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Article

Disputing the green valley theory of galaxy evolution

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SUMMARY

Fully understanding the process of galaxy evolution has long been a conundrum in astronomical research, given the limited amount of precise observational data and the complexity of processing the many factors that lead to the development of a galaxy. These include a galaxy's many shapes or morphologies, the presence of dark matter, the interactions between galaxies, and the distance at which galaxies can be observed. A crossroad in elucidating galaxy evolution—where star-forming "blue" galaxies transition to quiescent "red" galaxies—exists between the green valley and red-herring hypotheses. The former theory postulates that the green valley is a significant step in galaxy evolution, specifically, a transitory phase between "blue" and "red" galaxies. The latter asserts that the green valley is not an actual phase but a visual consequence of that unseen transition. This study aimed to evaluate the validity of these two theories. The Set of Identifications, Measurements, and Bibliography for Astronomical Data (SIMBAD) and the NASA Extragalactic Database (NED) were used to mine galaxies (N=293) that were then sorted into three bins: normal spirals, barred spirals, and ellipticals. We analyzed the ultraviolet-red color index means of the three bins and, after examining correlations between the means and galaxy subtypes, found a split between early- and late-type galaxy evolution. As a result, this study supports the red-herring hypothesis, with evidence that the green valley is only a byproduct of transitioning galaxies. Future research may examine quenching timescales and the effects of specific morphological features on galaxy evolution processes.

INTRODUCTION

Galaxies are vast swathes of stars, gas, dust, and cosmic matter bound together by gravity, varied by their shapes and contents (1-3). Galaxies can be classified as blue or red. Blue (active) galaxies refer to galaxies that are in the process of active star formation and are mostly spirals with high levels of gas and dust (4-7). Red (passive) galaxies have ceased star formation and are mostly ellipticals with low levels of gas and dust (8-9). These names may lead to confusion, as research has shown that optical color only sometimes differentiates active and passive galaxies due to dust reddening and the amount of metal in stars (metallicity), amongst other characteristics (9-13). In the present study, our use of the terms blue and red galaxies is not based on optical color but on star formation rates.

Edwin Hubble categorized galaxies by their shape or visual morphology (14). The three main galaxy types in the Hubble tuning-fork diagram—as it is called for the way it proposes galactic evolutionary pathways—are elliptical galaxies, lenticular galaxies, and spiral galaxies (see, e.g., Fig. 2 of Ref. 14) (14-16). Elliptical galaxies appear smooth and oval-shaped and often have older stars than other galaxies. Spiral galaxies have a flattened disk shape with spiral arms stretching outwards, and barred spirals, a subtype, have a rectangle-shaped bar passing through the middle of their disk center. Lenticular galaxies appear as a cross between elliptical and spiral galaxies, as they have both a central elliptical-shaped bulge and a flattened disk of outer stars surrounding the bulge (15-17).

Initially, the arrangement of Hubble's diagram led astronomers to believe that galaxies evolved from elliptical shapes into spirals, a concept that was widely accepted and reflected in the nomenclature "early-type" for elliptical galaxies and "late-type" for spiral galaxies (17-18). However, a paradigm shift occurred when astronomers later postulated that galaxies formed as spirals initially, and ellipticals or lenticulars were only created through later mergers. This latter theory, now widely accepted in the field, presents a fascinating evolution of our understanding of galaxy formation (19).

In the evolution of galaxies, galaxy mergers, a process where galaxies are gravitationally pulled together to form a larger galaxy, play a crucial role. They transform spirals into ellipticals as gravity breaks down their spiral arms (19). However, astronomical observations indicate that to fully explain why active star-forming galaxies transition into passive, quiescent galaxies; mergers would need to occur at a more frequent rate, which is not the case (20). This underscores the importance of a more comprehensive theory of galaxy evolution. One such theory is the process of quenching, a phenomenon where star formation slows down due to a lack of cold gas. Quenching provides a key understanding of the gradual transition of galaxies from a star-forming stage to a quiescent stage over lengthy timescales, a process that gravity-driven galaxy mergers alone cannot explain (21-23).

The ultraviolet-red (*u-r*) color index measures galaxy colors under the ultraviolet-optical spectrum. The star-forming sequence is blue in the ultraviolet-to-optical color region and is thus known as the blue cloud; it contains galaxies with higher star formation rates (24-25). The passive sequence is optically redder and includes galaxies with lower star formation rates (24-25). The region between the blue cloud and the red sequence is the green valley (see Fig. 2

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in Ref. 16) (25). Galaxies in the green valley are transitioning from blue to red galaxies due to star formation quenching, such as the Milky Way and Andromeda Galaxy. This region is comprised mainly of bulge-dominated disk galaxies, which combine features of spiral-type and elliptical galaxies (26-28). Several researchers have developed classification grids to keep track of the galaxies and their different sub-features, amongst them Graham, who improved upon the sequences of other well-known researchers (such as the Jean-Hubble tuning fork or the Aitken-Jean nebula sequence) by classifying early-type galaxy morphology with more detail (14). Graham's grid encompasses the sub-features of late-type galaxies and early-type galaxies to give a holistic overview of their strength and evolution (14).

The green valley has long been considered a critical phase in galaxy evolution. The classic theory of galaxy evolution posits that all galaxies evolve along a well-defined sequence, with actively star-forming blue cloud galaxies transforming into quiescent red galaxies via the green valley phase (14). The green valley is characterized by a decrease in star formation rate and an increase in bulge mass (the mass of the central region in a galaxy, particularly that of a lenticular or elliptical) accompanied by a decrease in metallicity (14). Conventional wisdom holds that galaxies spend similar time in the green valley phase during the transition from actively star-forming to quenched galaxies (7, 9, 29).

However, recent studies have challenged this assumption, suggesting that the green valley does not represent a significant stage in the evolution of galaxies (16, 32-33). One study suggests that the green valley is not a transitional phase but a manifestation of a morphological transition that occurs before star formation quenching, where galaxies exhibit a range of morphologies before the decrease in star formation rate (31). Another recent study provides further evidence for this by showing a strong correlation between the kinematics of galaxies and the quenching of star formation (32). Galaxies with a low ratio of rotational to random velocities are more likely to be quenched than galaxies with a high ratio, suggesting that the quenching of star formation is primarily driven by the internal dynamics of galaxies rather than by external processes such as mergers or interactions (33-34). From this collected information, these studies present evidence that the specific types of galaxies are more likely to have their own methods and timescales of quenching rather than collectively passing through a similar stage, as the green valley theory suggests.

Further evidence from the study comes from recent Hubble Space Telescope data: star formation quenching correlates with galaxy morphology, with early-type galaxies quenching more rapidly than late-type galaxies (35). The pathways for star formation quenching also diverge based on the timescales over which they occur based on how their gas reservoirs deplete (35-37). For further reference, the hypothesis that the green valley is not a significant transitional phase in galaxy evolution will henceforth be referred to as the "red-herring theory" to signify its divergence from the green valley theory.

These previous studies have analyzed different components of galaxy evolution (e.g., gravitational interactions, stellar wind feedback, and initial gaseous structures), but there is not one unified conclusion that can be determined from the quantitative evidence provided. It is necessary to determine if the green valley is a universal stage through which all blue-cloud galaxies transition to red-sequence galaxies on similar timescales and developmental mechanisms or, by contrast, if the red-herring theory holds, where late- and early-types have different evolutionary pathways through the green valley (38-40). This paper hypothesizes that the red-herring theory more accurately describes galaxy evolution than the green valley theory.

The objective of this study was to evaluate the green valley or red-herring theories by 1) determining the relationship between the *u-r* color index and galaxy morphology as galaxies evolve through the green valley and 2) calculating whether the numerical divergence of their *u-r* color index is correlated to early-or late-type classification.

We examined correlations between the rate at which stars in a galaxy were formed and their *u-r* color index ranges and adapted the classification grids developed by Graham to elucidate the relationship between galaxy sub-features and *u-r* color means (14). We found that the data was more consistent with the red-herring theory than the green-valley theory. The finding is significant in determining the phases of galaxy evolution and what occurs during its lifetime for different morphological types. Therefore, the result contributes to the establishment of a more accurate model of galaxy evolution and our understanding of a galaxy's life and transition stages.

RESULTS

Our study aimed to investigate the impact of galaxy morphology on star formation rates and determine distinct pathways for late and early-type galaxies. Late-type galaxies are characterized by a "spiral" morphology, and early-type galaxies have an "elliptical" or "lenticular" morphology, as mentioned earlier. We sought to determine if there were separate and distinct star formation rates for late- and early-type galaxies—which will be referred to as the "pathway" that they take—and if galaxy morphology affects the *u-r* color index of galaxies. To do this, we binned galaxies by morphology (elliptical, spiral, or barred) and performed a one-way ANOVA to determine whether quantifiable bin differences existed. Due to a paucity of data for lenticular galaxies in the databases, it was necessary to combine lenticulars and ellipticals in a bin. We found a statistically significant difference in *u-r* ($p < 0.05$) between at least two groups (**Table 1**). Therefore, it was necessary to determine where the difference lay: between normal and barred spirals, between normal spirals and ellipticals, or barred spirals and ellipticals. Because the sample size differed, we performed a Tukey-Kramer test to calculate the bin variance (41). The

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	17.913	2	8.957	17.537	$6.46 \cdot 10^{-8}$	3.027
Within Groups	148.109	290	0.511			
Total	166.022	292				

Table 1: Results of a one-way ANOVA test performed to determine if the groups have a statistically significant difference in their *u-r* color means.

TUKEY-KRAMER'S TEST			
Group Pairs	*Abs. Difference*	*α*	*Q Crit. Value*
Normal Spirals' vs Barred Spirals' *u-r*	0.077	0.05	0.089
Normal Spirals' vs Ellipticals' *u-r*	0.557	0.05	0.089
Barred Spirals' vs Ellipticals' *u-r*	0.48	0.05	0.089

Table 2: Results of a Tukey-Kramer's test performed to determine which two groups have a statistically significant difference in their *u-r* color means. The absolute difference is the numerical difference between the galaxy group pairs' *u-r* color means, α is the chosen significance level, and the q-critical value is the sample's test statistic.

Tukey-Kramer test for multiple comparisons revealed that the mean value of the *u-r* color indices was significantly different between normal spirals and ellipticals (absolute difference=0.557 > α = 0.05), as well as barred spirals and ellipticals (absolute difference=0.48 > α=0.05) (**Table 2**).

As a final step in confirming the distinct pathways of late-type and early-type galaxies, we utilized a box-and-whisker plot to compare the *u-r* color index ranges of the three galaxy bins (**Figure 1**). This visual representation revealed similar ranges and quartiles between normal and barred spirals—the late-type galaxies—(0.741 to 3.522 for spirals vs. 0.53 to 5.442 for barred spirals), while ellipticals—early-types—exhibited a numerically higher range (1.295 to 5.205). We identified an outlier with an *u-r* index of 10.9675 from the elliptical group. We found similar *u-r* color index ranges in normal-spiral and barred-spiral galaxies, showing their long evolution through the given index. In comparison, elliptical galaxies have a narrower distribution of *u-r* color index ranges, demonstrating that their star formation quenches faster than late types (**Figure 1**) (16). This is supported by research showing that late- and early-type galaxies are associated with two separate timescales for their star formation quenching: late-types take a long time for their gas to diffuse out of their reservoir (several billion years), whereas early-types quench rapidly (around one billion years) (16).

Graphing *u-r* color index means for early-type galaxies according to Graham's grid's lettering showed that early-type sub-features do not have distinguishable trends (**Figure 2**) (See the Methods section for term definitions). This means the sub-features, specifically bulge presence and ellipticity, do not have a noticeable effect on the *u-r* color means. However, organizing late-type galaxies according to Graham's grid showed clear trends for *u-r* color index means (**Figure 3**). This confirms that the arm looseness letter correlates with a decrease in the *u-r* color index. Thus, while the presence of bars did not affect the *u-r* color index, the looser the galaxy arms were, the lower the *u-r* color index.

DISCUSSION

The green valley theory holds that all galaxies, regardless of their morphology, would take the same graphical path through the green valley (with similar timescales) as their star formation started to quench. We aimed to examine the validity of the green valley theory and found that there were significantly different values between the *u-r* color index means of late-type galaxies (normal and barred spirals) and early-type galaxies (ellipticals). The *u-r* color index ranges of late-types and early-types differed as well, where early-type galaxies had a numerically greater range. Therefore, our results show evidence that late-type and early-type galaxies take two separate pathways through the green valley. To differentiate the original green valley theory from the hypothesis that our evidence supports, we will refer to the "green valley" as the "blue-to-red transition" from now on. In other words, our results support the red-herring theory that early- and late-type galaxies have different star formation rates through the blue-to-red transition (16). Recent studies examining late- and early-type galaxies about their star formation rates have also found a divergence between complete morphological evolution and complete star formation quenching (40, 42-44), further supporting the red-herring theory. These works also showed that the quenching rate for different morphologies differed, consistent with distinct timescales over which gas reservoirs are destroyed in late and early types.

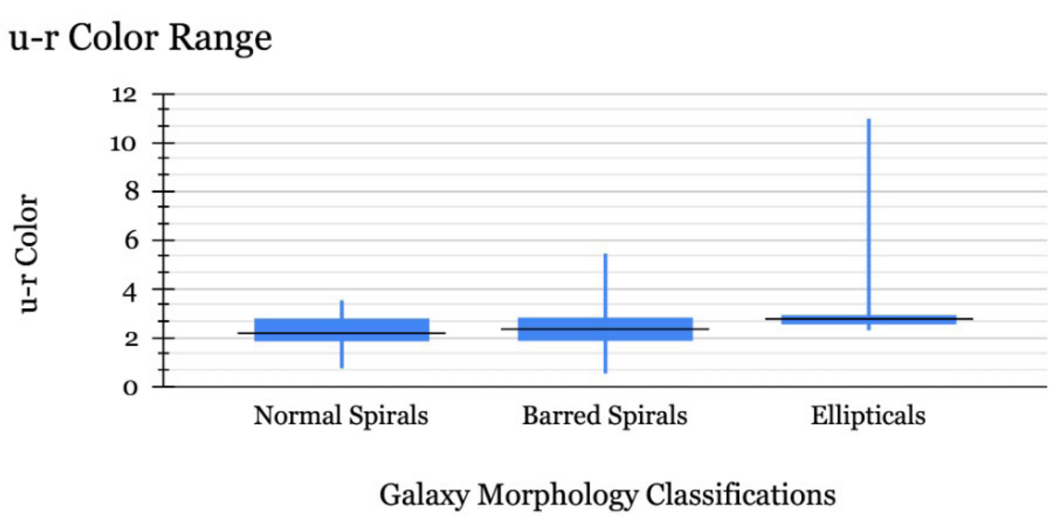

Figure 1: Box-and-whisker plots for normal spirals, barred spirals, and ellipticals to compare their ranges of *u-r* color. Numeric values on the y-axis signify magnitude difference measurements, where magnitude is a measure of luminosity.

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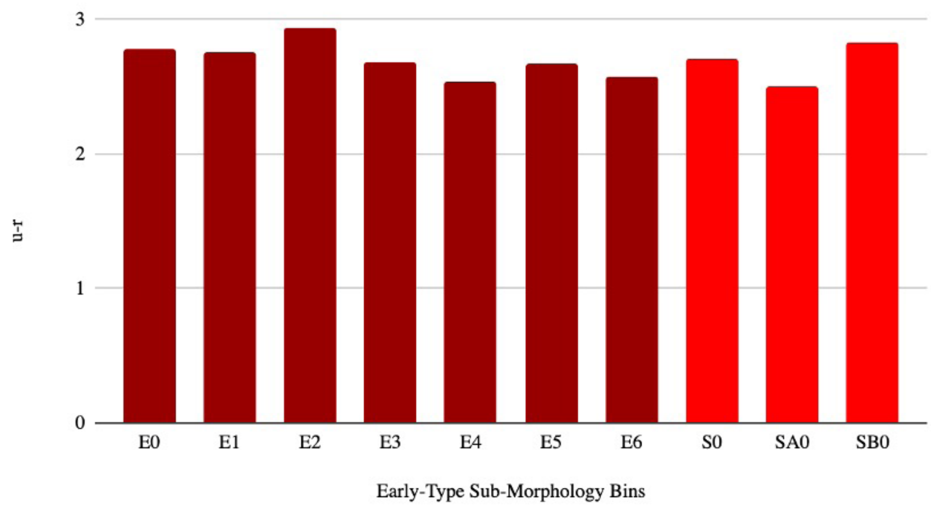

Figure 2: Bar graph categorizing the mean *u-r* color index for early-type galaxies, sorted by galaxy sub-class. Numbers on the y-axis signify magnitude difference measurements.

Additionally, sorting galaxy subtypes using the grid suggested by Graham revealed that the *u-r* color index range of late types is broader than that of early types (**Figure 1**, **Table 3**) (14). When correlated with the red-herring study done by Schawinski et al., the data serves as further evidence that the gas reservoirs of late types take far longer to destruct compared to early types (16). One possible reason for this is ram pressure stripping (the process by which a galaxy is stripped of its gasses by stellar winds), where violent events such as mergers or active galactic nucleus feedback abruptly push out all the cold gas from their reservoirs (45-47). Ram pressure stripping frequently occurs in early-type galaxies, which causes their reservoirs to deplete much faster than in late-types, where ram pressure stripping does not occur as frequently (45).

When evaluating the impact of sub-features on the late and early types separately (bar strength, spiral arm tightness, and nucleus size for the former, and bulge size and ellipticity for the latter), we determined that sub-feature differences can predict only late-type galaxies' sub-pathway. We found that late-type galaxies with classifiers ending in letters *c* or *d* tended towards lower *u-r* color indices than galaxies with classifiers ending in *a* or *b* (**Figure 2**). The lack of significant bar strength (represented by letters S, SA, or SAB) impact on the *u-r* color index does not agree with some current research (48-51). This may be due to some limitations in our study: First, we did not have access to visual classifications of the galaxies, leading to misleading numerical data as pertains to bar strength correlated with *u-r* color index and metallicity; Second, the need to combine lenticulars and ellipticals in a bin (due to the paucity of data) prevented the correlation of bar strength and *u-r* color index from being clearly defined.

	Early-Types			***Late-Types***				
Bins	*E*	*ES*	*S0*	*Sa*	*Sb*	*Sc*	*Sd*	*Sm*
No Bar	E0	EAS	SA0	SAa	SAb	SAc	SAd	SAm
Weak Bar	E1-E2	EABS	SAB0	SABa	SABb	SABc	SABd	SABm
Strong Bar	E3	EBS	SB0	SBa	SBb	SBc	SBd	SBm

Table 3: Graham's grid sorting with the main eight bins based on morphological structure (E, ES, S0, Sa, Sb, Sc, Sd, Sm) with further subcategories based on specific galactic features (13). S or SA signals no bar, SAB signals a weak bar, and SB signals a strong bar. The lowercase letter at the end of the identifier signifies how unwounded the spiral arms are compared to their nucleus size

To recap, based on our results, we conclude that early and late-type galaxies have different pathways through the blue-to-red transition; disc size and ellipticity do not affect the star formation rates of early-type galaxies; and arm tightness and nucleus size, but not the presence of a bar, affect the star formation rates of late-type galaxies.

Had we had more time to conduct this research, it would have been interesting to examine the outliers present in the *u-r* color index of certain galaxies—such as the elliptical NGC 807 (with a *u-r* color index of 10.9675) and the barred spiral M77 (with a *u-r* color index of 5.442). Further studies could determine if their sub-features influenced these galaxies' *u-r* color indices (51-53). The split of two pathways based on quenching timescales could also be explored, specifically how gas reservoirs' rapid or slow destruction affects their star quenching and why this occurs in different morphological types (54-55). One interesting question is why spiral galaxies' gas reservoirs are destroyed slowly (which causes long quenching timescales) despite their active galactic nuclei, which cause stellar winds to blow gasses out quickly. In addition, it is unknown what structural parameters cause the divergent evolution of late- and early-type galaxies (55-57). A better understanding of the features that influence galaxy evolution will allow us to predict future evolutionary changes in galaxies, including our own, and improve our concept of the universe, how it formed, and how it will continue to grow.

MATERIALS AND METHODS

Data Collection

Data on galaxies (N=293) from SIMBAD (reinforced by data from NED) was collected for their UV-optical color

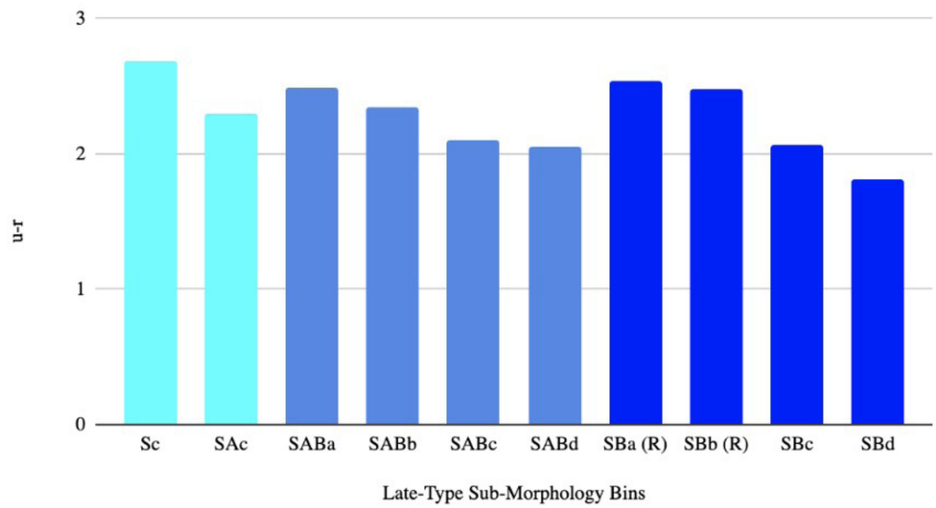

Figure 3: Bar graph categorizing the mean u-r color index for late-type galaxies in their sub-classified bins. Numbers on the y-axis signify magnitude difference measurements.

indices, radial velocity, and galaxy identifiers (signifying morphology) (56-57). Normal spirals (N=93), barred spirals (N=100), and ellipticals (N=100) were collected based on the letters at the beginning of their naming convention from the SIMBAD database. Due to a paucity of data in the database, an unequal sample size was collected for normal spirals.

Statistical Analysis

To group the galaxies, we referred to Graham's review of galaxy classification grids based on visual morphology (14). From these collective classifications, Graham constructed a grid that sorted galaxies into comprehensive sub-types that more accurately classified early- and late-type galaxies (**Table 3**). The number (0-3) or letter (A-B) shows the strength of a galaxy's sub-features, with a higher number meaning greater ellipticity and the letter B meaning a large bulge size. The galaxies are presented in order of non-barred to strong-barred, where S or SA signals no bar, SAB signals a weak bar, and SB signals a strong bar. The lowercase letter at the end of the identifier signifies the extent to which the spiral arms are unwound and their nucleus size. For the spiral arms, an alphabetically later letter signified loose arms; for nuclei size, a higher number signified a larger nucleus size (**Table 3**).

We ran a one-way ANOVA on the groups of normal spirals, barred spirals, and ellipticals to determine if there was a difference in the means of *u-r* color indices between the groups and, therefore, their star formation pathways. The ANOVA would return a specific p-value that, if below 0.05, would reject the null hypothesis and confirm a statistically significant difference. Since we rejected the null hypothesis in this research, we ran a Tukey-Kramer test on the *u-r* color index means and determined the differences between specific bins.

A box-and-whisker plot was performed on the *u-r* color indices of the three galaxy bins to determine the timescales over which the galaxies crossed the green valley. Finally, to determine if there were relationships between galaxy sub-features and *u-r* color index means, we sorted early- and late-types into sub-bins based on Graham's grid and created bar graphs to study their trends.

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