How to Correct for Dust Absorption in Starbursts

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Abstract. We review new and published results to examine how well the bolometric flux of starbursts can be recovered from ultraviolet (UV) and optical observations. We show that the effective absorption of starbursts can be substantial, up to \( \sim 10 \) mag in the far UV, and \( \sim 5 \) mag in H\( \alpha \), but apparently not as high as some claims in the literature (several tens to a thousand mag). The bolometric fluxes of an IUE sample of starbursts can be recovered to 0.14 dex accuracy using the UV flux and spectral slope. However, this relationship breaks down for Ultra Luminous Infrared Galaxies (ULIGs). The H\( \alpha \) flux combined with the Balmer decrement can be used to predict the bolometric flux to 0.5 dex accuracy for starbursts including most ULIGs. These results imply a foreground screen component to the dust distribution.

1 Introduction

Dust presents one of the biggest obstacles to interpreting observations of starburst galaxies in the optical and especially the ultraviolet (UV). The problem is difficult, because it depends not only on the amount of dust and its composition, but also the distribution of both dust and light sources. Faced with such complexity, the astronomical community’s response includes assuming that star formation remains mostly unobscured by dust \cite{12} to deriding those who even consider that UV and optical observations can be corrected for dust \cite{26}.

Here we use new and published observations to critically examine the importance of dust absorption in starburst galaxies, in order to answer the following: 1. Is dust important? 2. What is the dust geometry? 3. How does dust effect broad band colors and fluxes? 4. What does it do to emission line fluxes and line ratios? 5. Can we recover the bolometric flux of a starburst from its UV or optical properties?. The last question is a proxy for asking whether we can determine the star formation rate, but avoids distance uncertainties and assumptions about the lower end of the Initial Mass Function (IMF).

2 Samples and Tracers

We consider two samples of starburst galaxies, those observed in the UV by the International Ultraviolet Explorer (IUE), and starbursts found in the far-infrared (FIR) by the InfraRed Astronomical Satellite (IRAS). The samples are complementary. The IUE sample contains a lot of dwarfs as well as starbursts with \( L_{\text{bol}} \) as high as \( \sim 10^{11.5} L_{\odot} \). IUE starbursts are good templates for high-redshift
Fig. 1. a. (Left): The fraction of the intrinsic bolometric luminosity emitted as ionizing radiation (dashed), UV (solid), optical (dot-dashed), and infrared (dotted) for a constant star formation rate stellar population with a Salpeter IMF (limits 1–100 $M_\odot$) and solar metallicity [11].

b. (Right): Ratio of FIR to far UV (FUV) flux plotted against spectral slope $\beta_{STIS}$ for IUE starbursts (open circles) and ULIGs (squares). Here the FUV flux, $F_{FUV}$ and $\beta_{STIS}$ are derived from the STIS bandpasses used for the ULIG observations [6]. The right axis shows the effective UV absorption. The solid line shows a linear fit of $A_{FUV}$ to $\beta_{STIS}$ to the IUE sample. The horizontal line shows where the bolometric corrected UV and FIR fluxes are equal.

Lyman Break Galaxies [15,16]. The IRAS sample includes the most luminous starbursts, the Ultra-Luminous Infrared Galaxies (ULIGs: $L_{bol} \geq 10^{12} L_\odot$), but very few dwarfs. ULIGs make up < 6% of the FIR background [18], but may be good templates for high-redshift sub-mm sources which could contribute significantly to the star formation rate density at $z \geq 2$ [2].

We consider two tracers of star formation: the UV continuum, and Balmer emission lines. The UV continuum dominates the intrinsic (before dust) bolometric output of starbursts (Fig. 1a), and is sensitive to main sequence stars with $M_* > 5 M_\odot$. The Balmer lines are among the strongest in the optical and provide a good measure of the ionizing flux, and hence to stars having $M_* > 20 M_\odot$.

3 The IUE Starburst Sample

The FIR emission of a starburst represents the total luminosity absorbed by dust. For any star forming or young population, the dust heating is dominated by the UV, hence the FIR/UV flux ratio, or infrared excess (IRX) can be transformed directly into an “effective absorption”. Figure 1b plots IRX versus UV spectral slope $\beta$ ($f_\lambda \propto \lambda^\beta$) for both samples. Here $F_{FUV}$ is a generalized flux $\lambda f_\lambda$ evaluated at rest wavelength $\lambda = 1515\text{Å}$, where $f_\lambda$ is the flux density. Almost all...
galaxies emit more in the FIR than the UV, hence dust is clearly important for defining the spectral energy distribution. A strong correlation, the IRX-β relationship, is apparent for the IUE sample and readily fit by a linear relationship between effective UV absorption and β.

Figure 2 plots the absorption corrected UV flux, $F_{FUV,0}$ to $F_{bol}$ ratio versus β. The absorption comes from the fit plotted in Fig. 1b. The mean logarithmic ratio of the IUE sample is $\langle \log(F_{FUV,0}/F_{bol}) \rangle = -0.13$ with a scatter of 0.14 dex and no residual correlation with β. For the IUE starbursts, the FUV flux and β are sufficient to recover the $F_{bol}$ to 40% accuracy. For this sample Balmer fluxes from IUE aperture matched spectra are available. Figure 2b compares the ratio of dust corrected Hα flux $F_{Hα,0}$ and $F_{bol}$ with $E(B-V)_g$, the intrinsic reddening of the ionized gas. Again, there is no correlation between the two quantities. Note that the dust correction, $A_{Hα} = 2.5E(B-V)_g$, assumes a standard Galactic extinction law. The mean logarithmic ratio is $\langle \log(F_{Hα,0}/F_{bol}) \rangle = -2.43$ with a dispersion of 0.28 dex. The Balmer fluxes can recover the $F_{bol}$ to better than a factor of 2 in this sample. Calzetti et al. find that $E(B-V)_g$ measured from IR Paβ and Brγ to Balmer line ratios agrees well with that measured from only the Balmer lines.

**Fig. 2.** Ratio of recovered flux (observed flux corrected for dust absorption as deduced from reddening) to bolometric flux, $F_{bol}$, plotted against reddening indicator. Symbols are as in Fig. 1b. For the IUE sample $F_{bol}$ is a weighted sum of the observed UV and FIR fluxes, for the IRAS sample only the FIR flux is used. In Fig 2a (left), the numerator is the UV flux and the ratio is compared to the UV spectral slope β. In Fig. 2b (right), the numerator is the Hα flux and the ratio is compared to the reddening $E(B-V)_g$ determined by the Hα/Hβ decrement. The horizontal lines show model predictions from Starburst99 for a stellar population forming at a constant star formation rate for 100 Myr and having a Salpeter IMF with a lower mass limit of 1 $M_\odot$ and upper mass limits of 100 $M_\odot$ (solid line) and 30 $M_\odot$ (dashed line).
4 The FIR Selected Starburst Sample

Very few UV observations of ULIGs exist, perhaps because they were expected to be so dusty as to be invisible in the UV. However recent observations of ULIGs from the ground at $\lambda_c \sim 3400$ Å [22], and with HST at $\lambda_c \sim 2300, 1400$ Å [23] show that ULIGs do emit a small fraction of their bolometric luminosity in the UV.

We obtained Space Telescope Imaging Spectrograph UV images of seven galaxies with $L_{bol} \geq 10^{11.6} L_\odot$ [6]. In all cases the galaxies were detected in both the far UV (rest $\lambda_c \sim 1515$ Å) and the near UV (rest $\lambda_c \sim 2440$ Å) with some UV emission detected within a kpc of the nuclei [19]. However, in most cases the UV peak does not coincide well on the few hundred parsecs scale with the near IR emission. Figures 1b and 2a show that the IRX-β correlation underpredicts the bolometric flux of ULIGs by a factor ranging from $\sim 7$ to 90.

The situation is more optimistic with Balmer lines as shown in Fig. 2b which includes data on 28 IRAS galaxies with $L_{bol} > 10^{11.6} L_\odot$. The Hα fluxes were derived from narrow band images [1], while spectra from a variety of published sources [24,25,27] were used to remove [Nii] contamination and measure $E(B-V)_g$. After correcting for absorption, ULIGs have similar $\langle \log(F_{H\alpha,0}, F_{bol}) \rangle = -2.48$ to the IUE starbursts, with a somewhat larger dispersion: 0.51 dex.

One caveat is that these points represent total Hα fluxes corrected with nuclear ($R < 1$ kpc) line ratios. Gradients in $E(B-V)_g$ may mean that we overestimated $F_{H\alpha,0}$. Large spatial variations certainly exist in some galaxies as shown by the two data point for Arp220 in Fig. 2b. However, on average the gradients are shallow with typically $\Delta E(B-V)_g \approx 0.4$ mag out to $R = 8$ kpc (where the contribution to the total Hα flux is small) compared to $\langle E(B-V)_g \rangle \approx 1.1$ mag in the center [1]. Clearly, spectroscopy over the entire face of ULIGs is required to properly determine $F_{H\alpha,0}$. There is precious little of this available in the literature. While we can not yet rule out a fortuitous coincidence, Fig. 2b indicates that integrated Balmer line fluxes can be used to predict the bolometric flux of starbursts to a factor of about three accuracy, even in most ULIGs.

5 Discussion

UV color and/or Balmer line ratios can be used to crudely estimate the $F_{bol}$ of starbursts, even ULIGs. When looking at large samples an accuracy of $\sim 0.5$ dex should be sufficient for measuring integrated star formation rate densities. The effective absorption implied by Figs. 1b & 2b is $\lesssim 10$ mag in the far UV, and $\lesssim 5$ mag in Hα. Five to ten magnitudes of dust absorption is large (factor of $10^2$ to $10^4$ in attenuation), but not overwhelming. These results contradict the notion that star formation is essentially buried behind unmeasurabley large absorption in the UV and optical. Why is this?

First of all, our results do not rule out some very buried star formation. Perhaps the completely buried phase is of short duration, before stars migrate
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from their birth site or the surrounding dust and gas is cleared away by the supernovae [10]. This scenario may also explain the higher dust column density affecting emission lines compared to continuum radiation [5]. However, we have not found cases where all the star formation is buried behind several tens of magnitudes of absorption in both the UV and Hα. Some appropriately reddened emission usually gets out. Secondly, some claims for missing star formation are very model dependent. For example Poggianti [17] mentioned a short fall of a factor of three in Hα derived star formation rates compared to FIR estimates. However this is relative to a stellar population model of constant star formation rate with an assumed IMF upper mass limit $M_u = 100 \, M_\odot$. A deficit of 0.5 dex compared to this model is completely consistent with our results (Fig. 2b) which suggests $M_u \approx 50 \, M_\odot$ may be more appropriate. Aperture effects may be behind other claims of high extinction. For example Sturm et al. [21] use flux ratios of weak near to mid IR recombination and fine structure lines to infer a V band dust absorption of 30–80 mag for Arp220. However, the aperture size they use increases with wavelength, which can induce a spuriously large absorption since this source fills these apertures in Hα [1].

The correlation of effective absorption with $\beta$ (IUE sample) and Balmer decrement (both samples) strongly suggests a foreground screen dust geometry [3, 4]. While there is some hostility to such a model (e.g. [26]), we have yet to see these correlations well modeled without a screen contribution. However, this screen is not likely to be a thin uniform sheet encompassing all star formation tracers, otherwise the ULIGs would fall on the same IRX-β relationship as the IUE sample. The Charlot and Fall model [5] is a hybrid containing both foreground screen dust shells and mixed gas and dust. It works well for the IUE galaxies and perhaps can be adapted to fit the IRAS sample as well.

It should be no surprise that a foreground screen component is required, since a starburst can naturally produce such a screen. Its stellar winds and supernovae will evacuate a cavity around the starburst and power a galactic wind [7]. Most of the dust opacity will arise in the walls of this cavity. Any molecular clouds that wander into the cavity will be compressed by the high pressure within the starburst and hence have a low covering factor. Direct evidence for this scenario is given by Heckman et al. [8] who show that the metal content in the wind is directly related to the reddening. In particular, the depth of the blue shifted NaI absorption line in starbursts correlates well with both the optical continuum color and the Hα/Hβ ratio.

6 Conclusions

We conclude by answering the questions we posed at the start: 1. Yes, dust is important in most starbursts. 2. The dust geometry includes a strong foreground screen contribution, probably arising in a galactic wind. 3. Dust reddens the UV colors as the flux is diminished in the IUE starbursts, but this relationship breaks down for ULIGs. 4. Optical emission line flux ratios redden with increasing dust absorption for all types of starbursts. 5. The bolometric flux of starbursts can
be recovered from their UV color (except ULIGs) or more crudely, from Balmer line flux ratios (all starbursts). These results bode well for estimating the star formation rate density locally and out to high redshift from UV and optical surveys.

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