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ULTRAVIOLET TO INFRARED STAR FORMATION RATE INDICATORS AND GALAXY ENVIRONMENT

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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 band-passes. 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 re-emitted 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 9) and GALEX imaging for galaxies. The total

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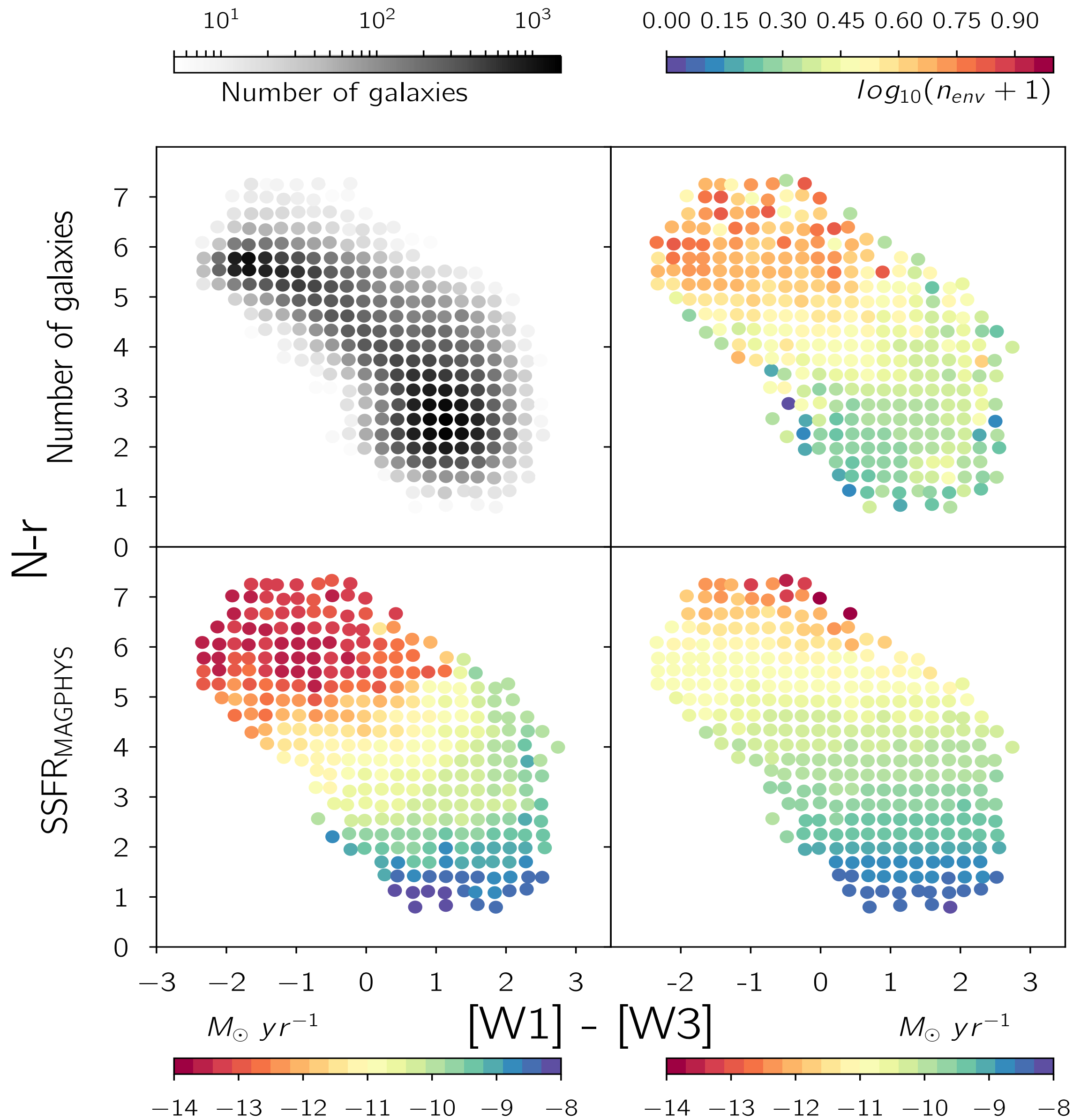

Figure 1. The SSFR measurements and environment shown the color-color space. Each point in the plot is shown at the mean colors in each of the bins we use. The grey value or color of the points in each panel show the mean value in each bin for the quantity described by the corresponding color bar. *Top 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 $v_{los} = \pm 1000 km/s$). *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 $\sim 150,000$. We define two samples from the NSA, one that we use to define environment(Environment Determining Population or EDP, hereafter) and one for which we determine star formation rates (Star Formation Rate Population or SFRP hereafter). We note that the SFRP is a subsample of the EDP. To get our EDP, we impose a volume-limited cut on this sample by retaining only galaxies with $-24.5 < M_r < -18.5$ which leaves us with 95,638 galaxies.

The star formation rate determinations we use here require both UV data and IR data. About 80% of our galaxies have UV data from GALEX analyzed in the NSA. To obtain infrared imaging for the data we have matched the objects from the NSA with the WISE (Wide-Field Infrared Survey Explorer) data **which catalog specifically? ALLWISE DR** 2013**?** with K-corrected WISE magnitudes. Now about 20% of the objects in the NSA do not have GALEX Photometry, which is crucial for us to determine our SFR's, especially the UVSFR's. Apart from that, less than 1% of the objects do not have reasonable optical/WISE fluxes. We removed all such objects with missing/faulty photometry in addition to correcting for edges in sample **(refer section Edge Effects)**. Since we intend to study the evolution of these galaxies through the optical-IR phase space, we imposed a cut in optical ($7.5 > N - r >= 0$) and infrared ($3.0 > [W1] - [W3] >= -3.0$) colors (top left corner of Fig. 1). Our SFRP ultimately consists of 61,046 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). **How was K-correction done for WISE?**

The environment tracing sample needs to be volume-limited; that is, to have an expected mean density independent of redshift. To achieve this, we restrict in absolute magnitude to $-18.5 > M_r > -24.5$. This yields a population of $95,638$ galaxies. zero/negative fluxes, to obtain 75476 galaxies upon which the star formation rate measurements were then performed. **is this last sentence still right?**

3. ESTIMATING THE SPECIFIC STAR FORMATION RATES

We compare two approaches to calculating specific star formation rates (SSFRs). The first uses UV, optical, and IR data. The second uses only the UV data.

3.1. *SED Fitting - MAGPHYS*

We develop here a method to quickly estimate SSFRs based on UV-optical and infrared colors. We begin by sorting galaxies into bins of the $N-r$ - $[W1]-[W3]$ color space (25×25; **what is size of bins in magnitudes**). Within each bin, we normalize the fluxes of each galaxy relative to a constant flux in the r-band, and then take the mean normalized flux in each band over all galaxies in the bin. This procedure yields a "template" SED for each bin in the color-color space.

We then use Multi-wavelength Analysis of Galaxy Physical Properties (**?**, MAGPHYS) to infer the SSFR for each template SED. MAGPHYS 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.

The results for the SSFRs thus obtained for each template are shown in the lower left panel of Figure 1 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.

The resulting distribution of the MAGPHYS-based SSFRs across the color-color space looks as we would expect it to for the most part. In UV-optical colors, blue galaxies have high SSFRs, and red galaxies have low SSFRs. However, there is also a dependence of SSFR on IR color; most notably, in the UV-optical green valley, the redder galaxies in the IR have higher SSFRs. These galaxies are

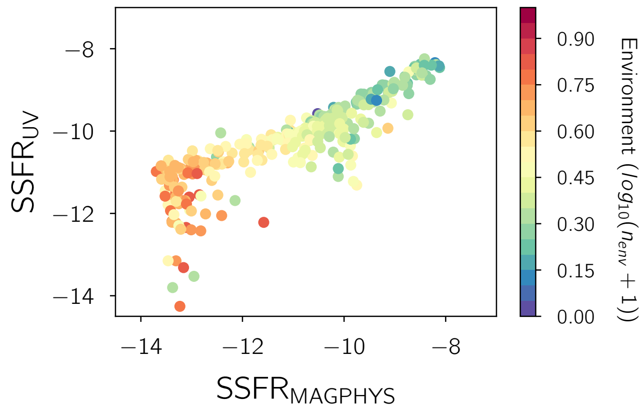

Figure 2. The two star formation rate estimates (from Fig.1) plotted against each other as a function of the environment; We notice two distinct set of outliers that seem to have lower UV SSFR's but similar environments to the galaxy bins with the same MAGPHYS SSFR's.

likely to be dust-extincted in the UV, with the reemission by dust reddening the IR colors.

In what follows, we will use the UV-optical and IR colors of individual galaxies, and the dependence of the SSFR on these colors shown in the lower left panel of Figure 1, to assign an SSFR to each individual galaxy.

3.2. *UV Star Formation Rates*

We also explore a simple method of determining star formation rates developed by Salim et al. (2007) that depends only on the UV fluxes of each galaxy. It assigns a star formation rate that is proportional to the UV luminosity (specifically the FUV band if we are looking at GALEX). Dust attenuation is also accounted for in this method by looking at the ratio of luminosities in the FUV and NUV bands.

According to this prescription (Salim et al. 2007), the star formation rate is given by:

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

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

If $N - r \geq 4.0$, i.e. for the red sequence galaxies,

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

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

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

This method effectively uses the UV slope to estimate the dust attenuation.

The lower right panel of Fig. 1 shows the mean UV SSFR as a function of color. Compared to the lower left panel, the UV SSFR's have a nearly monotonic relationship with UV-optical color whereas, as discussed above, the MAGPHYS SSFRs do not. Assuming the

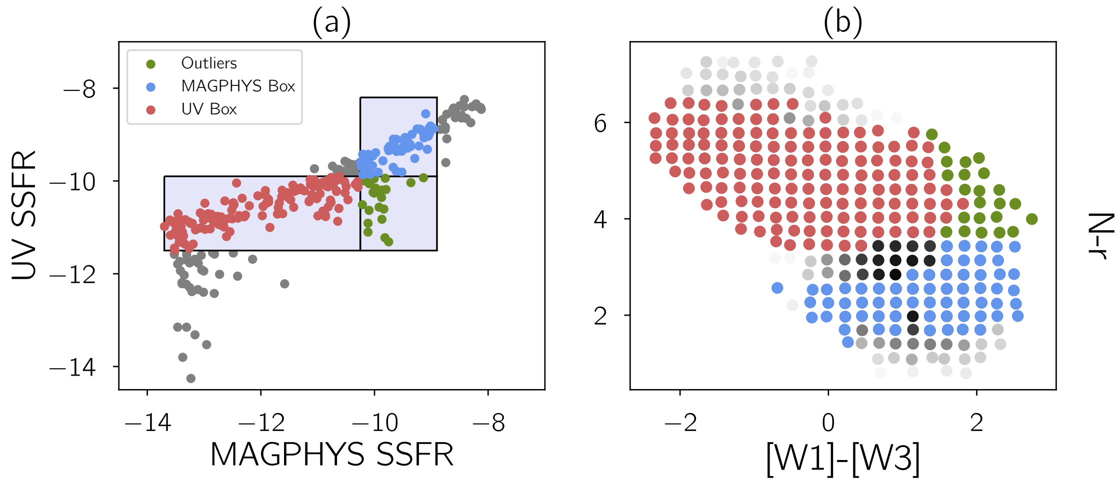

Figure 3. The outliers shown as a function of the Star Formation Rates as well as Optical and IR colors

MAGPHYS SSFRs are closer to correct, the UV-optical green valley contains a population of galaxies that are not truly transitioning but instead are reddened by the presence of dust. Furthermore, the nominally dust-corrected UV star formation rates do not successfully identify these galaxies. **it seems like a good idea to quantify the fraction of galaxies like this; say within $2.5 < N-r < 4.5$, what fraction have $W1-W3 > 1.5$, or something like that. might be good to answer that question in 3 bins of absolute magnitude too**

4. ENVIRONMENTS

We identified above a population of galaxies for wIn 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.

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.

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 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 $0.5 Mpc$ 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

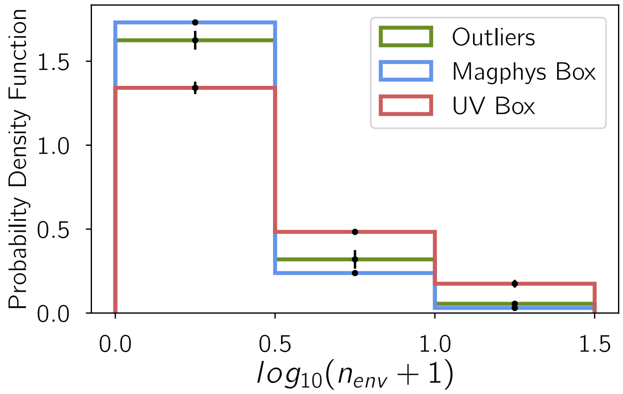

Figure 4. Probability density functions of the Environments of the three populations described in Fig. 2;

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).

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. 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