UMKC Summer of 2021 Research Summary

GALEX Analysis of Recently Quenched Ellipticals (RQEs) Technical Report

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Contents

List of Figures

1 Abstract

The role of star formation (SF) quenching in the hierarchical model of the development of galaxies in our universe has long been an unsolved puzzle. Here, using Galaxy Evolution Explorer (GALEX) + Sloan Digital Sky Survey (SDSS) data, I investigate SF signatures on a sample of 172 low-z ($z \leq 0.08$) Recently Quenched Ellipticals (RQEs). Through a careful analysis of Near-Ultraviolet (NUV) light, I discover 26 RQEs that have evidence of recent SF. Of the recent SF RQEs, they all are the lightest in stellar mass, bluest in color and faintest in r-band flux; which is in agreement with the hierarchical model of the development of galaxies. Furthermore, I discover at least 3 galaxies in this sample that can be considered actively star forming based on their urz color and location on NUVur color plots. Presumably, through an analysis of color-color-age plots, rejuvenation processes are the main cause of these active and recent SF ellipticals. Finally, I advise that the 3 ellipticals that were discovered to have active SF should be eliminated from further analyses of RQEs because they ultimately fail to be considered true RQEs.

2 Introduction

2.1 Motivation

The quenching of SF in galaxies is rather illusory. Recently in the literature, however, there have been some thoughtful analyses on SF quenching (Kalinova et al. 2021 [7]). Although, to get the full picture of galaxy evolution and growth, there are still some crucial questions to be answered to formulate the processes that galaxies undergo. One of these questions that is of relevance to this analysis is: What is the primary physical case of quenching and does quenching occur rapidly (< 1 billion years) only in small, dense massive galaxies? Answering this question is essential to understanding galaxy evolution and growth, and in particular understanding SF quenching. Recently Quenched Elliptical (RQE) galaxies are thought to be of a critical population that have recently or are currently undergoing SF quenching. Getting a better understanding of these peculiar galaxies are of the main motivation behind studying RQEs. To study these RQEs effectively however, a filtering of the current sample of RQEs needs to be done in order to validate that these galaxies truly are recently quenched. This is the main motivation of this GALEX analysis of RQEs.

2.2 Application to Larger Research Project

The larger research project of the research lead, Deepak Deo, is a rigorous analysis of the properties of low-z (z $\leq$ 0.08) RQEs. RQEs are a relevantly new distinguished population of galaxies that have not been extensively studied in extragalactic astronomy. Therefore, to get a better understanding of RQEs, that is, their history, development, environment, activity and color, Deepak Deo is foregoing a meticulous investigation of the nature of low-z RQEs. This research could prove to be of tremendous importance in understanding the different physical processes that cause SF quenching. Moreover, Deo's research will highlight why RQEs are special and are worth studying. For Deo's work to be successful, he need to have a representative sample of true RQEs, that is, RQEs that are physically undergoing SF quenching or have recently gone through SF quenching.

2.3 Research Goals and Description

The role of GALEX analysis, in conjunction with the larger research project of RQEs, is to eliminate any "fake" RQEs. That is, RQEs that have evidence of SF. If a galaxy is identified to have SF, then it shouldn't be considered recently quenched and should be eliminated from this RQE catalog. Essentially, this is exactly what the purpose of this analysis is. To eliminate any of these galaxies that are actively producing stars. Rejuvenation processes can cause these SF episodes in this ellipticals, or they can simply be a Green Valley (Schawinski et al. 2014 [1] [13]) galaxy with no SF transitioning to the red sequence.

Furthermore, the overarching goal of this GALEX analysis is to determine how quenched our sample of RQEs really are. My role is to find and study any rejuvenation signatures in the sample of RQEs. That is, signatures of SF or even recent SF due to a number of

[1]For a description of the Green Valley visit, Schawinski et al. 2014; https://arxiv.org/pdf/1402.4814.pdf

environmental factors. I will do this be employing the Galaxy Evolution Explorer (GALEX) data of Near-Ultraviolet (NUV) light. I also use Sloan Digital Sky Server (SDSS) data in the u-, r- and z-band filters. With this data, I created many plots and added multiple columns to these catalogs to investigate any SF signatures in the sample of RQEs. In this technical report I will explain the steps I took to contribute to the larger research effort of Deepak Deo

3 Sample

3.1 Sample description

The parent catalog utilized in this analysis is a sample of 172 RQEs which was developed and described in detail by McIntosh et al. 2014 [9]. In this paper, McIntosh describes the steps his group took to derive this sample of ellipticals and explain why they believe these galaxies have recently became quenched. In short, the description of RQEs is that their SF has recently been shut off and as a whole are becoming "red and dead". The 172 RQEs in this analysis, however, are interesting in the fact that they all appear more blue than the majority of the elliptical galaxy population. This is one of the reasons, among others, why they are considered recently quenched.

3.2 Obtaining the data

The data that is applicable for this research is from the Galaxy Evolution Explorer (GALEX) and the Sloan Digital Sky Server (SDSS). The data that is of interest from GALEX is the Near-Ultraviolet (NUV) magnitudes. While, the data that is of interest from SDSS is the u-, r- and z-band filter magnitudes.

The first action I took in obtaining the data was receiving the main "parent" catalog of the 172 RQEs from Deo. Once I had the catalog of our RQEs of interest, the next step was to match these galaxies with the sources observed from GALEX and download a new catalog of the GALEX data of these 172 RQEs. To do so, I had to use the Multi-Mission archive at the Space Telescope Science Institute (MAST) queries website [2] [1]. MAST publicly stores data taken from a multitude of space telescopes. To access the data stored in the MAST portal, and ultimately to download GALEX data of the 172 RQEs, I simply imported the 'astroquery.mast' module in python and accessed the 'catalog' function from the 'astroquery.mast' module. I received the bulk of the code in python to download the GALEX data from Deo, however this code had some imperfections and did not function properly. Some minor adjustments had to be made in the reading of the CSV parent catalog and writing of the new CSV file containing the GALEX data.

In trying to resolve the error in the GALEX code, I conducted a plethora of independent researching of reading and writing CSV files in python. While my own new knowledge of reading and writing CSV files was not what ultimately resolved the issue, even though a couple trial runs I ran from my new knowledge of this researching was very close to resolving the GALEX code issue, I nevertheless learned a lot about different ways to read and write

[2]MAST queries website `https://astroquery.readthedocs.io/en/latest/mast/mast.html`

CSV files in python. To my surprise, this new knowledge actually became very applicable in creating plots.

During this time, I expanded my searching into looking at relevant research papers[3]. on rejuvenation analysis of elliptical galaxies. The reason being, is to get a better sense of what other researchers have already done with GALEX data and what conclusions they have drawn. Also, skimming relevant papers for plots, and coming to understand what these plots mean, can give us a better idea of what plots we should make in this analysis, ultimately helping us decided what plots will help tell the story of RQEs the best.

While still stuck on the GALEX coding issue, I decided to move onto obtaining the SDSS data. To do this I employed the SDSS SkyServer DR15 web page [4] [3]. From here I uploaded only the first three columns of the parent catalog, from which I had to make in TOPCAT, and followed instructions from Deo on how to use the Structured Query Language (SQL) to download a catalog of the data that we wanted. Below is the SQL I used to download the data appropriate to our research needs.

```
SELECT
        p.objID,
        (p.modelMag_u-p.extinction_u) as uModelMag,
        (p.modelMag_r-p.extinction_r) as rModelMag,
        (p.modelMag_z-p.extinction_z) as zModelMag,
        (p.petroR90_r/p.petroR50_r) as conc,
        (p.petroR50_r) as R50r,
        (p.petroR90_r) as R90r
FROM #upload u
                JOIN #x x ON x.up_id = u.up_id
                JOIN PhotoObjAll p ON p.objID = x.objID
ORDER by x.up_id
```

Figure 1: Structured Query Language (SQL) to download SDSS data

With this SQL query I was successfully able to download a catalog of extinction corrected magnitudes in the u-, r- and z-band filters; as well as other pertinent data like the galaxies name, object ID, concentration and the radii containing 50% and 90% of the petrosian flux. These magnitudes from SDSS are in the AB magnitude system[5] [6] and were downloaded as model magnitudes.[6] [2]

The next step was trying to understand what the data from GALEX and SDSS physically represents. For this I created two README.txt files[7] for GALEX and SDSS containing the descriptions and units for each respective data columns. For SDSS I was able to complete

[3] Some relevant research papers on SF quenching I found were: Nogueira-Cavalcante et al. 2017 [10]; https://arxiv.org/pdf/1709.07015.pdf#page1, Kaviraj et al. 2008 [8]; https://arxiv.org/pdf/0711.1493.pdf and Schawinski et al. 2007 [12]; https://arxiv.org/pdf/astro-ph/0601036.pdf

[4] SDSS SkyServer DR15 web page: https://skyserver.sdss.org/dr15/en/tools/crossid/crossid.aspx

[5] For a description on magnitude systems visit: https://lweb.cfa.harvard.edu/~dfabricant/huchra/ay145/mags.html

[6] For a description of Model magnitudes from SDSS visit: https://www.sdss.org/dr12/algorithms/magnitudes/

[7] GALEX README.txt file https://docs.google.com/document/d/1_GH-0YqH977Zbqst3Gu6re5UxE7XKpn1dc-jRHaCT1w/edit. SDSS README.txt file https://docs.google.com/document/d/1MYM8OjkTHuAkonGpOipsbCD65jVNCAYs8BVLK2DmmHE/edit

this relatively quickly as I already had the catalog and ran into no major issues. For the GALEX README.txt file on the other hand, this took a lot longer as I didn't obtain the catalog until much later and there were a lot more data columns to be filled.

Finally, with the help of a mentor, Kameswara Mantha, many days after embarking on the journey to obtain the GALEX data, we resolved the GALEX coding issue and was able to match the galaxies in the parent catalog with the galaxies in MAST and download the GALEX data of our 172 RQEs of interest. The NUV magnitude of interest in the GALEX data is also in the AB magnitude system and was downloaded as model magnitudes. This was the last piece of the puzzle in obtaining the data that we needed to move onto correcting the data.

3.3 Correcting the data

Raw extragalactic data from telescopes and satellites, whether on Earth or in space, is tampered with before reaching the detectors in instruments to be measured. There are two main physical processes that interfere with the light on its way to us. The first being the shear physical distance between us and the sources of interest, coupled with the cosmological fact that the universe is accelerating in its expansion. This physical process causes a elongation in the wavelength of light during its journey; because of this the light that is observed is different than when it was emitted. The second physical process that tampers with the original emitted light from extragalactic sources is simply stuff in the way of lights path. Light encounters clouds of gas and dust along its trek and is absorbed or scattered from the molecules that constitute these gas/dust clouds. The process of correcting the former is called K-Correction, while the process of correcting the latter is called Extinction Correction. Both of witch are pertinent in the GALEX and SDSS data obtained for this analysis.

Fortunately, when I was downloading the SDSS data from the SkyServer DR15 website, I was able to directly obtain extinction corrected data from specifying in the SQL query "extinction". This was of huge help and a big time saver as I did not have to manually correct the data myself. To extinction correct the GALEX data, contrarily, I did have to manually correct the data myself. To do this, I first had to do my research on how to extinction correct extragalactic data. I found many useful websites and published research papers on extinction correction (links below):

Websites and research papers over extinction correction:

1. `https://astronomy.swin.edu.au/cosmos/I/Interstellar+Reddening`
2. `https://w.astro.berkeley.edu/~ay216/08/NOTES/Lecture05-08.pdf`
3. `https://iopscience.iop.org/article/10.1086/316293/pdf`
4. `https://www.cloudynights.com/articles/cat/articles/basic-extragalactic-\ astronomy-part-3-luminosity-corrections-cosmological-extinction-and-mas\ -r3221`
5. `https://dust-extinction.readthedocs.io/en/stable/dust_extinction/extinction.html#extvsatt`

With the help of these references above and the research lead Deepak Deo, I was able to acquire the equation for the extinction parameter necessary for correcting for galactic extinction. The extinction correction equation is:

$$A_v = 8.741 * E(B - V). \tag{1}$$

Where E(B-V) is the difference in the observed and emitted color in the B and V bands, respectfully. Av is called the extinction parameter and represents the extinction at a particular wavelength. The constant 8.741 was obtained from referring to section 3.4 in Vaddi et al. 2016 [14]. From here, I went into TOPCAT, loaded in the GALEX catalog, created a new column for the extinction parameter, and then finally created another new column for the extinction corrected NUV magnitudes by simply subtracting the raw NUV magnitude data by the extinction parameter.

The next correction that is of interest for our data was K-Correction. Similarly with extinction correction, I researched how to perform K-Correction on extragalactic data, from which I found a plethora of useful websites and papers that helped me get a grasp on performing K-Correction on extragalactic data.

Websites and research papers over K-Correction:

1. `https://iopscience.iop.org/article/10.1086/524677/pdf`
2. `https://iopscience.iop.org/article/10.1086/431416/pdf`
3. `https://arxiv.org/pdf/astro-ph/0606170.pdf`
4. `https://properphysics.wordpress.com/2015/04/25/k-correction/`
5. `http://kcorrect.org`
6. `http://kcor.sai.msu.ru/getthecode/#python`
7. `https://github.com/nirinA/kcorrect_python`
8. `https://extinction.readthedocs.io/en/latest/`
9. `https://arxiv.org/pdf/astro-ph/0210394.pdf`

To help me further in K-Correcting our data I emailed Dr. Blanton who is an astrophysicist with New York University who has written a code called kcorrect[8], which can be made applicable to all extragalactic sources at any redshift. Dr. Blanton pointed me in the direction of the python version of the code called kcorrect python[9]. I downloaded and tried using this code to K-Correct our data but unfortunately was meet with error after error in the code. Around this time, I had a meeting with Deo where he advised me to use the calculate kcorrection GALEX code that he has used in the past. Once I got this code I began to revise it for our GALEX and SDSS data. However, again I was meet with error's

[8] kcorrect: `http://kcorrect.org`

[9] kcorrect python: `https://github.com/nirinA/kcorrect_python`

in the code. With time becoming short for the rest of the research project, Deo made the executive decision to disregard K-Correction for our data, where he explained to me that the results we obtain from our plots will not be heavily effected from excluding K-Correction. While K-Correction was never successfully performed on the GALEX and SDSS data, I nevertheless learned substantially about what K-correction is, why we would want to perform K-Correction and how to perform such a correction to extragalactic data.

4 Analysis

4.1 Plotting the data

There are 3 main plots that are crucial to telling the story of RQEs and rejuvenation. These plots are: color-mass plots, color-magnitude plots and color-color plots. More specifically, the color-mass plot is (NUV-r) versus stellar mass, the color-magnitude plot is (NUV-r) versus Mr and the color-color plot is (NUV-r) versus (u-r). There are two justifications behind making these plots. One, the research lead, Deo, explained that these are going to be the main plots that will help tell the story of RQEs the best, and two, because similar type plots are in the literature that is of relevance to this analysis. In this section I will describe the process of creating these plots.

The steps I took into creating these 3 plots were all about the same. I created all of the plots in this analysis in the software PyCharm in the programming language Python. The outline of the python code to create these plots are all very similar. For all of them, there are 4 main structures in the code that are imperative to creating a plot. The first one is loading in the necessary modules in the code. This is a necessary step because without it we wouldn't be able to incorporate numbers or use a certain function to plot the data. Below is an example of what modules I loaded in to create the plots.

```
import numpy as np
import matplotlib.pyplot as plt
from astropy.io import ascii
```

Figure 2: Modules imported in code to plot

The next main structure of the code to create plots is loading in the catalogs of interest and creating subsets of these catalogs. These catalogs came from the first section in this research overview, *Obtaining the Data*. This step is extremely important because without it we wouldn't have any data points in our plots. Below is an example of catalogs I loaded in to create our plots.

```python
file_1 = '/Users/slaterjonesoden/Desktop/GALEX_analysis/EC_RQE_SDSS_data.csv'
SDSS_sample = ascii.read(file_1, format='csv')

file_2 = '/Users/slaterjonesoden/Desktop/GALEX_analysis/172_GALEX_mast_catalog.csv'
GALEX_sample = ascii.read(file_2, format='csv')

file_3 = '/Users/slaterjonesoden/Desktop/GALEX_analysis/RQE_sample_data.csv'
RQE_sample = ascii.read(file_3, format='csv')

good_subset1 = SDSS_sample[np.where(SDSS_sample['rModelMag'] != -99)]
good_subset2 = SDSS_sample[np.where(SDSS_sample['uModelMag'] != -99)]
good_subset3 = GALEX_sample[np.where(GALEX_sample['EC_nuv_mag'] != -99)]
good_subset4 = RQE_sample[np.where(RQE_sample['age(years)'] != -99)]
```

Figure 3: Catalogs loaded in and subsets created in code

The third main structure of the code I wrote to create these plots is arguably the most important part. This is the line of code that actually creates the plots. This step is successful because we imported the module 'matplotlib.pyplot'. This module takes on catalogs/subsets and creates plots based on the criteria and format that the user gives. Below is an example of the line of code I wrote in order to create the color-mass plot.

```python
plt.plot(good_subset3['logMstar[Msun]'], good_subset2['EC_nuv_mag'] - good_subset1['rModelMag'],
        marker='.', markersize=5, color='black', linestyle='None', alpha=0.99, label='RQEs')
```

Figure 4: Line of code to create plots

The last main structure of the code to create plots is defining the axes of the graph, showing the plot, and saving the plot. What I mean by defining the axes is setting the limits of each axis, creating the tick marks that will go on each axis, and naming the label of each axis. The showing and saving of the plot is rather self explanatory. If we do not show the plot, no plot will be generated, and if we do not save the plot, no plot will be saved to the computer. In this structure we can also define legends of the plot that can help differentiate the data points. Below is an example of the last main structure of the color-mass plot.

```python
plt.xlim([10, 11.5])
plt.xticks([10.0, 10.3, 10.6, 10.9, 11.2, 11.5], fontsize=16)
plt.ylim([1.0, 8.0])
plt.yticks([1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0], fontsize=16)
plt.xlabel('$log_{10}$(Stellar Mass)', fontsize=18)
plt.ylabel('(NUV - r) Color', fontsize=18)
plt.legend(loc=2, fontsize=11)

plt.tight_layout()
plt.savefig('/Users/slaterjonesoden/Desktop/GVCut&ColorCoded_(NUV-r)_vs_StellarMass_plot.png',
            format='png', bbox_inches='tight')
plt.show()
```

Figure 5: Defining axes, showing and saving plots

The 3 basic color-mass, color-magnitude, and color-color plots were all created using these 4 main structures of code. Of course for each of them, small changes had to be made in the loading of the catalogs, the line to actually plot the data and the last main structure in defining the axes of the plot. Nevertheless, each 3 main plots incorporated these 4 structures of code. Below are the first color-mass, color-magnitude, and color-color plots I created for this analysis.

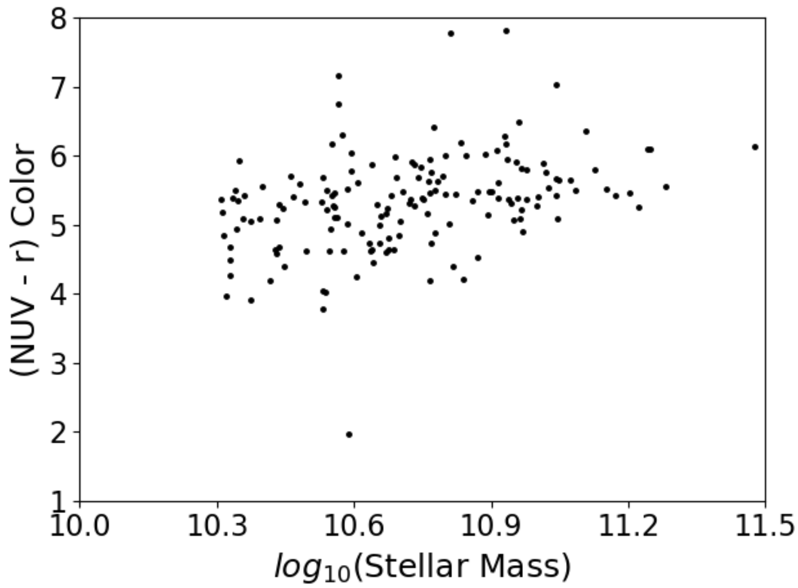

Figure 6: (NUV-r) vs Stellar Mass plot

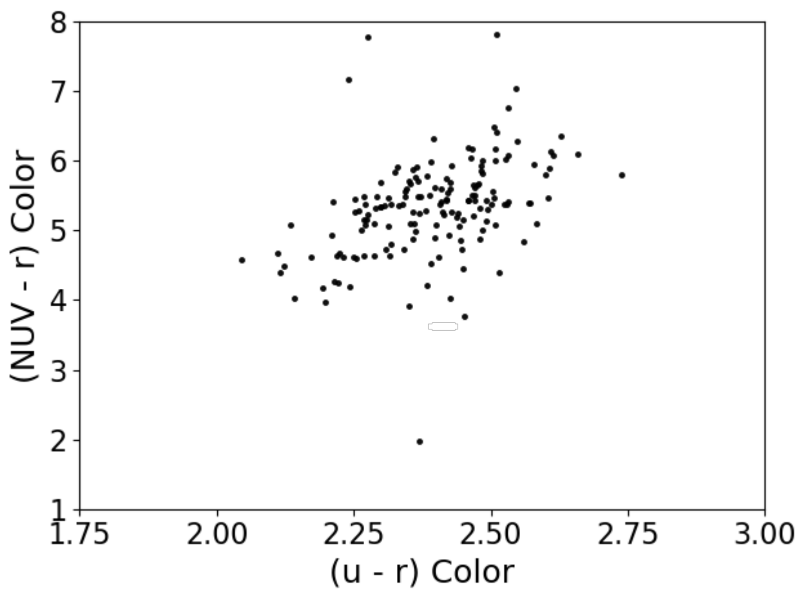

Figure 7: (NUV-r) vs (u-r) plot

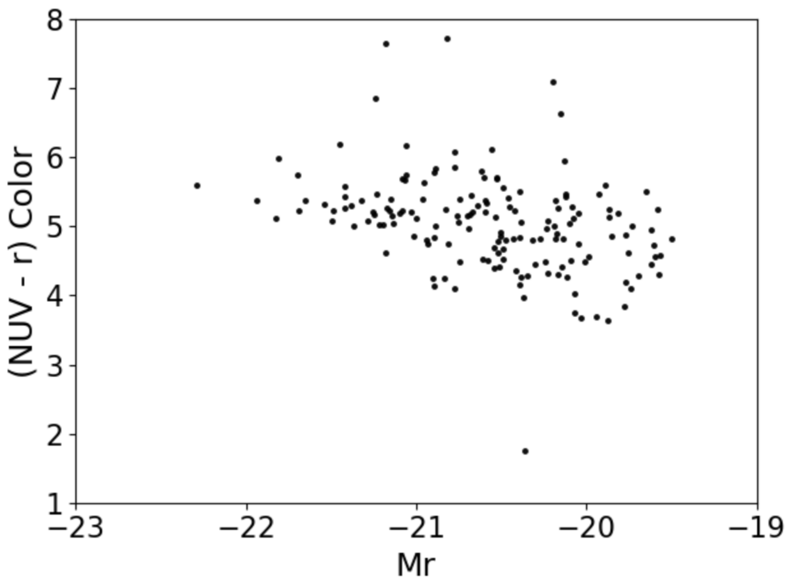

Figure 8: (NUV-r) vs Mr plot

4.2 First Interpretations of Main Plots

Before moving onto adding more information to these plots, its important to first analyze these plots and make sure they make sense. This is a crucial step in the analysis of the data because without it there could be a simple graphing mistake in these plots that could prevail throughout the rest of this analysis. Or, on the other hand, there could be concepts that are not understood or features not noticed in these initial plots that could hinder the success of adding more information to these plots.

Lets begin by first analyzing the color-mass plot. As we can see, there is a slight positive trend from left to right in the data points. In thinking about this, this makes sense because as you increase in stellar mass you are more likely to find a galaxy with a more red NUVr color. This feature in the plot is supported by urz color-color-velocity dispersion plots and Velocity Dispersion vs Stellar Mass plots, where it is observed that Early Type Galaxies (ETGs) have greater (u-r) and (r-z) colors (i.e., are more red in color) (Brammer et al. 2009 [5]), have a greater velocity dispersion than Late Type Galaxies (LTGs) and, on average, have a higher stellar mass than LTGs. Therefore, in first analysis of the color-mass plot of these RQEs the trend in the data points can be justified.

Lets now analyze the color-color plot. Just as in the color-mass plot we see a positive trend going from left to right. This also makes sense and can be easily justified. In the bottom left corner of this plot we have the bluest NUVr and ur colors, whereas in the top right corner we have the reddest NUVr and ur colors. Therefore, it makes sense to see a positive slope in this plot. On the contrary, it would not make sense to see a negative slope here, because it would be very unlikely to see a very blue ur color (e.g, (u-r) = 1.75) galaxy and an associated red NUVr color (e.g, (NUV-r) = 7.5). Thus, the first analysis of this color-color plot is logical.

In the color-magnitude plot we see a different trend than in the two previous plots. However, in careful inquiry of this plot, the negative trend we see can be legitimized. First to note, the magnitude plotted here is the Absolute Magnitude [10] in the SDSS r-band filter. We know that ETGs are more red than LTGs (Brammer et al. 2009 [5], Baldry et al. 2004 [4]). We also know that the u-band filter in SDSS is centered on bluer light than in comparison with the r-band filter. Thus, galaxies that are more blue will have a more negative u-band absolute magnitude than r-band absolute magnitude [11]. In the plot, we see the reddest galaxies having the most negative r-band absolute magnitude and the more blue galaxies having more positive r-band absolute magnitudes. Therefore, the interpretations of this color-magnitude plot make sense with the locations of the SDSS filters on the wavelengths of light.

4.3 Adding Information to Main Plots

After I created and interpreted these initial plots, my next task was to add more information that could be useful in acquiring new intellect from these plots. The first additional information I added to these plots was a Green Valley cut, from which we acquired from Salim 2015 [11]. These Green Valley cut plots are below:.

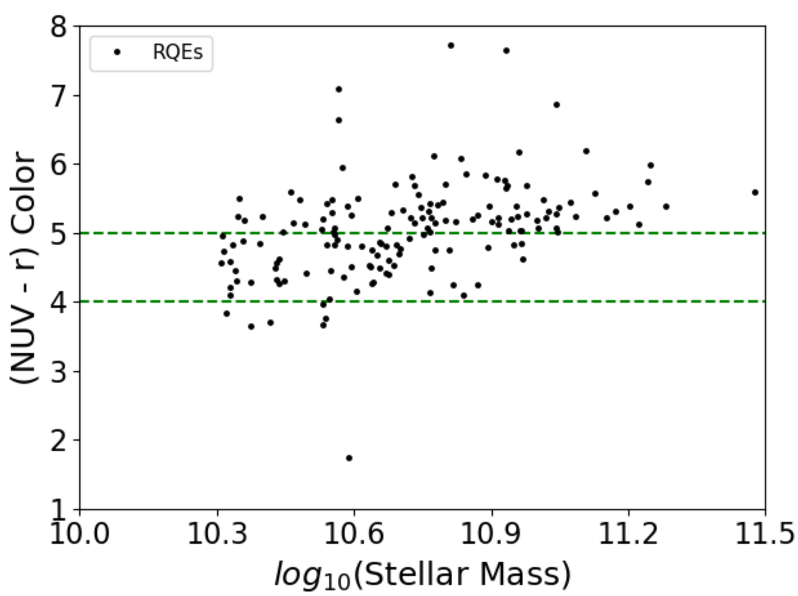

Figure 9: (NUV-r) vs Stellar Mass plot with GV cut

[10] For a description on Absolute Magnitude visit: `http://csep10.phys.utk.edu/OJTA2dev/ojta/c2c/ordinary_stars/magnitudes/absolute_tl.html`

[11] Recall the magnitude system in Astronomy is reversed. A more luminous galaxy will have a more negative absolute magnitude, whereas a fainter galaxy will have a more positive absolute magnitude

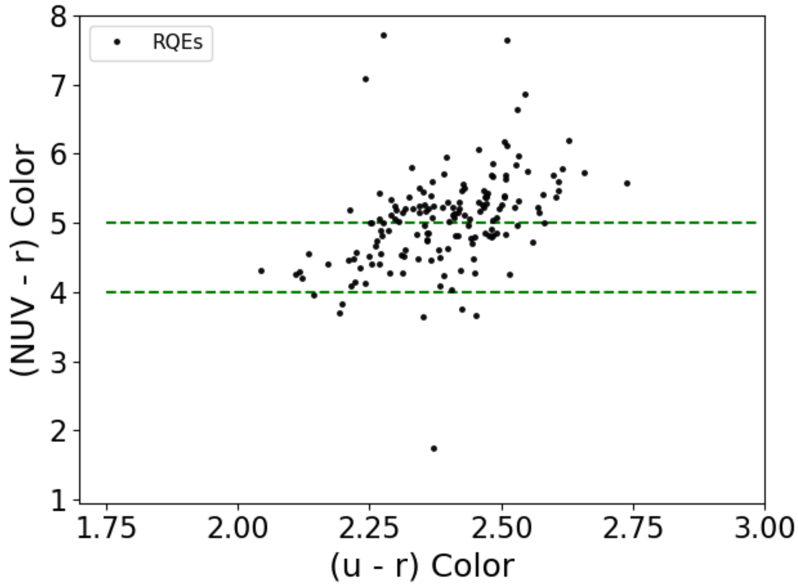

Figure 10: (NUV-r) vs (u-r) plot with GV cut

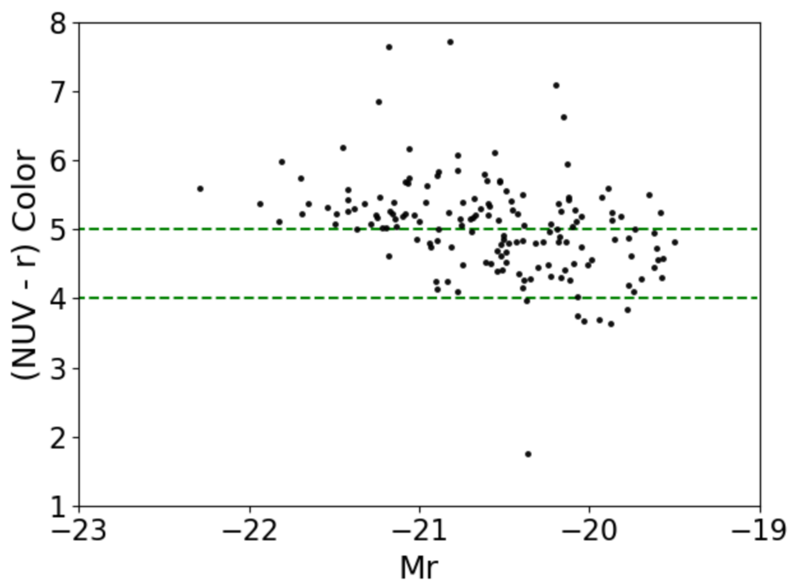

Figure 11: (NUV-r) vs Mr plot with GV cut

In adding a green valley region in these plots, we begin to get a sense of where the RQEs in this sample lie in the color bimodality of galaxies. Galaxies below the green valley region are considered to be star forming, while galaxies above the green valley region are considered to be quiescent and non-star forming. Galaxies in the green valley region have been speculated to be moving from the blue cloud to the red sequence (i.e., in the process of quenching SF). As we can see, there is a significant fraction of this sample that lies within the green valley region. This is not much of a surprise as this sample of RQEs was devised in the fact that they could be a new generation of ETGs. Also not to surprising is that a large number of this sample lies above the green valley region. What is interesting though, is that some of these RQEs do in fact lie below the green valley region. This would mean that these galaxies have had recent SF in their past or are actively producing stars. To distinguish between recent and active SF we need to add more information to these plots, which will be addressed below. For now, we can notice that by adding a green valley cut in these main plots, we have begin to unveil SF signatures in some of these RQEs.

The next information I added to the main plots in this analysis was color coding the data points based off of two criteria. Criteria one, star forming and quiescent[12], from which blue represents star forming and red quiescent. Criteria two, central and satellite[13], where red represents a central and blue represents a satellite. The star forming color coded plots are below:

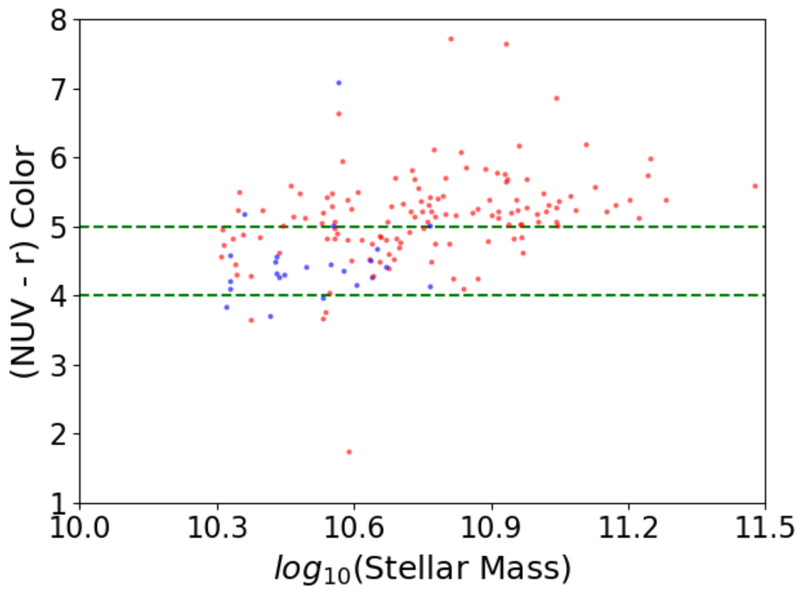

Figure 12: SF color coded (NUV-r) vs Stellar Mass plot

[12]This color selection of star forming and quiescent is based on the color-color plot in McIntosh et al. 2014 [9]

[13]A central galaxy here is one that lies in the center of a small group, whereas a satellite is orbiting the center of a small group

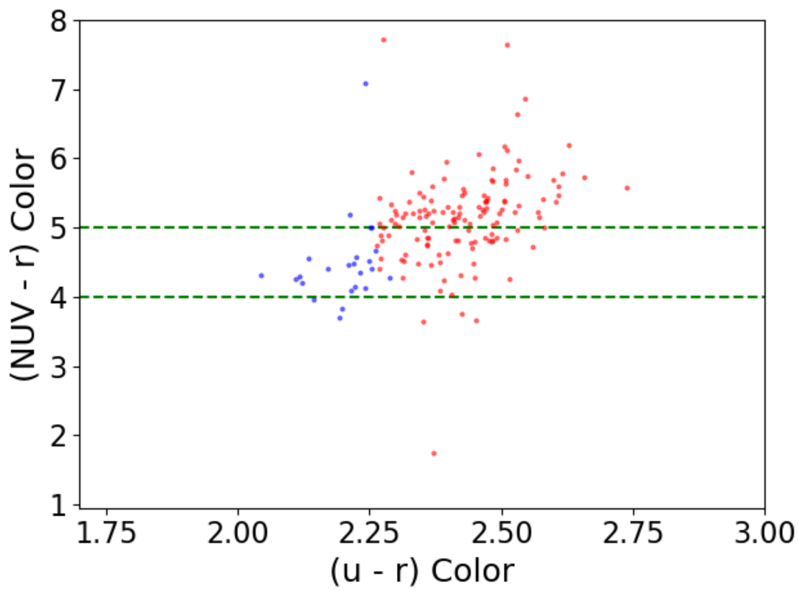

Figure 13: SF color coded (NUV-r) vs (u-r) plot

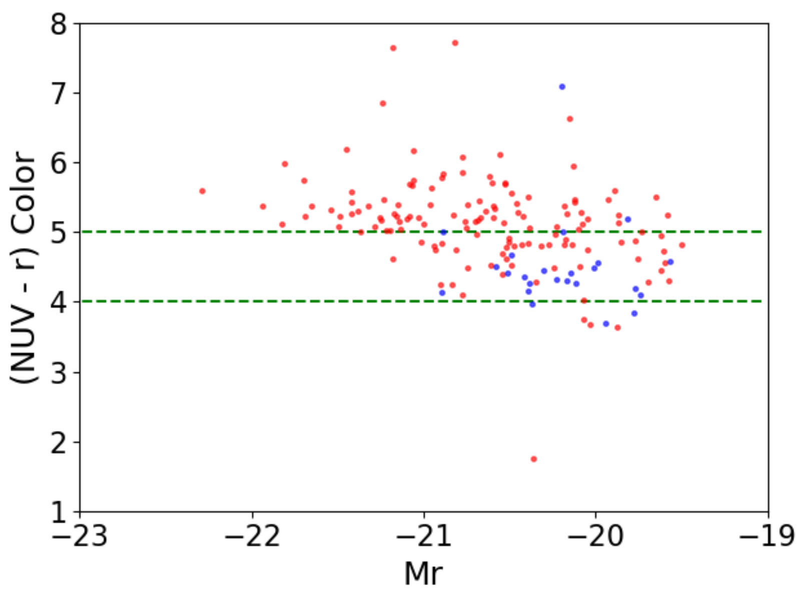

Figure 14: SF color coded (NUV-r) vs Mr plot

Adding a star forming and non-star forming color coded selection to these plots raises some interesting points. First it should be mentioned that this color selection is based solely on the urz diagram of these RQEs and not on their NUVr color. Figure 18 below shows the urz color selection plot for these RQEs. Now, the first interesting point is that 26 of these RQEs are considered to be SF galaxies based on their urz color. The second interesting point is that we see blue color coded RQEs in all three regions of the plots (i.e. star forming region, green valley region and the quiescent region). A color coded blue SF galaxy in the star forming region can probably be considered an ongoing star forming galaxy. Which if this is the case, it presumably shouldn't be considered an RQE. From the plots we can see at least 3 of them that fit this case. On the other hand, a color coded blue SF galaxy in the green valley or quiescent region cannot be considered an ongoing star forming galaxy. Rather, it as presumably had recent SF in the past via rejuvenation process. There are at least 23 RQEs that fit this case.

Lastly, I want to address the location of these color coded blue SF RQEs. In the color-mass plot we see that these RQEs are $\leq 10^{10.7} M\odot$. This makes sense as blue star forming galaxies are, on average, smaller. In the color-color plot we see all of the color coded blue SF RQEs are $<$ (u-r) = 2.26, which is in perfect agreement with the urz SF selection. Finally, in the color-magnitude plot we see that blue SF RQEs are $\geq$ -21 Mr. This means that the RQEs that have SF signatures in this sample are smallest in stellar mass, bluest in ur color and dimmest in r-band flux. Which is all in agreement with the first interpretations I acquired from the initial plots in this analysis. With adding a star forming and non-star forming color coded selection to these 3 main plots, we can gain a substantial amount of knowledge of these RQEs that wouldn't have been afforded with no SF color coded selection

Lets now take a look at the central and satellite color coded selection plots. Recall, centrals are color coded red, while satellites are color coded blue.

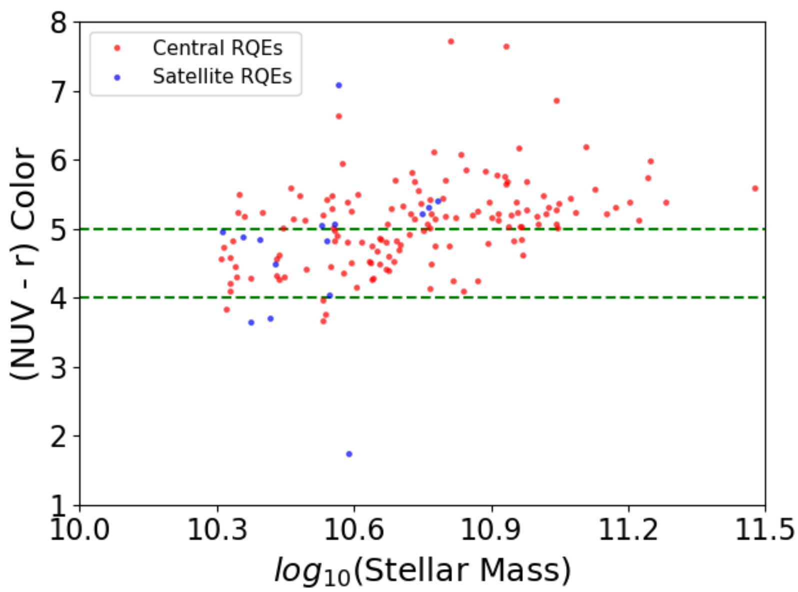

Figure 15: Central and satellite color coded (NUV-r) vs Stellar Mass plot

The reason why we would want to color code for central and satellite RQEs is because the quenched central RQEs in this sample are of a mystery. Meaning, we don't know why the central galaxies in this sample are not actively producing stars. Based on their local environment they should be producing stars. So, differentiating these data points by central and satellites can help in understanding the environments these galaxies are in and the effect their environment can have on their SF or quenching.

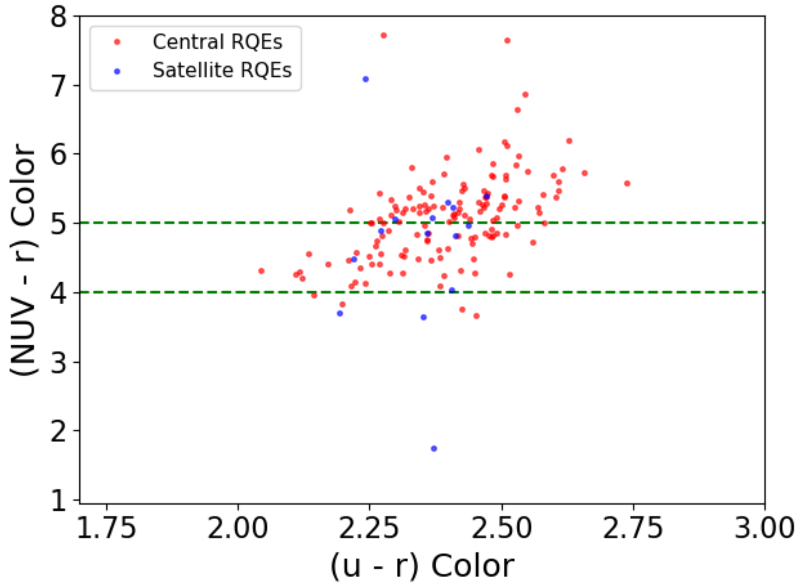

Figure 16: Central and satellite color coded (NUV-r) vs (u-r) plot

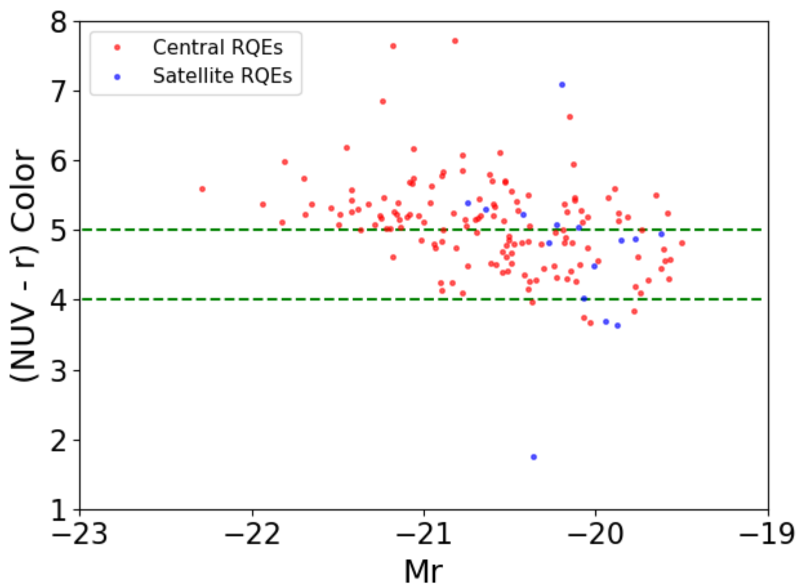

Figure 17: Central and satellite color coded (NUV-r) vs Mr plot

From these color coded selection plots we obtain 155 central RQEs and 17 satellite RQEs As you can see there are central RQEs in all 3 regions. Just as in the SF color coded selection plots we saw SF signatures in all 3 regions. In these color coded selection plots we see at least 4 central RQEs below the green valley region (i.e. in the star forming region). This means that these 4 central RQEs have either had recent SF in their pasts or are actively producing stars, presumably through rejuvenation processes. A cross analysis between these 4 central RQEs found here and the 3 star forming galaxies discovered in the SF color coded selection plots is needed to determine the true nature of these central RQEs. Upon further analysis it would be intriguing to find that these 4 central RQEs are not actively producing stars, but rather have had a brief SF episode. Furthermore, we see central RQEs scattered throughout the green valley region and quiescent region of these plots. These two regions constitute a total of 151 out of the 155 central RQEs in this sample. Again, further analysis is needed to determine why these 151 central RQEs are in the green valley region and/or the quiescent region. However, these 151 central RQEs are an excellent sample of true RQEs and should be used in later studies about the nature of RQEs

If should be noted that in future analysis of this sample, RQEs should be plotted with Star Forming Ellipticals (SFEs) and Long Quenched Ellipticals (LQEs) in these main plots. If time permitted we would have plotted SFEs and LQEs with RQEs in these plots to get a better sense of where these central and blue color coded SF RQEs lie in relation to SFEs and LQEs. Seemingly, the 3 blue color coded SF RQEs discovered in this sample should lie close if not in the same region of SFEs. On the other hand the RQEs found to be non star forming in the SF color coded plots and found to be in the quiescent region should lie near the LQEs. RQEs found to be in the green valley region with no SF signatures should lie in between these two populations. Plotting this sample of RQEs with SFEs and LQEs would be a second validation that the RQEs discovered in this analysis to be non star forming and in the green valley region are truly recently quenched and can be safely used in further studies of RQEs.

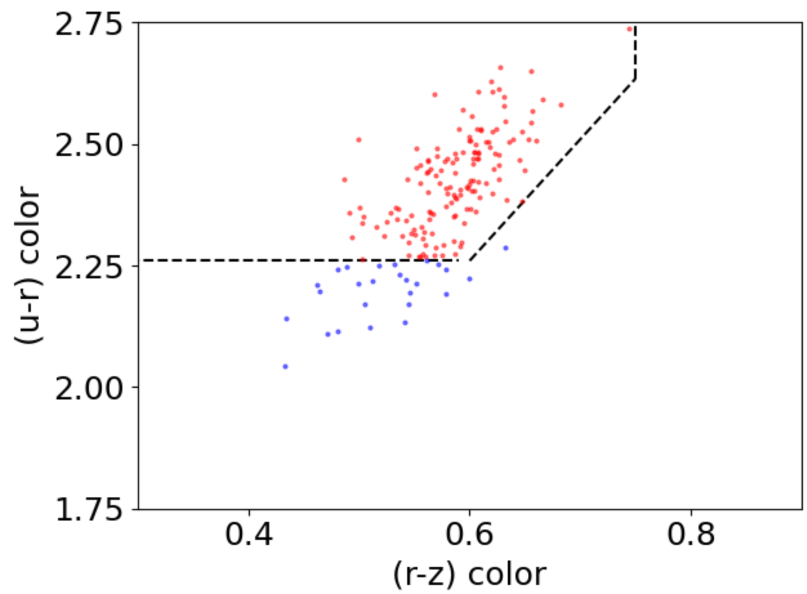

Figure 18: urz diagram for SF color coded galaxies

The last information I added was a third dimension to the color-color plot. In each of these color-color plots I weighted each data point based on its stellar mass and age. The reason why we would want to add a color bar to the color-color plot is because by adding this third dimension we can "see" more than would be possible in only a two dimensional plot. Below are the 2 color-color plots with the added third dimension of a color bar.

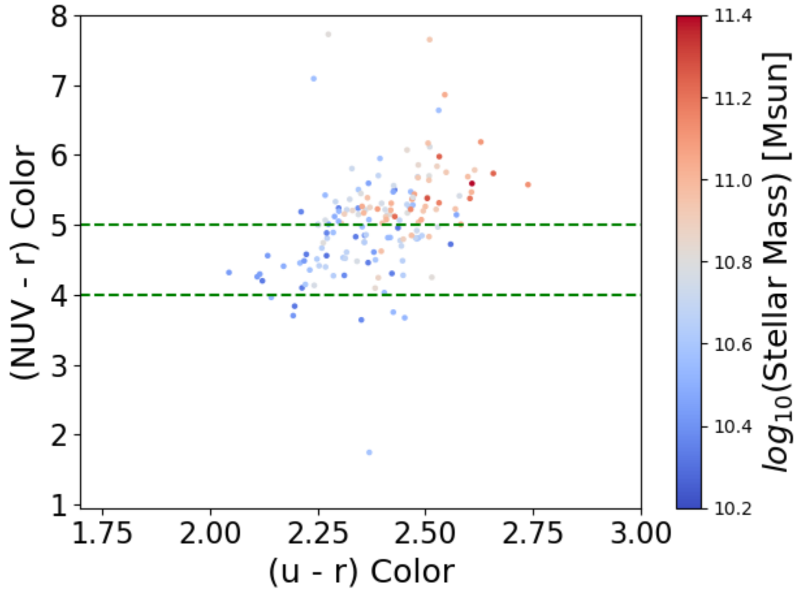

Figure 19: (NUV-r) vs (u-r) with Stellar Mass Color bar

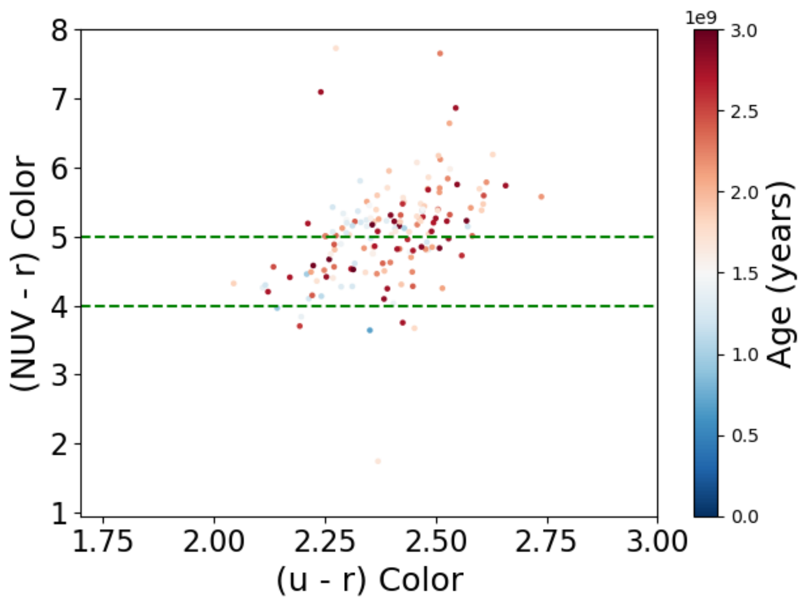

Figure 20: (NUV-r) vs (u-r) with Age Color bar

From these color bar plots we can see that we get this added third dimension. In Figure 19 we see the heaviest RQEs (i.e. greatest in stellar mass) are also the reddest in color. Whereas on the contrary, the lightest RQEs are the bluest in color. This is in agreement with my first interpretations of this color-color plot[14]. In Figure 20 we see a larger scatter in the data points; older galaxies and younger galaxies do not necessarily lie in separate regions

[14]See *First Interpretations of Plots* for a description.

of this graph. This can be representative of rejuvenation signatures in these RQEs. There are at least 2 RQEs that are $\geq$ 2.7e9 years old[15] that are below the green valley region. These RQEs are some of the oldest in the sample, but yet they have some of the bluest NUVr color. Meaning, the oldest RQEs in this sample have evidence of recent SF. If we did see two distinct populations in color based on age, this would be good evidence of a clear cut hierarchical path to galaxies becoming read and dead. We do not see this however. This is indicative of rejuvenation processes happen during SF quenching. Moreover, this is evidence that SF quenching doesn't happen all at once, but happens in stages, over a long period of time with episodes of SF that elongate the process.

4.4 Additional Plot

The additional plot I present here is a Signal-to-Noise Ratio (SNR) versus NUV exposure time. SNR is exactly as it sounds; it is the signal or number of raw counts from our sources, divided by the error or uncertainty in our measurement. Knowing the SNR for each galaxy is extremely important because it serves as a sanity check to verify if the conclusions that we have drawn from this analysis can be believed. If galaxies have an SNR ≥ 3 we can safely assume our conclusions are correct. However, if galaxies have an SNR < 3 than we are not safe to make accurate conclusions on these galaxies. Below is the SNR plot for this sample of RQEs

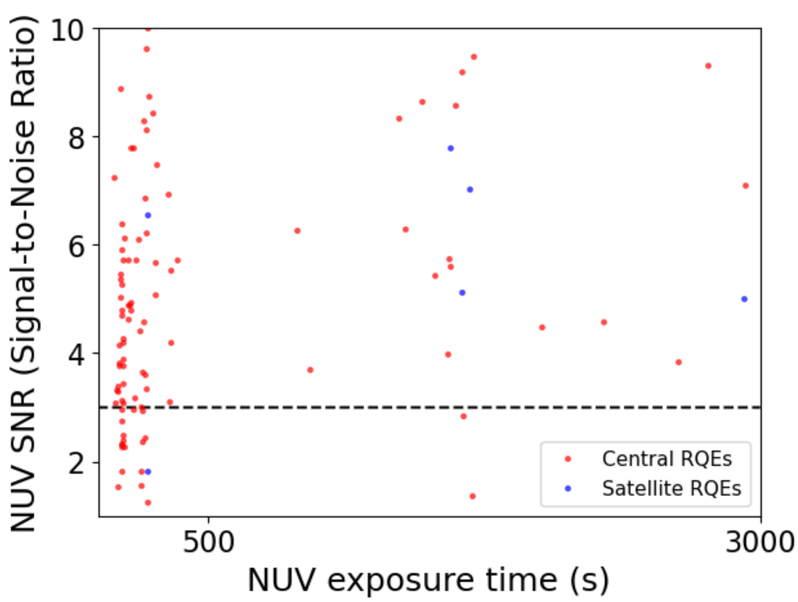

Figure 21: SNR vs exposure time

As we can see there are at least 18 RQEs in our sample with a SNR < 3. These galaxies would need to be excluded when drawing conclusions from our plots. The good news is that there are at least 154 RQEs in our sample with a SNR ≥ 3. With over 88% of our sample

[15]This age was determined by its light weighted age.

having a SNR ≥ 3 this is good evidence that the conclusions drawn in this analysis section can be believed.

5 Results

5.1 Key Takeaways

The first key takeaway from this analysis is that there are at least 26 RQEs in this sample that have evidence of recent SF. Of these 26 RQEs, we discovered at least 3 of them that can be considered active SF galaxies. These 3 galaxies should not be considered recently quenched. They probably better fit as SFEs. Thus, we have detected at least 3 "fake" RQEs in this sample. A refinement of this RQE catalog should be done to include only true RQEs. The second key takeaway is that of these 26 recent SF RQEs, they are all the smallest in stellar mass, bluest in color and faintest in r-band flux; this is in agreement with the hierarchical model of the development of galaxies. The third key takeaway is that although this analysis is in agreement with the hierarchical model of the development of galaxies, it suggests that this model is not linear. Galaxies do not endure SF quenching in one single process, regardless of the actual physical case of the quenching. Rather, this analysis suggest that SF quenching happens in stages. A galaxy can begin to undergo SF quenching, but later on can have SF episodes due to rejuvenation processes from its environment.

The intellect gained from the results of this analysis agree that there is a hierarchical process in the development of galaxies from LTGs to ETGs. However, this analysis suggest that this hierarchical process is not as simple as previously imaged. Galaxies do not steadily reduce their SF in a linear manner. Rather this analysis suggests that the quenching of SF is a bumpy and long process. Galaxies can be reducing their SF or have essentially no SF and then go through a period of rapid SF in a short period of time. This can be especially true for galaxies labeled as RQEs. Lastly, we learned that this sample of 172 ellipticals should be refined to include only the true RQEs, which excludes 3 galaxies identified to have active SF. Of the 169 RQEs left in this sample, 23 were discovered to have recent SF, while the other 146 were not discovered to have recent SF. This means that 84% of these RQEs have had no recent SF in their and can be considered far along in the quenching process.

6 Conclusion

In this GALEX analysis we examined a sample of 172 elliptical galaxies that were previously defined to be recently quenched. We downloaded relevant GALEX + SDSS data of these RQEs to identify any recent SF. Of these 172 ellipticals, 26 were found to have recent SF, while 3 of the 26 were identified to have active SF. Therefore, these 3 SF ellipticals should not be considered recently quenched and should not be included in a further analyses of RQEs. Furthermore, we discovered that this analysis highlights the fact that there is most likely a hierarchical development of galaxies from small lenticular LTGs to large spheroidal ETGs. While this analysis does not suggest a linear evolution from LTGs to ETGs, it nevertheless suggest this hierarchical development.

References

[1] MAST Queries (astroquery.mast) — astroquery v0.4.4.dev2005.

[2] Measures of Flux and Magnitude \textbar SDSS.

[3] SDSS SkyServer DR15.

[4] I. K. Baldry, M. L. Balogh, R. Bower, K. Glazebrook, and R. C. Nichol. Color bimodality: Implications for galaxy evolution. *AIP Conference Proceedings*, 743:106–119, 2004.

[5] G. B. Brammer, K. E. Whitaker, P. G. van Dokkum, D. Marchesini, I. Labbe, M. Franx, M. Kriek, R. F. Quadri, G. Illingworth, K.-S. Lee, A. Muzzin, and G. Rudnick. The Dead Sequence: A Clear Bimodality in Galaxy Colors from z=0 to z=2.5. *The Astrophysical Journal*, 706(1):L173–L177, November 2009.

[6] Wirth Gregory. Astronomical Magnitude Systems. Publication Title: Astronomical Magnitude Systems.

[7] V. Kalinova, D. Colombo, S. F. Sánchez, K. Kodaira, R. García-Benito, R. González Delgado, E. Rosolowsky, and E. A. D. Lacerda. Star formation quenching stages of active and non-active galaxies. *Astronomy & Astrophysics*, 648:A64, April 2021.

[8] Sugata Kaviraj, Sebastien Peirani, Sadegh Khochfar, Joseph Silk, and Scott Kay. The role of minor mergers in the recent star formation history of early-type galaxies. *Monthly Notices of the Royal Astronomical Society*, 394:1713–1720, April 2009.

[9] Daniel H. McIntosh, Cory Wagner, Andrew Cooper, Eric F. Bell, Dušan Kereš, Frank C. van den Bosch, Anna Gallazzi, Tim Haines, Justin Mann, Anna Pasquali, and Allison M. Christian. A new population of recently quenched elliptical galaxies in the SDSS. *Monthly Notices of the Royal Astronomical Society*, 442:533–557, July 2014.

[10] J. P. Nogueira-Cavalcante, T. S. Gonçalves, K. Menéndez-Delmestre, and K. Sheth. Star formation quenching in green valley galaxies at 0.5 z 1.0 and constraints with galaxy morphologies. *Monthly Notices of the Royal Astronomical Society*, 473:1346–1358, January 2018.

[11] Samir Salim. Green Valley Galaxies. *Serbian Astronomical Journal*, (189):1–14, 2014.

[12] K. Schawinski, S. Kaviraj, S. Khochfar, S. J. Yoon, S. K. Yi, J. M. Deharveng, A. Boselli, T. Barlow, T. Conrow, K. Forster, P. G. Friedman, D. C. Martin, P. Morrissey, S. Neff, D. Schiminovich, M. Seibert, T. Small, T. Wyder, L. Bianchi, J. Donas, T. Heckman, Y. W. Lee, B. Madore, B. Milliard, R. M. Rich, and A. Szalay. The Effect of Environment on the Ultraviolet Color-Magnitude Relation of Early-Type Galaxies. *The Astrophysical Journal Supplement Series*, 173:512–523, December 2007.

[13] Kevin Schawinski, C. Megan Urry, Brooke D. Simmons, Lucy Fortson, Sugata Kaviraj, William C. Keel, Chris J. Lintott, Karen L. Masters, Robert C. Nichol, Marc Sarzi, Ramin Skibba, Ezequiel Treister, Kyle W. Willett, O. Ivy Wong, and Sukyoung K. Yi. The green valley is a red herring: Galaxy Zoo reveals two evolutionary pathways towards quenching of star formation in early- and late-type galaxies. *Monthly Notices of the Royal Astronomical Society*, 440:889–907, May 2014.

[14] Sravani Vaddi, Christopher P. O'Dea, Stefi A. Baum, Samantha Whitmore, Rabeea Ahmed, Katherine Pierce, and Sara Leary. Constraints on Feedback in the Local Universe: The Relation between Star Formation and AGN Activity in Early-type Galaxies. *The Astrophysical Journal*, 818:182, February 2016.