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Hidden Star Formation: The Ultraviolet Perspective

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Abstract. Many recent estimates of the star formation rate density at high redshift rely on rest-frame ultraviolet (UV) data. These are highly sensitive to dust absorption. Applying a correlation between the far-infrared (FIR) to UV flux ratio and UV color found in local starbursts to galaxy samples out to $z \sim 3$, one can account for most of the FIR background. However, the correlation is based on a sample that does not include the most extreme starbursts, Ultra Luminous Infrared Galaxies (ULIGs). Our new UV images of ULIGs show that their FIR fluxes are underpredicted by this correlation by factors ranging from 7 to 70. We discuss how ULIGs compare to the various types of high-z galaxies: sub-mm sources, Lyman Break Galaxies, and Extremely Red Objects.

1. Why observe star forming galaxies in the ultraviolet?

About 60% of the *intrinsic* bolometric luminosity of star forming populations is emitted between 912Å and 3000Å with little variation in this fraction with star formation duration (from models of Leitherer et al. 1999). Hence UV light is potentially very useful for measuring star formation. It represents direct emission from hot main-sequence stars, the same stars that will provide the majority of the mechanical energy feedback into the ISM. The UV spectrum is very rich in features that can be used to diagnose the stellar populations and intervening ISM. The overall intrinsic spectral slope in the UV is fairly constant. For young ionizing populations it is set by the Rayleigh-Jeans tail of the Planck

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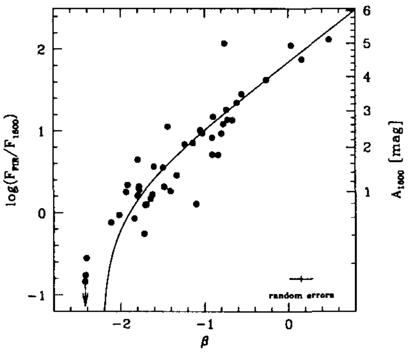
function. When looking at high redshifts the importance of the rest-frame UV increases; at a fixed bandpass it is the last stop before the Lyman-edge.

The big problem with using UV measurements is dust, which most efficiently absorbs and scatters UV radiation. The absorbed UV light is reradiated at far infrared (FIR) wavelengths. Not only is the amount of dust important, so too is its distribution. If the geometry is unfavorable, as in the mixed stars and dust model, then the UV emission will be dominated by the stars closest to the observer and the center may be practically invisible (e.g. Witt, Thronson, & Capuano 1992). Fortunately, this is not the case for a wide range of starburst galaxies as shown in Fig. 1. For them the FIR to UV flux ratio, or infrared excess (IRX), which gives the effective dust absorption, correlates with the UV spectral slope β (Meurer et al. 1995, 1999). This is a prediction of the dust screen model (Witt et al.). While variations on this geometry can also explain this correlation (Calzetti 1997; Charlot & Fall 2000), the mere fact of this correlation allows one to recover the intrinsic luminosity of starbursts using UV quantities alone.

2. Applying IRX-β to the high-redshift universe

Lyman Break Galaxies (LBGs) at $z \sim 3$ are similar to local starbursts. In particular they have similar SEDs (Dickinson 2000), spectral properties (Tremonti et al. 2000), ISM dynamics (e.g. Pettini et al. 1998), and surface brightnesses (Meurer et al. 1997). They are also noticeably redder than dust-free starbursts. Meurer et al. (1999) used the rest frame colors of LBGs and the IRX-β correlation to estimate that the Hubble Deep Field LBG sample suffers from a factor of about five in dust absorption at rest $\lambda_0 \approx 1600$Å. It is hard to test whether the IRX-β correlation actually holds for LBGs because predicted FIR fluxes are typically just below current detection limits with instruments such as SCUBA. Other data show that what little we know about the LBGs is consistent with them obeying the same reddening law as local starbursts. For instance, we assumed that the FIR-radio correlation holds, and took the LBGs with the top ten predicted FIR emission and predicted summed radio fluxes of 27 $\pm 5\,\mu$Jy, and 105 $\pm 24\,\mu$Jy (assuming a 0.3 dex uncertainty on each flux) at observed frame wavelengths 3.5cm and 20cm, while the Richards (2000) data yield measured summed fluxes of 28 $\pm 10\,\mu$Jy, and 100 $\pm 33\,\mu$Jy respectively. Adopting IRX-β, Adelberger & Steidel (2000) show that the UV detectable galaxies at $z = 1, 2$ and 3 can account for most or all of the FIR background at 850 μm.

This rosy view of the utility of UV astronomy flies in the face of what we have learned over the last few decades: that dust enshrouded star formation is best seen in the infrared. Would not dust obstruct our view of star formation, even at high-z? The bright SCUBA sources, in particular, are inferred to have $z \approx 1 - 3$, usually have little or no rest-frame UV emission and probably have an equal contribution to the star formation rate density as non-dust corrected LBGs (Barger, Cowie, & Richards 2000). They have $L_{\rm bol} > 10^{12}\,L_\odot$, so the best local analog to them are thought to be the Ultra-Luminous Infrared Galaxies (ULIGs). Relatively little was known about the UV properties of ULIGs, until Trentham, Kormendy & Sanders (1999) presented weak UV detections of three ULIGs with HST's *Faint Object Camera* and Surace & Sanders (2000) showed that they are detectable from the ground in the U' band.



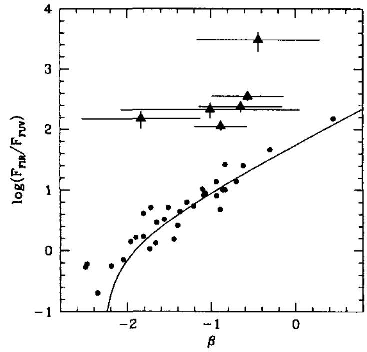


Figure 1. (Left) The $IRX \equiv F_{\rm FIR}/F_{\rm UV}$ versus β relationship of local starbursts observed by IUE (Meurer et al. 1999). Here the UV flux is measured at $\lambda_0 = 1600$Å, and the left axis converts IRX to the effective absorption A_{1600} in magnitudes.
Figure 2. (Right) The IRX-β plot for ULIGs (triangles) in relation to the IUE starbursts. Here β and the UV flux are measured photometrically through the actual or synthetic STIS bandpasses.

3. STIS UV Images of ULIGs

We have been granted HST time to image seven galaxies in the UV using the STIS (*Space Telescope Imaging Spectrograph*) MAMAs which have much higher sensitivity than the FOC. Our sample was chosen to have $\log(L_{\rm bol}/L_{\odot}) \geq 11.6$, starting in $L_{\rm bol}$ where the IUE sample ends. So far six galaxies have been observed, five of these are ULIGs. We detect all of these in both the far UV (FUV; $\lambda_c \approx 1460$Å) and near UV (NUV; $\lambda_c \approx 2350$Å). In both bands, UV emission can be detected projected to within 1 kpc of the infrared nuclei seen by NICMOS (Scoville et al. 2000). However, especially in the FUV, very little, if any UV emission is detected within the inner few hundred parsecs where most of the bolometric luminosity probably originates.

Figure 2 shows the IRX-β diagram for our sample compared to the IUE starbursts. Typically only 0.5% of the bolometric luminosity is observed in the FUV. Furthermore, the IRX-β correlation *under-predicts* the FIR emission of ULIGs by factors ranging from 7 to 70. The FIR flux is still under-predicted if only the light within 1 kpc of the IR nucleus is considered. In these galaxies IRX-β only gives a lower limit to the FIR flux. These results confirm that ULIGs represent galaxies with star formation almost totally hidden from the UV.

4. High-z Implications

Our work shows that we must still be cautious with rest-frame UV observations of galaxies: they may harbor hidden-star formation beyond that predicted with the IRX-β correlation. However, not all galaxies are as extreme as ULIGs. At

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high-z, the most luminous LBGs can not generally have IRX values like ULIGs or else more would be detected at 850μm with SCUBA (multiply predictions in Table 4 of Meurer et al. 1999 by 7 – 70). Could ULIGs be selected as LBGs? At $z = 3$ ULIGs would have an observed frame $V - I \leq 0.5$ ABmag. Presumably they would have very red $U - B$ colors resulting from the strong opacity of the Lyman forest and edge. Therefore, they should have the right colors to be selected as LBGs. However at this redshift they would be very faint, having $V \sim 27$ to 30 ABmag, at or beyond the limits of many current surveys such as the Hubble Deep Fields. So ULIGs still make good analogs to SCUBA sources, but probably only contribute to the faint end of the LBG population.

ULIGs have also been touted as good local prototypes for Extremely Red Objects (EROs). Using our photometry and published results we find that ULIGs emit enough rest-frame UV emission, that at $z = 1.8$ or 3.5 in the observed frame they would have $2.3 \leq R - K \leq 5.6$ ABmag. This is bluer than $R - K < 6$, the definition of EROs (Graham & Dey 1996). Since our sample is small, and some approach this limit perhaps some more extreme ULIGs may be recognized as EROs at high-z, but in general they would be too blue.

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