# Postprint: A Statistical Study of the Relationship Between Bars and Global Star Formation Properties in Galaxies

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## Abstract

There exists a complex interrelationship between the bar structure characteristics in disk galaxies and the galaxies' own environment as well as their overall star formation properties. Utilizing data from the detailed galaxy morphological feature measurement project Galaxy Zoo DECaLS, we constructed the largest-to-date sample of strong-bar, weak-bar, and unbarred galaxies with identical stellar mass distributions. After controlling for environmental effects by incorporating the dark halo mass and phase-space characteristics of the galaxies' host environments, we further conducted a comparative study of the star formation properties of strong-bar, weak-bar, and unbarred galaxies. The study reveals that the proportion of star formation quenching in barred galaxies is systematically higher than in unbarred galaxies, with the effect being more pronounced for strong bars. However, for galaxies that remain on the star-forming main sequence, there is no significant difference in star formation characteristics among strong-bar, weak-bar, and unbarred galaxies. These results suggest that bar features in galaxies may cause some galaxies to rapidly transition from a star-forming state to a quenched state during the timescale of their existence.

## Full Text

### Statistical Study of the Relationship Between Bar and the Overall Star Formation Properties of Galaxies

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## Abstract

The bar structure in disk galaxies exhibits complex interrelationships with both the galactic environment and the overall star formation properties of the host galaxy. Utilizing data from the Galaxy Zoo DECaLS project—a detailed galaxy morphology measurement program—we have constructed the largest sample to date of strong-bar, weak-bar, and non-barred galaxies with identical stellar mass distributions. By controlling for environmental effects through the dark matter halo mass and phase-space characteristics of the host halo, we further compare the star formation properties among these three populations. Our study reveals that the fraction of quenched galaxies is systematically higher in barred galaxies than in non-barred galaxies, with this effect being more pronounced for strong bars. However, for galaxies that remain on the star-forming main sequence, there is no significant difference in star formation characteristics among strong-bar, weak-bar, and non-barred galaxies. These results suggest that, over the timescale of its existence, a bar may cause some galaxies to rapidly transition from a star-forming state to a quenched state.

**Keywords:** barred spiral galaxy; star formation; environment

## 1. Introduction

Bars represent a crucial substructure in disk galaxies, extending across the central regions and playing a significant role in galactic formation and evolution [?, ?, ?]. Observational studies indicate that barred spiral galaxies constitute over one-third of the cosmic population, with reported fractions ranging from 30% to 60% across different samples and redshifts [?, ?, ?, ?]. Numerical simulations similarly yield varying results, but generally find barred galaxy fractions above 30% [?, ?, ?]. Previous research typically classifies bars as either strong (SB) or weak (WB) based on parameters such as width, length, or their ratios relative to the host galaxy.

Observations demonstrate that bar presence and strength correlate closely with galactic physical properties. Cervantes et al. [?] found that strong bars preferentially reside in redder galaxies, while weak bars are more common in bluer systems. Lee et al. [?] similarly reported that weak bars tend to appear in lower-mass, bluer galaxies, whereas Kim et al. [?] noted that weak-bar galaxies closely resemble non-barred galaxies in specific star formation rate (sSFR), multi-band colors ($g - r$, $NUV - r$, mid-infrared $[3.4] - [12]$), and neutral hydrogen (HI) content.

The conventional understanding posits that bars drive gas inflow from the outer disk to the central region, triggering a temporary enhancement of star formation rate (SFR) at the galaxy's core [?]. Once this gas reservoir is depleted, the galaxy as a whole enters an extended period of reduced star formation—the "quenched" phase [?, ?]. Consequently, the observed redder colors of strong-bar galaxies cannot be simplistically attributed to bar-induced quenching. Moreover, due to the relatively small sample sizes of weak-bar galaxies, their impact on overall galactic properties remains understudied.

Bar formation mechanisms are complex, involving both internal dynamical instabilities and external environmental perturbations. Numerical simulations suggest bars may form through self-gravitational instabilities in isolated disks [?] or be triggered by galaxy interactions [?]. Furthermore, the local environment, particularly on small scales, may significantly influence bar evolution. For instance, strong interactions in galaxy pairs can destroy bar structures [?], while flyby encounters [?] or mergers [?] can weaken bars, shorten their lengths, or even completely disrupt them.

Observational consensus on the relationship between bars and environment remains elusive. Tawfeek et al. [?] investigated correlations between large-scale galaxy cluster structures and bar properties, finding the highest bar fractions in spiral galaxies at cluster outskirts and in elliptical galaxies within the virial radius. Conversely, other studies argue that environment plays a minimal role: Sidney [?] found no significant difference in bar formation across groups, clusters, and field environments; Barazza et al. [?] reported similar bar fractions, lengths, and widths in clusters and the field; and Sarkar et al. [?] concluded that bar formation is dominated by internal processes rather than environmental effects.

While the connection between bars and environment remains unclear, the relationship between star formation and environment is well-established. For example, ram-pressure stripping in galaxy clusters [?] removes gas from galaxies, suppressing star formation and transforming them into quenched systems, thereby explaining the redder colors of galaxies in massive halos. Additionally, galaxy mergers [?] can drive gas toward the center, triggering starbursts; post-burst gas depletion subsequently reduces star formation, leading to quenching.

Given these complexities, if bar formation and evolution are indeed environmentally dependent, the observed correlations between bars and overall star formation properties must be re-examined. Moreover, due to the difficulty in identifying weak bars, detailed studies separating the causal relationships among bar features (strong and weak), SFR, and environment remain scarce. Recently, Galaxy Zoo DECaLS (GZD) released a new public volunteer-based morphological classification dataset capable of capturing subtle features such as weak bars and spiral arms with enhanced clarity. This study leverages the GZD sample to analyze the interplay among bars, SFR, and environment in barred galaxies while improving our understanding of weak-bar characteristics. Our advantage lies in the unprecedented sample size provided by GZD, enabling more detailed analysis than previously possible. The paper is organized as follows: Section 2 describes the data, Section 3 presents our statistical results, and Section 4 summarizes and discusses our findings.

## 2. Data

This section details the galaxy samples and related data used in this work. GZD data are introduced in Section 2.1, star formation and environmental parameters in Section 2.2, and sample definitions in Section 2.3.

**2.1 Bar-Related Information** Our barred galaxy sample is derived from the GZD project data released by Walmsley et al. [**?**]. Originating from the Sloan Digital Sky Survey (SDSS), Galaxy Zoo engages citizen volunteers to classify galaxy images, addressing the challenge of processing vast astronomical datasets. DECaLS, one of three sub-surveys within the DESI imaging program, offers photometric depths over one magnitude deeper than SDSS, enabling clearer resolution of fine morphological features [**?**]. The GZD project comprises three phases: GZD-1 (beginning 2015), GZD-2, and GZD-5 (concluding 2020). Across these phases, volunteers classified 313,789 galaxies from the SDSS main galaxy sample (defined as $r < 17.77$ mag), voting not only on the presence of substructures such as bars, spiral arms, and bulges, but also on their strengths and multiplicities. The GZD-5 decision tree provides more detailed classifications than its predecessors. Given GZD-5's substantially larger dataset, the team employed an active learning algorithm to prioritize "information-rich" galaxies for volunteer analysis. Subsequently, a Bayesian deep learning algorithm was trained on these volunteer classifications and used to predict responses for all galaxies across all three GZD phases. The dataset utilized in this work comprises these algorithmic predictions.

Our analysis focuses on bar structures. Prior to bar classification, we select face-on spiral galaxies from the sample. This refined sample serves as our basis for bar analysis, subdivided into strong-bar, weak-bar, and no-bar (NB) galaxies. Using the GZD-5 decision tree, we select galaxies where the product of voting fractions for "spiral galaxy (Features or Disk)" and "face-on (Not Edge On)" exceeds 50%, yielding 56,912 sources. We designate this the "Morph" sample.

From the Morph sample, we classify galaxies based on predicted voting data: those with "no-bar" voting fraction > 50% are designated non-barred galaxies (33,486 objects); among the remainder, those with "weak-bar" voting fraction exceeding "strong-bar" are classified as weak-bar galaxies (16,703 objects), and the rest as strong-bar galaxies (6,723 objects). Figure 1 [Figure 1: see original paper] illustrates this selection process.

*Note: Strong-bar classification requires "no-bar" voting fraction* $< 50\%$ *AND "strong-bar" voting fraction* $>$ *"weak-bar" voting fraction; weak-bar classification requires "no-bar" voting fraction* $< 50\%$ *AND "strong-bar" voting fraction* $<$ *"weak-bar" voting fraction; non-barred classification requires "no-bar" voting fraction* $> 50\%$.

**2.2 Additional Galaxy Parameters** For star formation parameters, we utilize the GALEX-SDSS-WISE Legacy Catalogue-X2 (GSWLC-X2), which covers 90% of the SDSS main galaxy sample area. Galaxy-wide SFR and stellar mass ($M_*$) are derived from spectral energy distribution (SED) fitting combining UV/optical photometry and infrared luminosity. We compute specific star formation rate as $sSFR = SFR/M_*$. Cross-matching the Morph sample with GSWLC-X2 yields 43,221 sources, designated the "Morph-SFR" sample.

For environmental parameters, we employ the galaxy group catalog of Yang et al. [**?**]. Their SDSS DR7 group catalog provides group properties including coordinates, redshift, luminosity, stellar mass, and dark matter halo mass ($M_h$) for each galaxy. The catalog offers six variants based on different redshift combinations (SDSS only, SDSS+2dF, SDSS+2dF+nearest-neighbor interpolation+ROSAT X-ray cluster data) and magnitude systems (Petrosian vs. model). To minimize uncertainties from redshift interpolation while ensuring total flux coverage, we cross-match the Morph sample with the SDSS+2dF+model magnitude subsample, obtaining halo information for 35,807 galaxies (the "Morph-Mh" sample). Unmatched sources primarily result from the group catalog's magnitude limit of $r < -19.5$ mag [**?**]. The catalog provides two halo mass estimates—derived from group stellar mass and group luminosity; we adopt the stellar mass-based values.

We compute the group radius at 180 times the cosmic mean density ($r_{180}$) as the virial radius using:

$$r_{180} = 1.26h^{-1}\left(\frac{M_h}{10^{14}h^{-1}M_\odot}\right)^{1/3}(1+z_{\text{group}})^{-1}$$

where $r_{180}$ is in Mpc, $z_{\text{group}}$ is group redshift, and we adopt $h = 0.73$. We define the most massive galaxy as the group center and compute projected distances $r$ for other members, normalizing by $r_{180}$ to obtain $r/r_{180}$ as a measure of position within the halo.

Additionally, we compute line-of-sight velocity differences $|\Delta V|$ between each galaxy's recession velocity and the group's mean velocity. Following Yang et al. [**?**], we apply the gapper estimator [**?**] to compute group line-of-sight velocity dispersion $\sigma$, but only for groups with three or more members (comprising ~20% of the group sample). Consequently, the "Morph-Mh/$\sigma$" sample containing both halo mass and $\sigma$ values contains 8,142 galaxies.

In summary, we obtain parameters including halo mass ($M_h$), relative recession velocity ($|\Delta V|$), velocity dispersion ($\sigma$), and normalized halo position ($r/r_{180}$). Section 3.1 employs these to construct phase-space diagrams for analyzing the dynamical state of galactic environments.

Notably, GSWLC-X2 adopts a Chabrier IMF [?] and cosmology ($\Omega_m = 0.272$, $\Omega_\Lambda = 0.728$, $h = 0.704$), while Yang et al. [?] use ($\Omega_m = 0.238$, $\Omega_\Lambda = 0.762$, $h = 0.73$). Given our sample's mean redshift $z \sim 0.1$, we ignore differences in $\Omega_m$ and $\Omega_\Lambda$ but uniformly apply $h = 0.73$ to correct SFR and stellar masses from GSWLC-X2.

**2.3 Sample Summary** Table 1 summarizes our samples. The "Morph" sample (56,912 galaxies) contains only bar information. The "Morph-SFR" sample (43,221 galaxies) adds star formation parameters. The "Morph-Mh" sample (35,807 galaxies) includes bar and halo mass information. The "Morph-Mh/$\sigma$" sample (8,142 galaxies) further incorporates velocity dispersion. The intersection of "Morph-SFR" and "Morph-Mh" yields the "Morph-Mh-SFR" sample (31,754 galaxies), while "Morph-SFR" and "Morph-Mh/$\sigma$" intersect to produce the "Morph-Mh/$\sigma$-SFR" sample (7,127 galaxies). Different samples are used for different analyses, with subpopulation counts provided in Table 1.

For comparative studies, we construct control samples by matching parameters (e.g., stellar mass, halo mass) in logarithmic space with a tolerance of 0.1 dex.

## 3. Statistical Results

This chapter presents our findings: Section 3.1 examines bar galaxies' star formation, Section 3.2 their environment, and Section 3.3 their star formation after environmental control.

**3.1 Barred Galaxies and Star Formation** Figure 2 [Figure 2: see original paper] displays the stellar mass and sSFR distributions (scatter points and density contours) for the three bar types in the Morph-SFR sample, with $\log(M_*/M_\odot)$ on the x-axis and sSFR on the y-axis. Red, green, and blue denote strong-bar, weak-bar, and non-barred galaxies, respectively. Marginal plots show the stellar mass and sSFR distributions. The red density curves reveal that strong-bar galaxies tend to be more massive and have lower sSFR than weak-bar and non-barred galaxies. Due to the intrinsic correlation between stellar mass and sSFR, we control for stellar mass when comparing sSFR characteristics. Since our focus is the relationship between bar features and sSFR, and galaxy colors (particularly $NUV - r$) directly reflect sSFR, we do not control for color in this or Section 3.3.

Using the strong-bar sample, we construct control samples by one-to-one matching non-barred and weak-bar galaxies within 0.1 dex in stellar mass, yielding 5,151 galaxies of each type. Figure 3a [Figure 3: see original paper] shows the sSFR histograms for these mass-controlled samples. The dashed line at $sSFR = -10.8$ separates star-forming (right) from quenched and green valley galaxies (left). Barred galaxies exhibit sSFR distributions skewed toward lower values, particularly strong-bar galaxies. The inset lists median sSFR values with errors estimated via 1,000 bootstrap resamplings. The medians confirm that barred galaxies have lower sSFR than non-barred galaxies, with strong bars showing the strongest effect.

Since quenched galaxies constitute a minority, their signature may not be prominent in overall sSFR distributions. We therefore introduce the quench fraction parameter:

$$F_{\text{quench}} = \frac{N_{\text{quench}} + N_{\text{GV}}}{N_{\text{Total}}}$$

where $N$ represents galaxy counts. Figure 3b [Figure 3: see original paper] shows $F_{\text{quench}}$ for the three bar types, binned by stellar mass. All samples show increasing $F_{\text{quench}}$ with mass [**?**], but systematic differences exist: strong-bar galaxies exhibit significantly and systematically higher $F_{\text{quench}}$ than weak-bar and non-barred galaxies, while weak-bar galaxies are marginally higher than non-barred galaxies.

**3.2 Barred Galaxies and Environment** This section analyzes environmental parameters: halo mass ($M_h$), normalized position ($r/r_{180}$), and normalized line-of-sight velocity ($|\Delta V|/\sigma$). Figure 4a [Figure 4: see original paper] presents $M_h$ histograms for mass-controlled samples from the Morph-Mh-SFR sample (4,273 galaxies of each type). Strong-bar galaxies clearly inhabit more massive halos, as confirmed by the median $M_h$ values in the inset.

Halo mass alone does not fully characterize environment; position and velocity within the halo are equally important. Phase-space diagrams effectively trace cluster formation histories and galaxy orbital histories [**?**]. The diagram's x-axis is $r/r_{180}$ and y-axis is $|\Delta V|/\sigma$, distinguishing virialized (dynamically relaxed) from infalling regions [**?**]. We examine whether these dynamical states correlate with bar strength using the Morph-Mh/$\sigma$-SFR sample, controlling for both stellar mass and halo mass (0.1 dex tolerance) to obtain 1,031 galaxies of each type. Figure 4b [Figure 4: see original paper] shows the phase-space diagram, with the dividing line from Jaffé et al. [**?**]:

$$\frac{|\Delta V|}{\sigma} \leq 1.5 - 1.25\frac{r}{r_{180}}, \quad \frac{r}{r_{180}} \leq 1.2$$

Subtle differences emerge: the fractions in the virialized region are 0.81, 0.77, and 0.79 for strong-bar, weak-bar, and non-barred galaxies, respectively. Strong-bar galaxies show the highest virialized fraction, consistent with their preference for dense environments. Interestingly, weak-bar galaxies show the lowest virialized fraction rather than non-barred galaxies, though differences are not statistically significant given the errors. Larger samples are needed to confirm any phase-space distribution differences.

In summary, barred and non-barred galaxies inhabit systematically different environments, particularly in halo mass, with strong-bar galaxies favoring dense environments. Since dense environments suppress star formation, the higher quenched fractions and lower sSFR observed in Section 3.1 may be environmentally biased.

### 3.3 Star Formation in Barred Galaxies After Environmental Control

Using the Morph-Mh/$\sigma$-SFR sample, we simultaneously control stellar mass and halo mass, then separate virialized and infalling galaxies to eliminate phase-space-related environmental biases. This yields 786 control galaxies of each type in the virialized region and 138 in the infalling region. Figure 5 [Figure 5: see original paper] presents results: panels a, c, e show virialized region properties; panels b, d, f show infalling region properties.

Figures 5a and 5b display sSFR histograms. In both environments, strong-bar galaxies have lower median sSFR than weak-bar and non-barred galaxies, with the difference more pronounced in the virialized region. Figures 5c and 5d show $F_{\mathrm{quench}}$: in all sub-environments, barred galaxies exhibit higher quenched fractions than non-barred galaxies, with strong bars showing the strongest effect. Thus, even after controlling for mass and environment, galaxies with more prominent bars contain higher proportions of quenched systems.

To investigate the physical mechanism, we examine whether bars systematically reduce sSFR in star-forming galaxies. Figures 5e and 5f show sSFR distributions for star-forming galaxies only ($sSFR > -10.8$): 1,503 galaxies in the virialized region and 300 in the infalling region. After controlling for mass and environment, the median sSFR values show no significant differences among the three bar types. Two-sample KS tests confirm that the sSFR distributions are statistically indistinguishable (p-values shown in the insets). This contradicts the hypothesis that bars uniformly lower sSFR.

Combining these results, the systematically lower average sSFR in barred galaxies (Figures 5a, b) arises from their higher quenched fractions (Figures 5c, d). When considering only star-forming galaxies, barred and non-barred galaxies show similar star formation properties after accounting for selection biases. This is our primary conclusion.

If bar features drive the elevated quenched fractions, the quenching process must be rapid, leaving the sSFR distribution of star-forming galaxies unaffected. Alternatively, the correlation could be reversed: quenched galaxies may more easily develop bars. Our statistical study establishes only correlation, not causation. Disentangling these scenarios requires numerical simulations [**?**, **?**], which is beyond our current scope.

## 4. Summary and Outlook

This work combines GZD bar classifications with GSWLC-X2 star formation data and Yang et al. [?] group catalog environmental information to assemble the largest sample of strong-bar and weak-bar galaxies to date. After controlling for mass and environmental differences, we systematically analyze correlations between bars and star formation. Our main conclusions are:

1. **Barred galaxies are more massive, have lower sSFR, reside in more massive halos, and are more frequently found in virialized regions than non-barred galaxies. These trends are stronger for strong bars than weak bars.**
2. **At fixed mass and environment, barred galaxies exhibit higher quenched fractions, with strong bars showing more significant effects than weak bars.**
3. **At fixed mass and environment, star-forming galaxies on the main sequence show no significant difference in sSFR between barred and non-barred galaxies.**

Our study is the first to systematically remove environmental biases, revealing physical connections between bar features and star formation properties that are valuable for barred galaxy research.

Our sSFR measurements describe global star formation, which may be insensitive to localized processes. Bar effects might be regional rather than global. For example, Lin et al. [?] found that bars only suppress SFR in central regions. If the central SFR constitutes a small fraction of the total, its suppression would not significantly reduce global sSFR, making average sSFR differences undetectable in star-forming barred galaxies. Future work should: (1) quantify bar strength [?] rather than relying on visual classifications, and (2) perform spatially resolved SED fitting across multiple bands in large samples to analyze how bars affect internal star formation processes, following Lin et al. [?].

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## References

[1] Kormendy J, Kennicutt R C. ARA&A, 2004, 42: 603
[2] Lin L, Li C, He Y, et al. ApJ, 2017, 838: 105
[3] Kim E, Hwang H S, Chung H, et al. ApJ, 2017, 845: 93
[4] Nair P B, Abraham R G. ApJS, 2010, 186: 427
[5] Nair P B, Abraham R G. ApJL, 2010, 714: L260
[6] Lee G H, Park C, Lee M G, et al. ApJ, 2012, 745: 125
[7] Guo Y, Jogee S, Finkelstein S L, et al. arXiv:2210.08658, 2022
[8] Rosas G Y, Bonoli S, Dotti M, et al. MNRAS, 2020, 491: 2547
[9] Zana T, Lupi A, Bonetti M, et al. MNRAS, 2022, 515: 1524
[10] Bi D, Shlosman I, Romano-Díaz E. ApJ, 2022, 934: 52

[11] Cervantes S B, Li C, Park C. ApJ, 2015, 807: 111
[12] Consolandi G, Dotti M, Boselli A, et al. A&A, 2017, 598: A114
[13] Tahmasebzadeh B, Zhu L, Shen J, et al. ApJ, 2022, 941: 109
[14] Martinez-Valpuesta I, Aguerri, J A L, González García A C, et al. MNRAS, 2017, 464: 1502
[15] Tawfeek A A, Cervantes Sodi B, Fritz J, et al. ApJ, 2022, 940: 1
[16] Zana T, Dotti M, Capelo P R, et al. MNRAS, 2018, 479: 5214
[17] Ghosh S, Saha K, Di Matteo P, et al. MNRAS, 2021, 502: 3085
[18] Sidney van den B. AJ, 2002, 124: 782
[19] Barazza F D, Jablonka P, Desai V, et al. A&A, 2009, 497: 713
[20] Sarkar S, Pandey B, Bhattacharjee S. MNRAS, 2021, 501: 994
[21] Boselli A, Fossati M, Sun M. A&ARv, 2022, 30: 3
[22] Petersson J, Renaud F, Agertz O, et al. MNRAS, 2023, 518: 3261
[23] Chabrier G. PASP, 2003, 115: 763
[24] Walmsley M, Lintott C, G'eron T, et al. MNRAS, 2022, 509: 3966
[25] Géron T, Smethurst R J, Lintott C, et al. MNRAS, 2021, 507: 4389
[26] Yang X, Mo H J, van den Bosch F C, et al. ApJ, 2007, 671: 153
[27] Beers T C, Flynn K, Gebhardt K. AJ, 1990, 100: 32
[28] Salim S. Serbian Astronomical Journal, 2014, 189: 1
[29] Donnari M, Pillepich A, Nelson D, et al. MNRAS, 2021, 506: 4760
[30] Muzzin A, van der Burg R F J, McGee S L, et al. ApJ, 2014, 796: 65
[31] Jaffé Y L, Smith R, Candlish G N, et al. MNRAS, 2015, 448, 1715
[32] Cavanagh M. K, Bekki K, Groves B A, et al. MNRAS, 2022, 510: 5164
[33] Rosas-Guevara Y, Bonoli S, Dotti M, et al. MNRAS, 2022, 512: 5339

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