Passive but not resigned

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Galaxies can either be classified as "star forming", if they are relatively new and forming stars, or "quiescent", if they are older and produce significantly less stars. In this report, we aim to examine three different colour-colour galaxy categorisation approaches, and compare their ratios of star forming to quiescent galaxies with those gathered via a full spectra energy distribution fitting, in order to determine their efficiency in galaxy classification. This was attempted with data from the latest release, as of writing, of the Cosmic Evolution Survey (COSMOS2020), in the $0 < z < 3$ redshift range. The comparisons were done in the entire range at once, as well as separately in six different redshift bins. Finally, the three criteria are examined with pseudo-confusion matrices, excluding galaxies with a specific star formation rate between -11 to -10, which are the so-called "green valley" galaxies in the midpoint of the two previous classifications. We found that, before the removal of the green valley, the criteria did not yield very reliable results, yet upon the removal two of them gave very satisfying results.

I. INTRODUCTION

A. Competences Acquired

Given the pedagogical nature of this study, the true focus of this document is in what the author has learned, and therefore that will be discussed before all else. The competences acquired in the making of this paper can be summarised as:

- Experience in important science/astrophysics tools, such as *JupyterLab*, *astropy*, *matplotlib* and the COSMOS2020 catalog. There are specific details of these subjects which cannot be learned in undergraduate classes on a theoretical level, and must be grasped by experience instead. There are multiple ways of extracting, organising and exhibiting data, and to do this in a way that is appropriate for science requires an intuition that only practice can build.

- Familiarisation with the workflow of a research project in the context of astrophysics. Just by observing the supervisor's feedback and way of explaining things, I got more accustomed, even if only on a superficial level, to "thinking like a scientist";

- Deeper comprehension on cosmology, photometry and the life cycle of galaxies and stars.

B. Context

Galaxies, despite seemingly unchanging in a human perspective, still have a life cycle. First, gravitational attraction brings clumps of gas and dust together, forming an aggregate. This in turn increases the gravitational attraction, bringing about more mass, and so on. Finally, this aggregate will be significant enough for one to call it a galaxy.

As the matter keeps being pushed together by gravity, the gas gets denser and heats up. Eventually, stars are born. Accordingly, we call galaxies in this early stage of their lives *star forming*. Star formation is a very energetic process, hence it is no surprise that the light emitted from such young galaxies is, in general, of very high energy, and thus they are more blue in colour. But, after many gigayears of such energetic processes, a galaxy becomes less and less "fertile", birthing fewer stars as the system evolves. Therefore, they emit light of lower energies, which means they are more red in colour. We call such galaxies *quiescent* or *passive*. And although the behaviour of galaxies seems, broadly speaking, bimodal, we may define yet a third category, that of the *green valley* galaxies, composed of those in the transition phase between the two modes.

Categorise discretely as we may, a galaxy's life is still a continuous process. Inevitably, one comes across a galaxy whose exact class is ambiguous, and must face the problem of defining the precise criteria for categorisation if they intend to classify them. In this paper, we will compare and scrutinise different criteria for the classification of galaxies.

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C. Methods

From the context given in the previous section, it is evident that in this study we seek to analyse galaxies fundamentally from the light they emit. Hence the core of this project is in photometry, which is the measurement of light using, as a basis for quantification, brightness as perceived by the human eye. In the context of astronomy, telescopes measure, at various wavelengths, the luminance flux of celestial objects in a certain point of the night sky. By systematically repeating this over an extended area of the sky, we can catalog flux data and map out the observable Universe around Earth, in what are called "surveys". And, since the speed of light is finite (and the Universe is expanding), the light emitted from far away objects may take a long time to reach our telescopes. We can, quite literally, look at the past of our Universe. Because the distribution of galaxies beyond ours is continuous, we can "build a timeline" and attempt to understand the history and development of galaxies and the structures they form since the Big Bang.

The data utilised in this paper was taken and filtered from the 2020 release of COSMOS [4], The Cosmic Evolution Survey. It is an astronomical survey that has been gathering photometric data since 2003. The data obtained is from the "COSMOS field", a two square-degree patch of the sky which is mostly undisturbed by the Milky Way's gas clouds. Seen from the Earth, it has roughly the area of 16 full moons, covering more than two million galaxies and three quarters of the age of the Universe. With the 2020 release of the catalog we were able to investigate galaxies with redshift up to $z = 3$, whereas with previous versions, reliable data was only available up to $z = 2$ for our purposes. This allows us to better contemplate different selection criteria.

In this paper, we consider three criteria. The first two criteria base their classifications on $U - V$ vs. $V - J$ colours. Every object in the catalog has a rest-frame flux associated with each section, or band, of the electromagnetic spectrum. So, to draw these plots, we simply gather the data from the U, V and J bands of each object in the field, then plot all the $U - V$ values on one axis and all $V - J$ values on another. The third criteria considered does the same, but with a $NUV - r$ vs. $r - J$ plot. As shall be seen briefly, the position of a galaxy in these plots has a significant correlation to which part of their life cycle they're in.

D. Aims

We used four different criteria to produce a fraction of the amount of star forming objects over the amount of passive objects, $\frac{SF}{Q}$. Given that galaxies produce fewer stars as they get older, this evidently gives us information on the age of galaxies. Further, since we examine this ratio as a function of redshift, we can get a glimpse into the evolution of galactic structures as a whole.

E. Summary

This paper's sections are organised as follows.

1. Introduction
2. Sample: introduce the COSMOS2020 catalog and specify how it was put to use;
3. Methods: present the selection criteria examined;
4. Results: exhibit all data output acquired;
5. Discussion: use results to compare the methods' capabilities in interpreting the sample data;
6. Conclusion

II. SAMPLE

The data used in this study was collected from the COSMOS2020 catalog [4], to which we applied the following filters:

- `FLAG_COMBINED` $= 0$;
- `lp_type` $= 0$, which denotes a galaxy;
- `ez_z_phot`< 3, which is the EAZY software's [2] redshift. We limited ourselves to galaxies in the redshift range $0 < z < 3$ in order to have reasonable statistics, since there isn't enough data beyond $z = 3$;
- `UVISTA_Ks_MAG_AUTO`< 22.4, which is the Ultravista Ks band AB magnitude (column 187 of the catalog). This magnitude upper limit serves to avoid noisy data.

Having gathered the relevant data from the catalog, 70553 (4.1%) objects remained from an original 1720700. The resulting sky distribution can be seen in figure 1. As one can see, there are white spots on the figure due to very bright stars that outshine the background galaxies, preventing their appropriate examination. For this reason, such regions are masked and ignored. The corresponding redshift distribution can be verified in figure

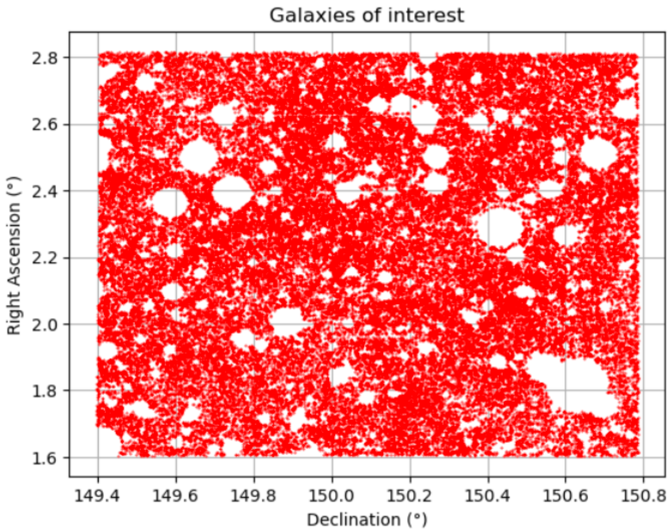

Figure 1. Map of the galaxies in the COSMOS2020 catalog with Ks magnitude < 22.4. The red dots represent galaxies, and the white spots are points without useful data due to bright stars.

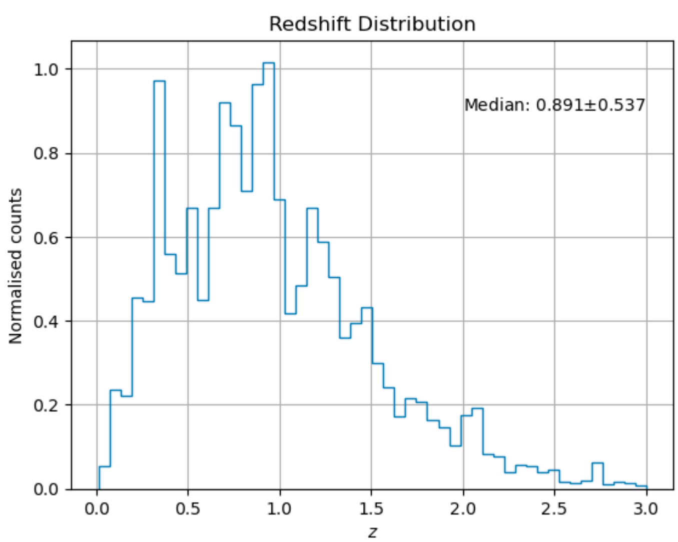

Figure 2. Redshift distribution of the sample.

2. From it, we can see that the median redshift in the distribution is $z \approx 0.89$, which corresponds to an age of the Universe of around 6.38Gyr.

III. METHODS

In this section, we elucidate the criteria used for galaxy categorisation. The first two selection criteria are based on $U - V$ vs. $V - J$ colours. That is to say, we take the rest-frame AB magnitude on the U, V and J bands for each galaxy, and plot the galaxies accordingly. For these first two, we first accessed the absolute rest-frame AB *fluxes* of the U, V, J bands through EAZY [2], by calling the parameters `ez_restU`, `ez_restV` and `ez_restJ` of the catalog. Then, the fluxes were converted to magnitudes with $m = -2.5 \log_{10} f \times 10^6/3631$, such that m is the magnitude and f is the flux at a given band, in μJy. The same logic applies for the $NUV - r$ vs. $r - J$ colours, except here, the absolute rest-frame AB magnitudes were directly obtained with LePhare [1] using the `lp_MNUV`, `lp_MR` and `lp_MJ` parameters of the catalog. For simplicity, U, V, J, NUV and r will, in this paper, refer to the rest-frame AB magnitudes in the respective bands, gathered as explained above.

The first selection criterion to be considered, which we will call *UVJ-1*, is taken from [5]:

$$\begin{cases} (U-V) > 0.88 \times (V-J) + 0.69 & \forall z \in [0.0, 0.5] \\ (U-V) > 0.88 \times (V-J) + 0.59 & \forall z \in [0.5, 1.0] \\ (U-V) > 0.88 \times (V-J) + 0.49 & \forall z \in [1.0, 2.0] \\ (U-V) > 1.3 & \forall z \\ (V-J) < 1.6 & \forall z \end{cases} \quad (1)$$

Because of the photometric nature of this study, unobscured quiescent galaxies could be mistaken for star forming ones. The fourth condition serves to rule out such galaxies. Further, objects with a lot of surrounding dust may be misinterpreted as quiescent galaxies, and the last condition serves to rule out those objects. Also, for the general sample $0 < z < 3$, the condition for $z \in [0.0, 0.5]$ was used, as it adjusts best to the data.

The second criterion, which we will refer to as *UVJ-2*, is defined as

$$\begin{cases} (U-V) > 0.88 \times (V-J) + 0.42 & \forall z \\ (U-V) > 1.3 & \forall z \\ (V-J) < 1.6 & \forall z \end{cases} \quad (2)$$

As the reader might have noticed, it has the same last two conditions as *UVJ-1*. It is, however, optimised for the new data in the 2020 release of COSMOS, and for our $0 < z < 3$ redshift range. The third criterion, which we will call *NUV-r-J*, is taken from [3] and is used for the $NUV - r$ vs. $r - J$ plots:

$$\begin{cases} (NUV-r) > 3 \times (r-J) + 1 & \forall z \\ (NUV-r) > 3.1 & \forall z \end{cases} \quad (3)$$

Finally, we will consider, as a benchmark criterion, the specific star formation rate, or sSFR. The specific star

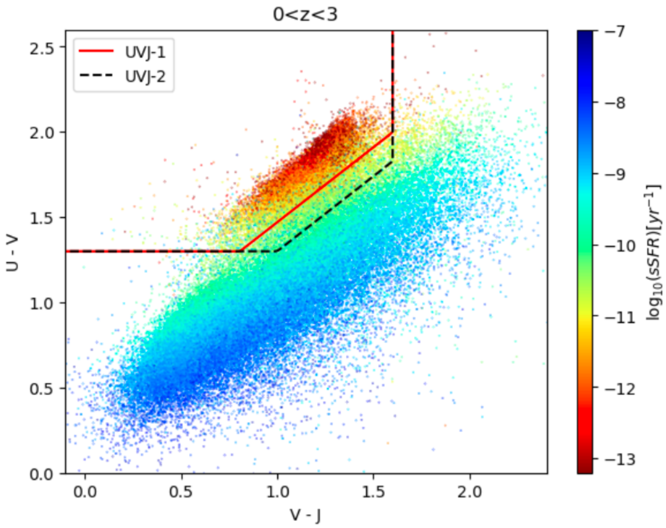

Figure 3. $U-V$ vs. $V-J$ colour-colour diagram for $0 < z < 3$.

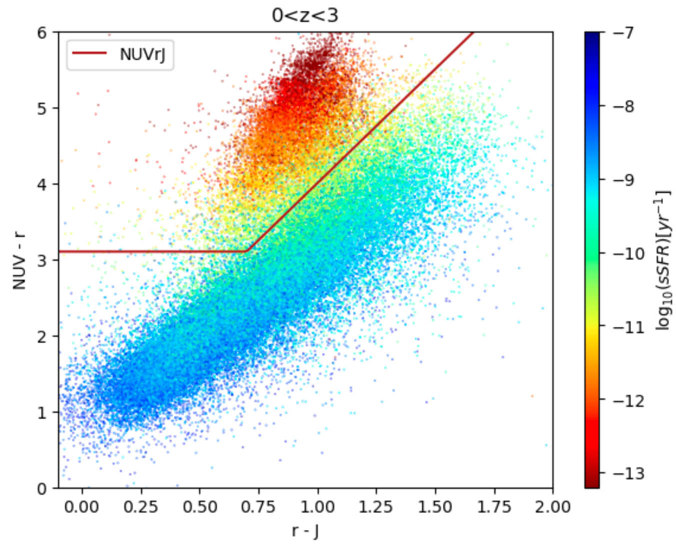

Figure 4. $NUV - r$ vs. $r - J$ colour-colour diagram for $0 < z < 3$.

formation rate of a galaxy is, as the name suggests, a measure of the rate at which a galaxy produces new stars, which we obtained via LePhare's `lp_sSFR_med` in the catalog. Of course, any conclusions drawn will be solely dependent on the validity of the chosen benchmark. This criterion also includes the green valley category, which is useful in determining and separating the more ambiguous objects of the sample. It is as follows:

$$\begin{cases} \text{sSFR} > -10 & : \text{Star forming} \\ -11 < \text{sSFR} < -10 & : \text{Green valley} \\ \text{sSFR} < -11 & : \text{Quiescent} \end{cases} \tag{4}$$

IV. RESULTS

In order to compare the criteria discussed in the previous section, we made the $U-V$ vs. $V-J$ and $NUV-r$ vs. $r-J$ colour-colour diagrams, which can be seen in figure 3 and figure 4 respectively. Finally, with the data on the specific star formation rate of the galaxies in the sample, the histogram in figure 5 was made. It displays the star formation rate of all objects in the sample.

With the results thus exhibited, we were finally able to compare the proportion of star forming and quiescent galaxies for the various criteria. Such ratios can be seen, for criteria *sSFR*, *UVJ-1*, *UVJ-2* and *NUVrJ*, in Table I. It can be seen that, for $0 < z < 3$, *UVJ-1* is the criteria that gives the largest number of star forming galaxies - 11% more than *sSFR*. For this reason, it also gives the lowest number of passive galaxies, which is not too different from *sSFR*'s (a difference of less than 3%). This indicates that, in this redshift range, *UVJ-1* identifies green valley galaxies almost exclusively as star forming ones.

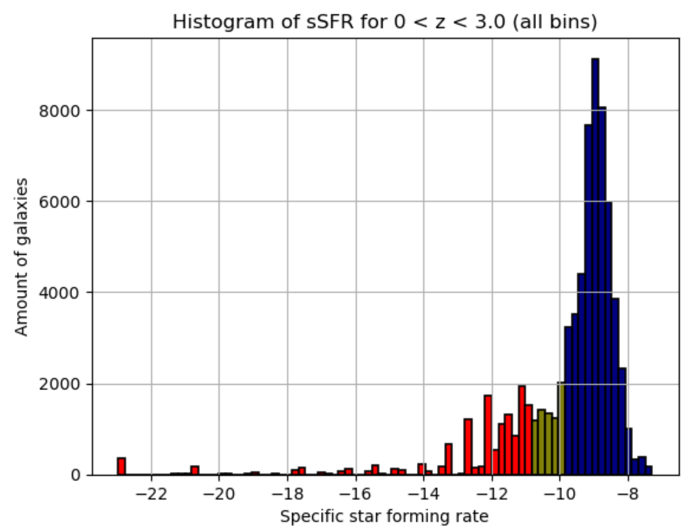

Figure 5. Histogram of specific star formation rate (sSFR) for the $0 < z < 3$ redshift range. The red bars represent quiescent galaxies, the green bars represent green valley galaxies, and the blue bars represent star forming galaxies.

Conversely, *UVJ-2* has a more reasonable estimate for the star forming galaxies (2.2% more than *sSFR*) and an inappropriate estimate for the quiescent galaxies (7.7% more than *sSFR*). This is an indicator that this criterion tends to identify green valley galaxies as quiescent, though it also misidentifies a few quiescent galaxies as star forming.

Criteria	Star Forming	Green Valley	Quiescent
sSFR	51 677 - 73.3%	7 014 - 9.9%	11 845 - 16.8%
UVJ-1	60 596 - 85.9%	–	9 957 - 14.1%
UVJ-2	53 279 - 75.5%	–	17 274 - 24.5%
NUVrJ	43 477 - 61.6%	–	27 076 - 38.4%

Table I. Proportion of galaxy types for each criteria considered, in the redshift range $0 < z < 3$.

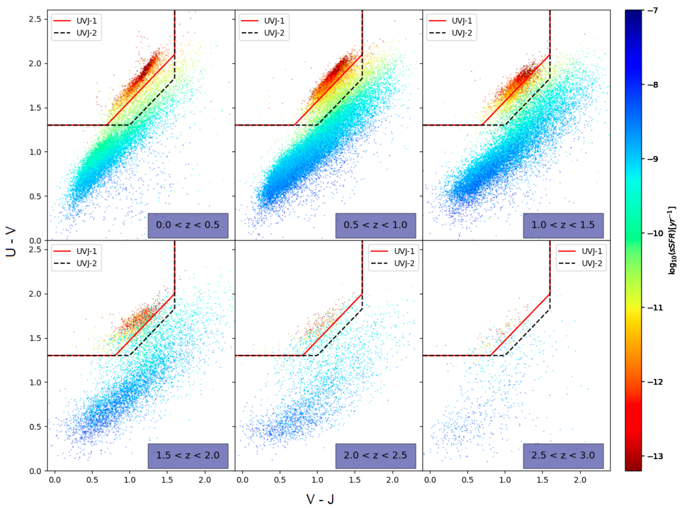

Figure 6. $U - V$ vs. $V - J$ colour-colour diagrams for each redshift bin separately.

NUVrJ yields the most dissimilar results, with 11.7% less star forming galaxies and 21.6% more quiescent ones. It has more than double the quiescent galaxies as reported via *UVJ-1*. Clearly, this criterion does not only identify green valley galaxies as passive, it identifies even star forming galaxies as passive. This serves as a prime example of why colour-colour diagrams must be used with care when it comes to this type of classification.

V. DISCUSSION

In this section we will analyse each criterion's ability to classify the galaxies in the sample. To do this, we subdivided the data into 6 different redshift bins, specifically $0 < z < 0.5$, $0.5 < z < 1$, $1 < z < 1.5$, $1.5 < z < 2$, $2 < z < 2.5$ and $2.5 < z < 3$. A scatter plot for each redshift bin can be seen in figures 6, for the $U - V$ vs. $V - J$ colours, and 7, for the $NUV - r$ vs. $r - J$ colours.

Further, the histogram in figure 8 displays sSFR for each separate redshift bin, and the ratios of star forming/green valley/quiescent galaxies for the separated redshift bins can be seen, for criteria *sSFR*, *UVJ-1*, *UVJ-2* and *NUVrJ*, in Tables II, III, IV and V respectively. Finally, figure 9 shows the percentage of star forming and

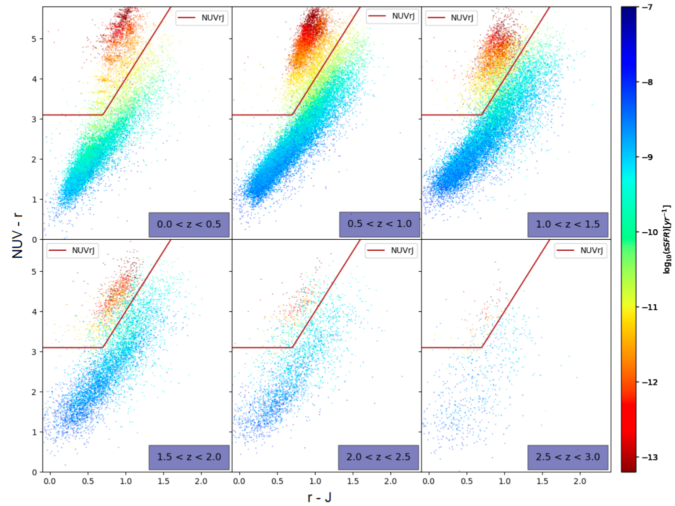

Figure 7. $NUV - r$ vs. $r - J$ colour-colour diagrams for each redshift bin separately.

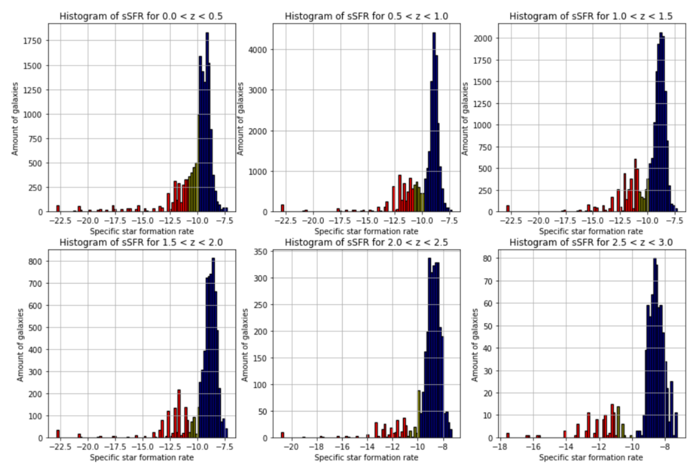

Figure 8. Histogram of specific star formation rate (sSFR) for each separate bin. The red bars represent quiescent galaxies, the green bars represent green valley galaxies, and the blue bars represent star forming galaxies.

quiescent galaxies for all criteria as a function of redshift.

At this point we may finally examine, with the separated redshift bins, how the fraction of star forming to quiescent galaxies evolves with redshift for the various methods. We can see that for *UVJ-1*, the ratio of star forming galaxies increases, from 69% at $z = 0$, to 90.4% at $z = 2.5$. This is not very reliable because in *sSFR*, our reference criterion, the ratio of star forming galaxies decreases with z, except for a slight decrease at the end which is likely due to the small sample size at $2.5 < z < 3.0$ - this redshift bin only has only 764 objects, and at its redshift midpoint, $z = 2.75$, the age of the Universe would be around 2.4Gyr. This is in line with the currently accepted cosmological picture, according to which the amount of star forming galaxies should

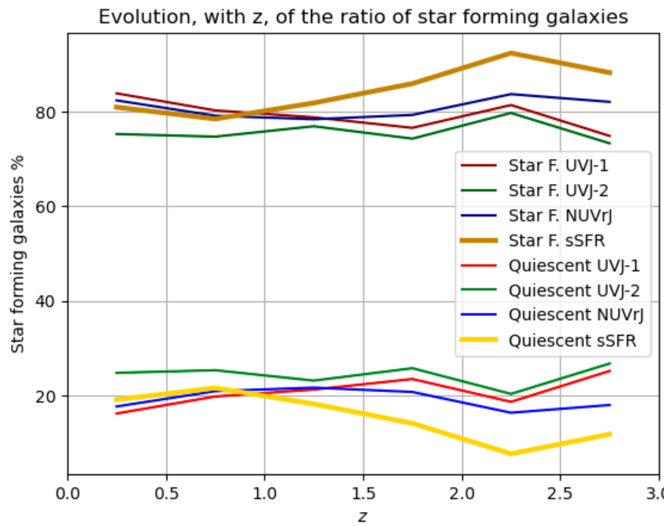

Figure 9. $NUV - r$ vs. $r - J$ colour-colour diagrams for each redshift bin separately.

z	Star Forming	Green Valley	Quiescent
$0.0-0.5$	10 263 - 69.0%	2 185 - 14.7%	2 416 - 16.3%
$0.5-1.0$	19 491 - 69.8%	3 087 - 11.0%	5 352 - 19.2%
$1.0-1.5$	12 869 - 75.3%	1 363 - 8.0%	2 855 - 16.7%
$1.5-2.0$	5 656 - 82.3%	289 - 4.2%	926 - 13.5%
$2.0-2.5$	2 744 - 90.4%	67 - 2.2%	226 - 7.4%
$2.5-3.0$	654 - 85.6%	23 - 3.0%	87 - 11.4%

Table II. Galaxy classification according to the *sSFR* criterion. Each line corresponds to a specific redshift range.

decrease with the aging of the Universe, since the galaxies age with it. Hence, according to the *sSFR* criterion, the ratio of star forming galaxies has decreased from around 90% to around 70% in the last ≈ 10 Gyr ($0 < z < 2.5$). As a result, the proportion of passive galaxies has almost doubled in this redshift range.

On the other hand, *UVJ-2* is more consistent. Despite minor fluctuations in the star forming ratio, it stays relatively the same throughout $0 < z < 3$, at around $\approx 75\%$. This is still not too reliable given that, according to *sSFR*, the ratio should decrease, but it is still more appropriate than *UVJ-1*.

z	Star Forming	Quiescent
$0.0-0.5$	12 466 - 83.9%	2 398 - 16.1%
$0.5-1.0$	22 418 - 80.3%	5 512 - 19.7%
$1.0-1.5$	13 464 - 78.8%	3 623 - 21.2%
$1.5-2.0$	5 261 - 76.6%	1 610 - 23.4%
$2.0-2.5$	2 472 - 81.4%	565 - 18.6%
$2.5-3.0$	572 - 74.9%	192 - 25.1%

Table III. Galaxy classification according to the *UVJ-1* criterion. Each line corresponds to a specific redshift range.

z	Star Forming	Quiescent
$0.0-0.5$	11 187 - 75.3%	3 677 - 24.7%
$0.5-1.0$	20 866 - 74.7%	7 064 - 25.3%
$1.0-1.5$	13 141 - 76.9%	3 946 - 23.1%
$1.5-2.0$	5 104 - 74.3%	1 767 - 25.7%
$2.0-2.5$	2 421 - 79.7%	616 - 20.3%
$2.5-3.0$	560 - 73.3%	204 - 26.7%

Table IV. Galaxy classification according to the *UVJ-2* criterion. Each line corresponds to a specific redshift range.

z	Star Forming	Quiescent
$0.0-0.5$	12 245 - 82.4%	2 619 - 17.6%
$0.5-1.0$	22 102 - 79.1%	5 828 - 20.9%
$1.0-1.5$	13 395 - 78.4%	3 692 - 21.6%
$1.5-2.0$	5 449 - 79.3%	1 422 - 20.7%
$2.0-2.5$	2 542 - 83.7%	495 - 16.3%
$2.5-3.0$	627 - 82.1%	137 - 17.9%

Table V. Galaxy classification according to the *NUVrJ* criterion. Each line corresponds to a specific redshift range.

Finally, *NUVrJ*'s star forming ratio is also relatively constant throughout, but is much higher than the previous, staying at about 82%. Clearly, it classifies what would be green valley galaxies in *sSFR* as star forming. In this context, then, *NUVrJ* is no more acceptable than the last criterion.

We further investigated the efficiency of each criteria in determining the star forming and passive galaxies utilising pseudo-confusion matrices. The results are reported in the pseudo-confusion matrix of figure 10, which juxtaposes the data acquired using the *UVJ-1* and *sSFR* criteria for $0 < z < 3$. Figures 11 and 12 do the same, but for *UVJ-2* and *NUVrJ* instead. For this to be possible, it was necessary to remove, from the sample, all galaxies classified as pertaining to the green valley according to *sSFR*. This is necessary, since the other criteria do not have such a classification, and removing this ambiguous middle ground may enhance the efficiency of such criteria.

From figure 10, we see that about $\approx 95\%$ of the galaxies are classified similarly between *UVJ-1* and *sSFR*, when the green valley is removed. This effect is magnified in *UVJ-2*, whose matrix shows that about $\approx 98\%$ of the galaxies are classified equally. For *NUVrJ*, however, we see that around $\approx 15\%$ of the galaxies were wrongly classified as quiescent, according to *sSFR*.

VI. CONCLUSION

In this report, we compared different criteria for the classification of galaxies as star forming or quiescent. In order to do this, we used the COSMOS2020 catalog [4],

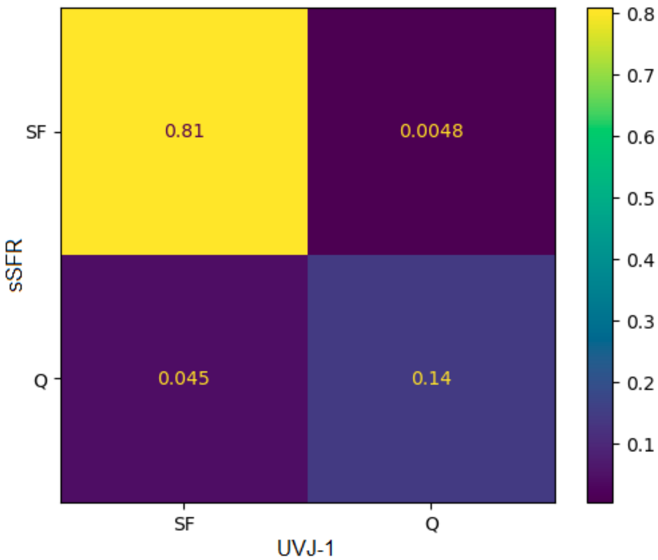

Figure 10. Pseudo-confusion matrix with *UVJ-1* criterion representing the horizontal axis and *sSFR* as the vertical axis.

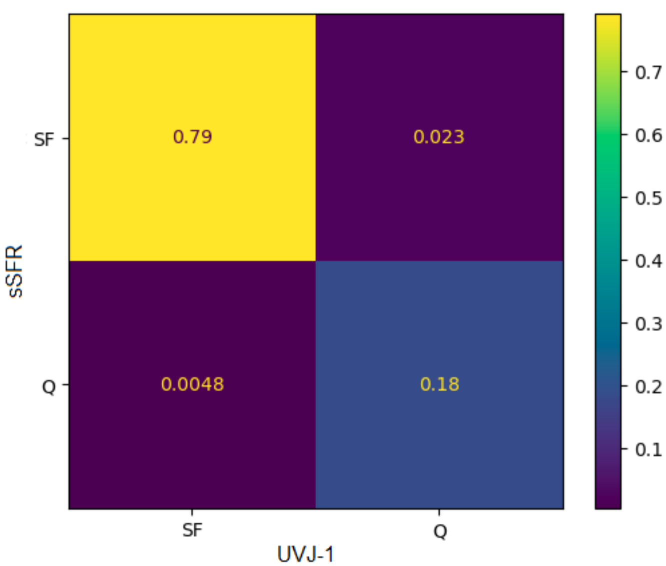

Figure 11. Pseudo-confusion matrix with *UVJ-2* criterion representing the horizontal axis and *sSFR* as the vertical axis.

from which we extracted a sample of around 70 000 galaxies at $0 < z < 3$, with a Ks rest-frame AB magnitude (as in the UVISTA survey) lower than 22.4. The median redshift of this sample was of $z \approx 0.89 \pm 0.54$. Defining U, V, J, NUV and r as the rest-frame AB magnitudes in the corresponding colour bands, we considered 3 criteria for galaxy classification, which were referred to as *UVJ-1* [5], *UVJ-2* and *NUVrJ*. The magnitudes were obtained using *EAZY* [2] and *LePhare* [1]. With them, $U - V$ vs. $V - J$ and $NUV - r$ vs. $r - J$ colour-colour diagrams were plotted, and a table was made for a quantitative analysis of each method. Furthermore, the benchmark for com-

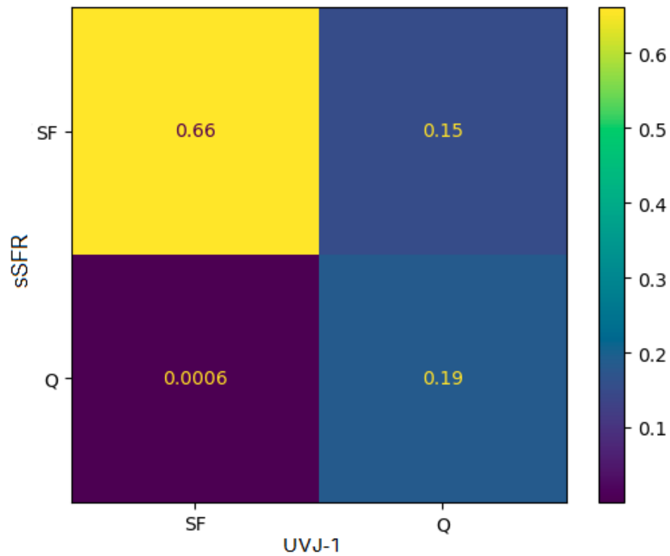

Figure 12. Pseudo-confusion matrix with *NUVrJ* criterion representing the horizontal axis and *sSFR* as the vertical axis.

paring the methods was established by a criterion based on the specific star formation rate. We called this criterion *sSFR*. Histograms of the specific star formation rate were then plotted.

The main results of this holistic analysis for $0 < z < 3$, with respect to the sSFR criterion, are as follows:

- *UVJ-1* found a much larger ratio of star forming galaxies (85.9% vs. 73.3%) and a similar ratio of quiescent galaxies (14.1% vs. 16.8%);
- *UVJ-2* obtained a similar ratio of star forming galaxies (75.5% vs. 73.3%) though its quiescent ratio is significantly larger (24.5% vs. 16.8%);
- *NUVrJ* detected a lower ratio of star forming galaxies (61.6% vs. 73.3%), yet a much higher ratio of quiescent galaxies (38.4% vs. 16.8%).

Additionally, we separated the data into 6 different redshift bins: $0 < z < 0.5$, $0.5 < z < 1$, $1 < z < 1.5$, $1.5 < z < 2$, $2 < z < 2.5$ and $2.5 < z < 3$. Colour-colour diagrams, specific star formation rate histograms and tables with the ratio of star forming to quiescent galaxies were made for each bin and each criterion. In this more comprehensive inspection we found that, in COSMOS2020, with respect to the *sSFR* criterion:

- *UVJ-1* seems less reliable, since its ratio of star forming galaxies decreases as z increases, which is the opposite of what is predicted using *sSFR*;
- *UVJ-2* also seems less reliable, because the ratio of star forming galaxies stays relatively the same as

z increases. This is more dependable than *UVJ-1*, but still not ideal;

- *NUVrJ* is less reliable than *UVJ-2*, given that, even though its ratio of star forming galaxies also stays relatively constant, it is even more distant from *sSFR*.

We proceeded with a further comparison using pseudo-confusion matrices, which was only possible by excluding the green valley galaxies from the sample. The obvious benefit of this is that we eliminate ambiguous objects, possibly enabling the three criteria considered to be useful in some capacity. With this analysis, we found that:

- *UVJ-1* is accurate, with around 95% of classifications equal to those of *sSFR*;
- *UVJ-2* is remarkably accurate, with around 98% of classifications equal to those of *sSFR*;
- *NUVrJ* was less accurate, since it misidentifies 15% of the galaxies as quiescent, despite the removal of the green valley from the sample.

In conclusion, *UVJ-1* and *UVJ-2* are reliable methods for the categorisation of galaxies, as long as objects with a specific star formation rate between -11 and -10 are ignored. They are not very dependable otherwise. On the other hand, *NUVrJ* does not hold well, with or without green valley galaxies. In any case, it is clear that colour-colour criteria still suffer from systematics that are strongly linked with the data set used. An interesting outcome of this work is that a full spectra energy distribution fitting, as the one done with LePhare, provides more physically motivated results.

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