV 1500Å luminosity. The younger, attenuated clusters represent 27% of the FUV luminosity. The older, unattenuated clusters have only 6% of the FUV luminosity.

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 β 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 β values. This lends weight to an interpretation of the redder β values of normal galaxies mostly in terms of dust, with a small contribution from SF histories.

4. EXPLORING ALTERNATIVES TO β

Fig. 1 demonstrates that it is difficult to estimate UV attenuations on the basis of UV colors alone. For

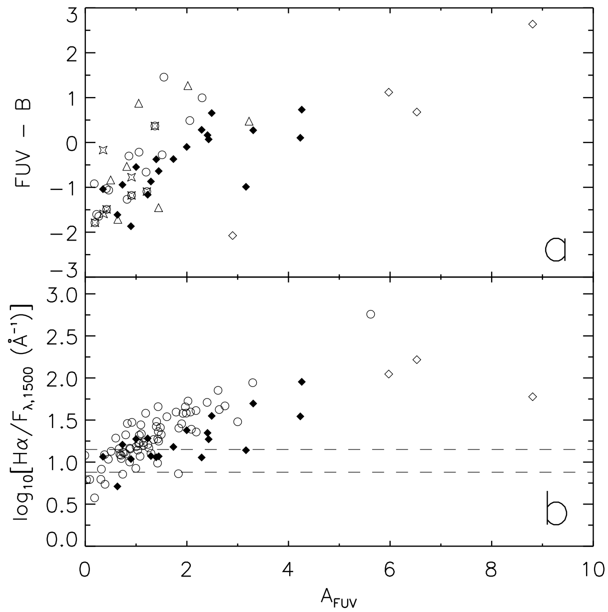

Fig. 3. Alternatives to β. Panel *a)* shows how FUV$-B$ colors correlate with $A_{\rm FUV}$. Symbols are as in Fig. 1. Panel *b)* shows Hα/FUV against $A_{\rm FUV}$. Normal galaxies are shown as open circles, starburst galaxies are shown as filled diamonds, and ULIRGs are shown as open diamonds. The two dashed lines depict the rough dust-free value of Hα/FUV (e.g., Kennicutt 1998, Sullivan et al. 2000).

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 Fig. 3, I examine two possible alternatives to β which 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 β (but would suffer more acutely from the effects of older stellar populations). In panel *a)* of Fig. 3, I show 1550Å FUV$-B$ colors against $A_{\rm FUV}$ for my sample galaxies. It is possible that FUV$-B$ is a slightly more robust indicator than β, in terms of estimating $A_{\rm FUV}$. However, the scatter is enormous: at a given FUV$-B$ color, the range in $A_{\rm FUV}$ is 3–5 magnitudes, or between 1 and 2 orders of magnitude.

Buat et al. (2002) suggest another potential extinction indicator: Hα/FUV. This indicator has the virtue that it is almost independent of SF history (although see Sullivan et al. 2000); however, it does depend on the relative distribution of dust around H II regions compared to the dust around OB associations (see, e.g., Bell et al. 2002). In panel *b)* of Fig. 3, I show integrated Hα/FUV for a sample of normal galaxies from Bell & Kennicutt (2001) as open circles. Matched aperture Hα/FUV values for starburst galaxies (Calzetti et al. 1994), and 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 Hα/FUV and $A_{\rm FUV}$; however, the scatter is a challenge to its usefulness. For example, at Hα/FUV ~ 10Å^{-1}, $0\,{\rm mag} \lesssim A_{\rm FUV} \lesssim 3\,{\rm mag}$, and at H$\alpha$/FUV ~ 100Å^{-1}, $A_{\rm FUV} \gtrsim 3\,{\rm mag}$.

Importantly, at a given $A_{\rm FUV}$, starbursts and ULIRGs tend to have bluer β values, bluer FUV$-B$ colors, and lower Hα/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.

5. CONCLUSIONS

Seven independent UV experiments demonstrate that quiescent, 'normal' star-forming galaxies have substantially redder UV spectral slopes β at a given $A_{\rm FUV}$ than starbursting galaxies. Using spatially resolved data for the LMC, I argue that dust geometry and properties, coupled with a small contribution from older stellar populations, cause deviations from the starburst galaxy β–$A_{\rm FUV}$ correlation. Neither rest frame UV-optical colors nor UV/Hα significantly help to constrain the UV attenuation. Thus, SF rates estimated from rest-frame UV and optical data alone are 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.

However, SF rates for high z galaxies derived from other wavelengths are also often subject to systematic errors of this magnitude. For example, sub-mm fluxes for high-redshift star forming galaxies sample rest-frame $\sim 200\mu$m: they must be converted to total IR flux assuming some dust spectrum. Adelberger & Steidel (2000) derive values of νI_ν at 200μm vs. $L_{\rm FIR}$ of about 0.06 and 0.13 for ULIRGs and starbursts respectively. Using Tuffs et al.'s (2002) *ISO* photometry of star-forming galaxies at 170μm as a constraint, I find that νI_ν at $\sim$200μm vs. $L_{\rm FIR}$ is roughly 0.2 for galaxies with warm dust (100/60μm ~ 1), growing to ~ 0.6 for galaxies with cold dust (100/60μm ~ 6). Thus, there is a factor of ~ 10 systematic error because of dust temperature which affects submm-derived SF rates (see also Dunne & Eales 2001). A similar limitation affects radio-derived SF rates: because of the mismatch in cosmic ray propagation and SF timescales, an order of magnitude scatter between radio flux and SF rate is easily possible (Bressan et al. 2002). Thus, when it comes to deriving SF rates for high-redshift galaxies from data at almost any wavelength, we are playing, at best, an order-of-magnitude game.

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Eric F. Bell: Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson AZ, 85716, USA (ebell@as.arizona.edu).

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