Calibrating UV Emissivity And Dust Absorption At $z \approx 3$

Gerhardt R. Meurer*, Timothy M. Heckman*, and Daniela Calzetti†

* The Johns Hopkins University, Baltimore, MD 21218
† Space Telescope Science Institute, Baltimore, MD 21218

Abstract. We detail a technique for estimating the UV extinction and luminosity of UV selected galaxies using UV quantities alone. The technique is based on a tight correlation between the ratios of far infrared (FIR) to UV flux ratios and UV color for a sample of local starbursts. A simple empirical fit to this correlation can be used to estimate UV extinction as a function of color. This method is applied to a sample of Lyman-break systems selected from the HDF and having $z \approx 3$. The resultant UV emissivity is at least nine times higher than the original Madau et al. [1] estimate. This technique can be readily applied to other rest-frame UV surveys.

INTRODUCTION

Most of the light from high mass stars is emitted in the ultraviolet (UV; $\lambda \approx 1100 - 3000\AA$), making it an attractive passband for tracing cosmic star formation evolution. This utility is accentuated with increasing redshift as the rest-frame UV emission enters the optical where modern detectors have quantum efficiencies approaching unity. Unfortunately, star formation occurs in a dusty environment, and dust efficiently absorbs and scatters UV radiation. This must also be the case in the early universe since dust has been observed in objects with $z > 4$ (e.g. [2]).

The challenge of interpreting rest-frame UV emissivities is to devise an adequate prescription to account for dust absorption. Currently there is much debate in the literature on what the proper dust correction prescription is, resulting in different groups estimating $\lambda = 1600\AA$ dust absorption factors ranging from a factor of about 3 (e.g. [3]) to 20 [4] at $z \approx 3$. The amount of high-$z$ dust absorption has a direct bearing on interpreting how galaxies evolve. Small dust corrections favor hierarchical models of galaxy formation, while large corrections favor monolithic collapse models [5].

Here we consider the UV luminosity density at $z \approx 3$ derived mainly from the $U$-dropouts in the Hubble Deep Field (HDF) [6]. Our technique [7] is based on the strong similarity between local starburst galaxies and Lyman-break systems (e.g. [8]). Throughout this paper we adopt $H_0 = 50\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $q_0 = 0.5$. 
METHOD

In earlier works [9,10], we showed that for local UV selected starburst galaxies, the ratio of far infrared (FIR) to UV fluxes correlates with UV spectral slope $\beta$ ($f_\lambda \propto \lambda^{\beta}$ - $\beta$ is essentially an ultraviolet color). This is illustrated in Fig. 1. Since $F_{\text{FIR}}$ is dust reprocessed UV flux, this empirical correlation can be used to recover the intrinsic UV flux from UV quantities alone. In addition, for starbursts, the $y$ axis can be transformed directly into a UV absorption [7]. The fitted line is a simple linear fit to the transformed data of the form: $A_{1600} \propto \beta - \beta_0$.

We selected our HDF $U$-dropout sample from a corner cut out of the $U_{300} - B_{450}$ versus $V_{606} - I_{814}$ color-color diagram ($V_{606} - I_{814} < 0.5$; $U_{300} - B_{450} \geq 1.3$) and adopted the same magnitude limits as Madau et al. [1]. We select in $V_{606} - I_{814}$ instead of $B_{450} - I_{814}$ [1] because (1) $V_{606}$ is less affected by the Lyman forest and edge than $B_{450}$, and (2) this selection yields fairly even cutoff in $\beta$, and hence in $A_{1600}$. Note that our selection recovers high-$z$ galaxies in the “clipped corner” of the Madau et al. [1] selection area, and includes no known low-$z$ interlopers.

We applied our absorption law fit to broad-band $V_{606} - I_{814}$ colors transformed into $\beta$. The transformation was derived from high-quality IUE spectra that were “redshifted” through the $z = 2$ to 4 range of $U$-dropouts. The transformation is linear in color with a quadratic $z$ correction. The $z$ correction is needed to account for the Lyman forest and Lyman-edge creeping into the $V_{606}$ band at high-$z$.

Figure 2 shows a test of our technique. It compares the ratio of (rest frame) optical emission line flux to UV continuum flux density for local starbursts, and
seven $U$-dropouts [3,11–13]. These ratios are not corrected for dust absorption. The overlap of the two samples indicates that $U$-dropouts are ionizing populations to the same degree as local starbursts. Hence their intrinsic UV spectrum should be similar. Pettini et al. [3] claim that $U$-dropouts probably suffer from little dust absorption since they tend to have fairly low $F_{\text{H}\beta}/f_{1600}$ values. However, this ratio can be misleading. In fact, $F(\text{line})/f_{1600}$ is not a good indicator of dust absorption: it does not correlate strongly with $\beta$, which we know to be a good indicator of dust absorption (Fig. 1). This is the case for both the local and $U$-dropout samples. The reason for this was first proposed by Fanelli et al. [14]: H$\text{II}$ emission lines are seen through a larger column of dust than than the general UV continuum thus cancelling the expected benefit in opacity of observing in the optical instead of the UV.

RESULTS

Figure 3 plots the absorption corrected absolute AB magnitude of the HDF $U$-dropouts versus $\beta$. The broken lines show $M_{1600\AA}$ in the absence of absorption correction. The data show an apparent color - luminosity correlation. This is in part due to the selection limits, but the lack of very luminous blue galaxies is real. This implies that there is a mass - metallicity relationship at $z \approx 3$. It also shows that the most luminous galaxies tend to have the most dust absorption. A similar color - luminosity correlation is seen in local starbursts [15].

Summing the results for the HDF $U$-dropouts yields lower limits to the intrinsic UV emissivity, and hence the star formation rate density:
\[ \rho_{1600,0} \gtrsim 1.5 \times 10^{27} \text{erg s}^{-1} \text{Hz}^{-1} \text{Mpc}^{-3} \]

\[ \rho_{\text{SFR}} \gtrsim 0.19 \text{M}_{\odot} \text{yr}^{-1} \text{Mpc}^{-3} \]

We find that \( \rho_{1600,0} \) is factor of 9.2 higher than \( \rho_{1600} \) first estimated by Madau et al. [1]. This difference is due to two effects: the dust absorption correction (factor of 5.5), and the improved \( U \)-dropout selection (factor of 1.7). These emissivities are still lower limits because we have made no completeness corrections, and because our \( V_{606} - I_{814} \) selection is only sensitive to galaxies with \( A_{1600} \lesssim 3.4 \text{ mag} \).

Recently, Madau et al. [5] (see also Madau, this volume) have fit models to cosmological emissivity data covering rest-wavelengths from the FIR to the UV and redshifts out to \( \sim 4 \). Their HDF \( U \)-dropout sample now has a selection similar to ours. Our \( \rho_{1600,0} \) estimate for the \( U \)-dropouts is a factor of 2.5 larger than their preferred model, which simulates the heirarchical collapse scenario and which includes a small amount of dust absorption. However it is only 30% larger than their “monolithic collapse” model. Hence, the initial phase of galaxy collapse was probably more rapid than predicted by heirarchical models and somewhat obscured from our view by at least modest amounts of dust.

REFERENCES

1. Madau, P., Ferguson, H.C., Dickinson, M.E., Giavalisco, M., Steidel, C.C., & Fruchter, A. 1996, MNRAS, 283, 1388
2. Guilloteau, S., Omont, A., McMahon, R.G., Cox, P., & Petitjean, P. 1997, A&A, 328, L1
3. Pettini, M., Kellogg, M., Steidel, C.C., Dickinson, M., Adelberger, K.L., & Giavalisco, M. 1998, ApJ, submitted
4. Sawicki, M., & Yee, H.K.C. 1997, AJ, 115, 1329
5. Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106
6. Williams, R.E., et al. 1996, AJ, 112, 1335
7. Meurer, G.R., Heckman, T.M., & Calzetti, D. 1998, ApJ, submitted
8. Lowenthal, J.D., Koo, D.C., Guzmán, R., Gallego, J., Phillips, A.C., Faber, S.M., Vogt, N.P., Illingworth, G.D., & Gronwall, C. 1997, ApJ, 481, 673
9. Meurer, G.R., Heckman, T.M., Leitherer, C., Kinney, A., Robert, C., & Garnett D.R. 1995, AJ, 110, 2665
10. Meurer, G.R., Heckman, T.M., Lehnert, M.D., Leitherer, C., & Lowenthal, J. 1997, AJ, 114, 54
11. Wright & Pettini, M. 1998, private communication.
12. Bechtold, J., Yee, H.K.C., Elston, R., & Ellingson, E. 1997, ApJ, 477, L29
13. Bechtold, J., Elston, R., Yee, H.K.C., Ellingson, E., & Cutri, R.M. 1998, preprint (astro-ph/9802230)
14. Fanelli, M.N., O’Connell, R.W., & Thuan, T.X. 1988, ApJ, 334, 665
15. Heckman, T.M., Robert, C., Leitherer, C., Garnett, D.R., & van der Rydt, F., 1998, ApJ, in press