Draft version April 10, 2018
Preprint typeset using LaTeX style emulateapj v. 12/16/11

ULTRAVIOLET TO INFRARED STAR FORMATION RATE INDICATORS AND GALAXY ENVIRONMENT

Nityasri Mandyam[1] and Michael R. Blanton[1]

Draft version April 10, 2018

ABSTRACT

Star-forming galaxies preferentially populate isolated regions, while non-star-forming galaxies preferentially exist in groups and clusters. We investigate how this relationship depends on the star formation rate indicator using full UV to IR photometry for a local sample of galaxies (redshift $z \sim 0.05$) with ultraviolet and optical photometry from the NASA Sloan Atlas and infrared photometry from WISE. We measure the Specific Star Formation Rates (SSFR) in two independent ways: (a) using MAGPHYS, a complete UV to IR SED fitting method that models dust absorption and emission; (b) using purely the UV light to quantify star formation rates and accounting for dust attenuation from the ratio of fluxes in FUV and NUV bands. We estimate environments using projected aperture densities and distances to the n^{th} nearest neighbor. We find that SSFR as measured including the infrared emission is more closely related to the galaxy environments than the UV indicator. Specifically, galaxies with high SSFR but with significant dust-obscuration cluster like non-dust-obscured galaxies with high SSFR. These findings are consistent with MAGPHYS faithfully accounting for the effect of dust on the UV and IR emission, and with the clustering of star forming galaxies being independent of their dust obscuration.

1. INTRODUCTION

Determining the formation history of galaxies is one of the most important tasks in astronomy. The average star formation rates of galaxies have reduced with cosmic time (as reviewed by Madau 2014) and star-forming galaxies "transition" to red and quiescent ones (e.g., Ilbert et al. (2013); Muzzin et al. (2013); Moustakas et al. (2013); Tomczak et al. (2014) among others). Many mechanisms have been proposed to explain the observed patterns of galaxy evolution but there are many unresolved questions regarding them. These mechanisms are known to have a some correlation with the environment, due to the fact that galaxy type depends on environment in the present day (**??**, and many others).

Star formation rate estimates are an important tool in the observational study of this problem (see the review of **?**). Spectroscopic indicators contain signatures of star formation in them; however, often a spectrum of the galaxy is not readily available and we have to rely on converting photometric fluxes to meaningful star formation estimates. In this paper we compare two specific ways to estimate star formation rates from photometry. The first is to fit physical models including stellar population models and dust to the spectral energy distribution (SED) of each galaxy using photometric data in various available bandpasses. The second is to use the far and near UV fluxes to estimate a dust-extinction-corrected UV luminosity and thus star formation rate.

The presence of dust is an important complication in this analysis. Dust absorbs preferentially in the UV/optical region of the galaxy spectrum and both extincts and reddens the photometric data. This energy is reemitted in the mid- to far-IR by polycyclic aromatic hydrocarbon molecules as well as warm and cold grains. Recent studies (**?**) find that in the nearby universe, almost 70% of the FUV luminosity is obscured by dust on an average. Although UV estimates of star formation do attempt to account for dust attenuation(Such as Salim et al. (2007) and?), the extensive reliance on UV SFR in the literature (cite Peng et al, Moustakas et al..?) makes it important to understand the extent to which the dust corrections for UV SFR estimates work relative to other methods of estimating SFR.

Here, we examine a sample of galaxies whose UV-IR photometry is available and estimate the star formation rate in two independent ways. First we exploit the fact that we have UV to IR photometry and perform SED fitting using MAGPHYS da Cunha et al. (2008), which accounts for dust by using a simple method of energy balance to obtain the specific star formation rates (SSFRs). The other method involves using purely UV photometry to estimate both star formation rate and dust attenuation using the prescription given by Salim et al. (2007). We also estimate the environments of our population.

We ask the following questions of this sample. How do these different star formation estimators disagree with each other? How does each estimate correlate with environment? Does one trace environment more closely? Under the assumption that the environment primarily correlates with the SSFR rather than dust obscuration's effect on the observables, studying this correlation will yield insights into the relative accuracy of the methods.

2. DATA

2.1. *Constructing a local sample spanning Ultraviolet to Infrared Imaging*

The sample on which we perform our measurements is based on the NASA-Sloan Atlas, a nearby galaxy sample which includes optical and ultraviolet imaging from SDSS and GALEX. We use the currently public version of the NSA (http://nsatlas.org) whose redshift range extends up to $z = 0.055$ and includes SDSS(Data Release 6) and GALEX imaging for galaxies. The total

[1] Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003

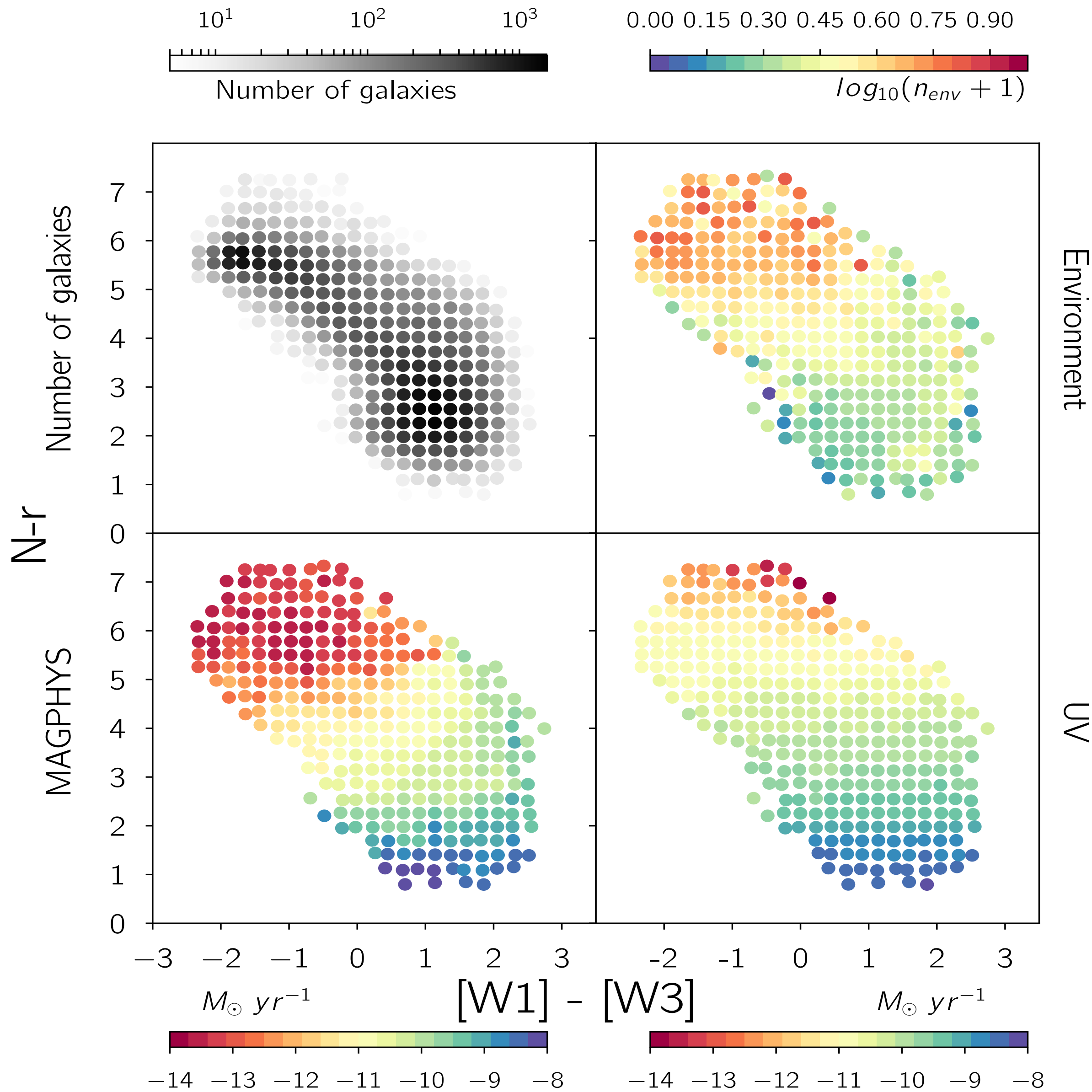

Figure 1. The SSFR measurements and environment shown the color-color space. Each point in the plot is shown at the mean colors in each of the bins we use. The grey value or color of the points in each panel show the mean value in each bin for the quantity described by the corresponding color bar. *top left* Logarithmic number density in each of the bins; all bins with less than 5 galaxies were discarded in this and the other panels. *top right* Environment; in each bin, the average number of nearest neighbors is calculated in a projected cylinder ($r_t = 0.5Mpc$ and $v_{los} = \pm 1000km/s$); *bottom left* the Specific Star Formation Rates obtained from MAGPHYS; *bottom right* UV Specific Star Formation Rates estimated by using the method described in Salim et al. (2007).

number of objects in the NSA catalog is $\sim 150,000$; however around 20% of the objects do not have GALEX photometry.

To obtain infrared imaging for the data we have photometrically matched the objects from the NSA with the WISE (Wide-Field Infrared Survey Explorer) data with k-corrected WISE magnitudes. Thus our sample in total contains $\sim 75,000$ objects with absolute magnitudes in the UV (F and N bands), optical (U,g,r,i and z bands) and infrared ($W1$,$W2$, $W3$ and $W4$ bands).

Add paragraph on Volume limited sample
We imposed a volume limited cut on the absolute magnitude ($-18.5 > M_r > -24.5$) to get an environment determining population of 95638 galaxies. After removing galaxies with zero/negative fluxes, we imposed a cut in optical ($7.5 > N - r >= 0$) and infrared ($3.0 > [W1] - [W3] >= -3.0$) colors to obtain 75476 galaxies upon which the star formation rate measurements were then performed.

3. ESTIMATING THE SPECIFIC STAR FORMATION RATES

3.1. *SED Fitting - MAGPHYS*

To understand the distribution of the Specific Star Formation Rates (hereafter SSFR) of our sample across the color-color space, the photometric fluxes in bands were normalized to an r-band flux of 1 Jy. The galaxies were then binned along the $N - r$ - $[W1] - [W3]$ space

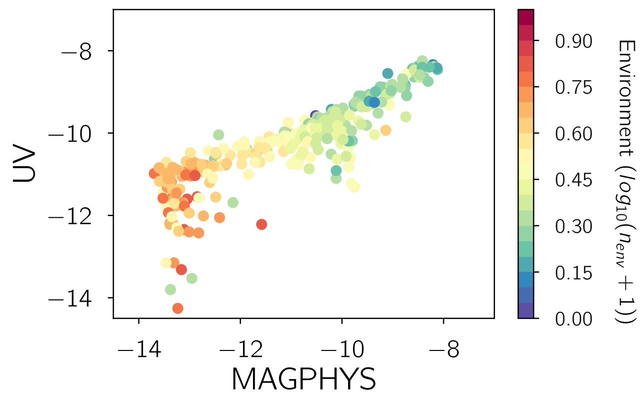

Figure 2. The two star formation rate estimates (from Fig.1) plotted against each other as a function of the environment; We notice two distinct set of outliers that seem to have lower UV SSFR's but similar environments to the galaxy bins with the same MAGPHYS SSFR's.

(25×25) and the mean flux in these bins were used for each band to obtain a "template" for each bin in the color-color space.

MAGPHYS - Multi-wavelength Analysis of Galaxy Physical Properties (**?**) is a simple, largely empirical but physically motivated model to interpret the mid- and far-infrared spectral energy distributions of galaxies consistently with the emission at ultraviolet, optical and near-infrared wavelengths. For every input galaxy with a set of observed fluxes in different bands, MAGPHYS generates an optical and infrared library at that redshift and then samples all template spectra whose fluxes obey a simple principle of energy balance: that the amount of energy absorbed by dust in the UV/Optical matches within some tolerance? the amount of infrared emission that is accounted for purely by dust. Once the templates have been sub-sampled thus, MAGPHYS uses chi-squared fitting to see which combination best reproduces the observed fluxes along with the likelihood for the distributions.

In order to circumvent the computational expense involved in fitting for every galaxy, we binned the galaxies along the color-color space and averaged the fluxes in each bin (which were normalized to an r band flux of $1Jy$) thus generating a "template galaxy" for each bin. The results for the specific star formation rates thus obtained are shown in Figure 2 along with the number distribution of the galaxies across the chosen bins. Note that bins with < 5 galaxies were omitted as those regions of the color-color space are obviously under-sampled.

3.2. *UV Star Formation Rates*

The star formation rate of a galaxy is highly constrained by its UV luminosity. We use a simple method developed by Salim et al. (2007) that exploits this feature and prescribes a star formation rate that is proportional to the UV luminosity (specifically the FUV band if we are looking at GALEX) via the Kennicutt-Schmidt relation. Dust attenuation is also accounted for in this method by looking at the ratio of luminosities in the FUV and NUV bands.

According to the prescriptionSalim et al. (2007), the star formation rate can be given by:

$$SFR = 1.08 \times 10^{-28} {L^0}_{FUV}$$

Where ${L^0}_{FUV}$ is the rest-frame FUV luminosity. This method accounts for dust attenuation of the FUV light as well by suggesting an attenuation factor A_ν which is obtained thus:

If $N - r \geq 4.0$,

$$A_\nu = \begin{cases} 3.32(F-N)+0.22, & \text{if}(F-N) < 0.95 \\ 3.37, & \text{if}(F-N) \geq 0.95 \end{cases}$$

And if $N - r < 4.0$, i.e. for the blue sequence galaxies,

$$A_\nu = \begin{cases} 2.99(F-N)+0.27, & \text{if}(F-N) < 0.90 \\ 2.96, & \text{if}(F-N) \geq 0.90 \end{cases}$$

4. ENVIRONMENTS

The resulting distribution of the SSFR's (Fig. 1) across the color-color space looks as we would expect it to for the most part - the bluer part of the space is filled with star-forming galaxies and the redder part of the space seems to contain a quiescent population. However we notice that the UV SSFR's have a nearly monotonic relationship with optical color while the MAGPHYS SSFR's do not. Particularly, in the region of the transitioning galaxies or the so-called "green valley" we notice that there seems to be a population of galaxies whose MAGPHYS star formation rates are closer to that of the bluer galaxies. This seems to validate our suspicion that the green valley contains a population of galaxies that aren't truly transitioning but are reddened by the presence of dust, a feature that the UV star formation rates do not seem to be able to capture. In order to confirm whether MAGPHYS is capturing something inherent to this population of galaxies, we estimate an independent physical property, namely the environments of our sample.

4.1. *Measures of Environment*

The Environment of a galaxy can be defined in many ways such as the fixed aperture counts, distance to the n^{th} nearest neighbor, Voronoi volumes, etc (**?**). We use counts in a projected fixed aperture of length 0.5 Mpc as our environment measure here. Around every galaxy we construct a projected cylinder with a radius (in the transverse direction) of $r_t = 0.5$ Mpc and a line of sight velocity window of $v_{los} = \pm 1000 km/s$ and count the number of neighbors(n_{env}) in this cylinder(Fig. 1, 2).

The environment trends are plotted in Fig 1.(b) as a function of optical and infrared colors. We find that the expected trend holds good, i.e., the star-forming bluer galaxies tend to exist in sparser environments on an average and that the red-and-dead population tends to exist in richer regions. The interesting feature we see occurs in the so-called green-valley region($3 < N - r < 5$). We

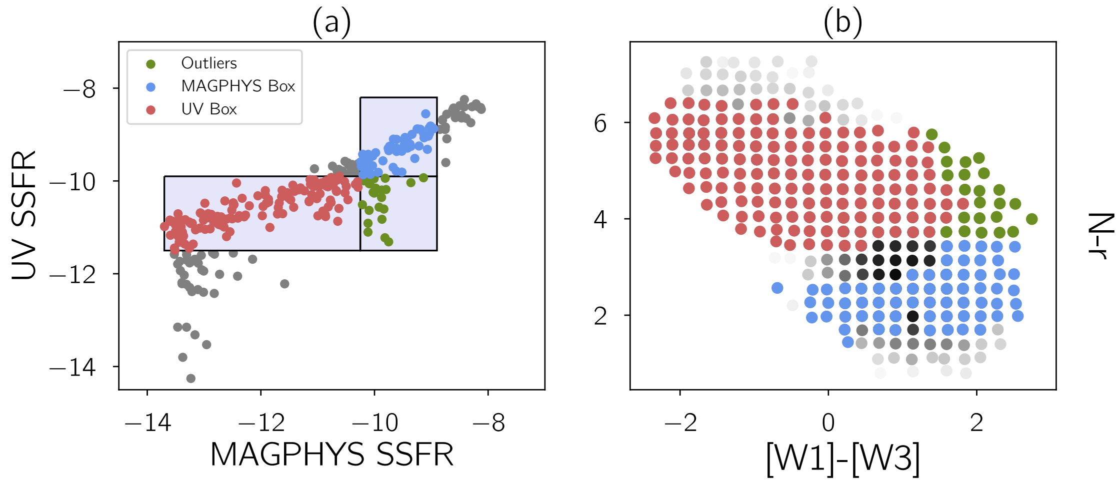

Figure 3. The outliers shown as a function of the Star Formation Rates as well as Optical and IR colors

find that the average environments of such galaxies with higher $[W1]-[W3]$ values have similar environments to the blue cloud.

4.2. *Edge Effects*

One of the challenges involved in finding environments in galaxy surveys is accounting for the survey edges in a meaningful way. For galaxies at the edge, part of the fixed aperture used to estimate the environments might lie outside the survey coverage and thus it is important to identify them and either discard them or assign an appropriate weight to them. To identify the edges, we use (Molly Swanson et. al.'s) `Mangle`, a suite of free open-source software designed to deal with complex angular masks in an efficient and accurate manner. First, the NYU-VAGC mask was used to obtain the angular mask for the NASA Sloan Atlas by using the *polyid* routine from `Mangle`. Then, the *ransack* routine was used to populate the mask with a random sample of $N = 10,000,000$ galaxies.

For each galaxy, we compute the angular separation θ_i that corresponds to our $0.5Mpc$ aperture at the redshift of that galaxy. We then count the number of galaxies n_i that lie within this angular separation and compare the value obtained to the expected value (Hahn et. al.):

$$\langle n \rangle_i = \frac{N}{A_{\rm EDP}} \times \pi\theta_i^2 \times f_{\rm thresh}$$

$A_{\rm EDP}$ is the total area of the mask and $f_{\rm thresh}$ is the fractional threshold for the edge effect cut-off. In our case, $f_{\rm thresh} = 0.8$ seemed to be a reasonable cut-off to impose. Wherever $n_i < \langle n \rangle_i$, we consider the galaxy to be near an edge and discard it from our sample. (% removed from our sample?)

5. THE ENVIRONMENTS OF THE OUTLIERS

In order to understand the relationship between the two SSFR measurements as a function of environment, Fig. 2 was produced, keeping the same binning along the $([W1]-[W3])$ and $(N-r)$ axes (as shown in Fig. 2). It is apparent from Fig. 2 that there is a population of galaxies that exists in a $-10.5 <$ MAGPHYSSSFR < -9.5 that not only have lower UV SSFR's but seem to exist in environments similar to the other galaxy bins in the same MAGPHYS range. From hereon we shall refer to this population as the "Outliers", to distinguish them from the *linear trend..?* in Fig. 2 and we proceed to identify these more concretely in Fig. 3(a). The galaxy bins with the same MAGPHYS SSFR's are identified as "MAGPHYS Box" and the bins with the same UV SSFR's are identified as "UV BOX" in Fig. 3(a).

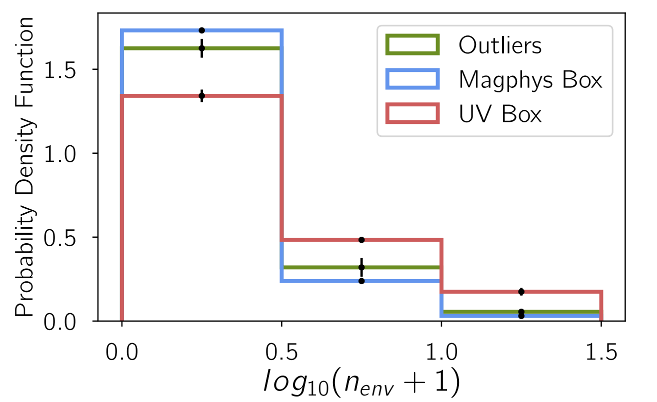

Figure 4. Probability density functions of the Environments of the three populations described in Fig. 2;

Upon identifying the same in the color-color space (Fig. 3(b)), we see the trends we had expected, namely that the Outliers would lie in the same optical color range as the UV box but have higher IR color; that the MAGPHYS Box occupies the bluer side in the optical color range while spanning almost the entire IR color range; and that the UV Box occupies the redder side in the optical color range while having lower IR color values. (I can surely write a better sentence than that... but we'll get to it later). This confirms our conjecture that these outliers might indeed be the dust-reddened "green valley" we originally set out to look for. To verify this, we unwrap the bins and look at the Probability Density Function of the Environments of the galaxies in these three regions in the mass range $9.5 < M_* < 10.7$ and the result of that is plotted in Fig. 4.

5.1. *Jackknife Errors*

To calculate uncertainty in the estimated probability density functions of the environments, $P_{i,\mathrm{bin}}$'s : $i = 1, 2, 3$ for each of the populations, we use the standard jackknife technique. Jackknife re-sampling gives us an internal error estimate that tests how representative a measurement/trend is of the data it is estimated with. We divide our entire sample into 20 subsamples with nearly equal co-moving volumes and estimate the same probability density functions(P_i^j's) for the whole sample while leaving out one subsample each time. We can then estimate our uncertainty for each bin in the PDF's thus:

$$\sigma_{i,\mathrm{bin}} = \sqrt{\sum_{j=1}^{j=20} (P_i^j - P_{i,bin})^2}$$

The jackknife errors are shown in Fig. 4 and confirm our hypothesis: that the Outliers are a little different than the MAGPHYS Box but still, very different from the UV Box.

6. SUMMARY AND CONCLUSION

- From Fig 1, we see that MAGPHYS SSFR identifies a region in the color-color space as dust-obscured star forming galaxies and correlates better with the environments of the galaxies.

- At the higher star formation end, we find that the dust-obscured star-formers as identified by MAGPHYS have environments comparable to the blue star-forming galaxies, confirming that this is indeed a physical effect we're seeing.

- Comparing the environment distribution of the Outliers relative to the galaxies with (a) the same MAGPHYS SSFR's as the Outliers and (b) the same UV SSFR's as the Outliers (Fig. 4), we find that the Outliers indeed have a similar environment distribution to the galaxies that have the same MAGPHYS SSFR's, i.e., they seem to favor lower environment densities mimicking the behavior of star-formers.

REFERENCES

da Cunha, E., Charlot, S., & Elbaz, D. 2008, Monthly Notices of the Royal Astronomical Society, 388, 1595

Ilbert, O., McCracken, H. J., Le Fvre, O., et al. 2013, Astronomy & Astrophysics, 556, A55

Moustakas, J., Coil, A. L., Aird, J., et al. 2013, The Astrophysical Journal, 767, 50

Muzzin, A., Marchesini, D., Stefanon, M., et al. 2013, The Astrophysical Journal, 777, 18

Salim, S., Rich, R. M., Charlot, S., et al. 2007, The Astrophysical Journal Supplement Series, 173, 267

Tomczak, A. R., Quadri, R. F., Tran, K.-V. H., et al. 2014, The Astrophysical Journal, 783, 85