

Statistical Study of the Relationship Between Bars and the Global Star Formation Properties of Galaxies (Postprint)

Authors: Mu Zihao, Shen Shiyin, Rafael S. de Souza, Ana L. Chies-Santos

Date: 2024-03-22T00:00:00+00:00

Abstract

A complex interrelationship exists between bar structure features in disk galaxies and both their residing environment and overall star formation characteristics. Utilizing data from the detailed galaxy morphological feature measurement project Galaxy Zoo DECaLS, we construct the currently largest sample of strong-bar, weak-bar, and non-barred galaxies with uniform stellar mass distributions. After controlling for environmental effects by incorporating the host dark halo mass and phase-space characteristics of the galaxies, we further conduct a comparative study of the star formation characteristics among strong-bar, weak-bar, and non-barred galaxies. The results demonstrate that the fraction of star formation quenching in barred galaxies is systematically higher than that in non-barred galaxies, with the effect being more pronounced for strong bars. However, for galaxies that remain on the star-forming main sequence, the star formation characteristics among strong-bar, weak-bar, and non-barred galaxies exhibit no significant differences. These results suggest that bar features in galaxies may rapidly drive some galaxies to transition from a star-forming state to a quenched state during their existence timescale.

Full Text

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

MU Zi-hao^{1,2}, SHEN Shi-yin^{1,3}, Rafael S. de Souza⁴, Ana L. Chies-Santos⁵

¹Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China

²University of Chinese Academy of Sciences, Beijing 100049, China

³Key Laboratory for Galaxy and Cosmology Semi-Analytical Research, Shanghai 200034, China

⁴Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK

⁵Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre 9500, Brazil

Abstract: The bar structure in disk galaxies exhibits complex interrelationships with both the environment in which the galaxy resides and its overall star formation properties. 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. After controlling for environmental effects by accounting for the host dark matter halo mass and phase-space characteristics, we further compare the star formation properties across 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 during the timescale over which bars exist, they 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 that extends across the central region and plays a significant role in galaxy formation and evolution. Observations indicate that barred spiral galaxies constitute more than one-third of the galaxy population, with reported fractions ranging from 30% to 60% depending on the sample and redshift. Numerical simulations similarly yield bar fractions consistently above 30%. Previous studies typically classify bars as either strong (SB) or weak (WB) based on parameters such as bar width, length, or their ratios relative to the host galaxy's dimensions. Observations have shown that the presence and strength of bars correlate closely with galaxy physical properties. Cervantes et al. found that strong bars preferentially reside in redder galaxies, while weak bars are more common in bluer galaxies. 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 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.

It is generally believed that bars drive gas inflow from the outer regions to the galactic center, triggering elevated star formation rates (SFR) in the nucleus. Once this gas supply is exhausted, 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 simply attributed to bar-driven quenching. Moreover, due to the relatively small sample sizes of weak-bar galaxies, their impact on global galaxy properties remains understudied.

Bar formation involves complex mechanisms related to both internal disk instabilities and external perturbations. Numerical simulations suggest bars can form through the disk’s own dynamical instability or be triggered by galaxy interactions. Furthermore, the 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 them, or even completely disrupt them. Observationally, the relationship between bars and environment remains inconclusive. Some studies find higher bar fractions in spiral galaxies at the outskirts of clusters or in elliptical galaxies within the virial radius, while others report no significant environmental dependence. For example, Sidney found no substantial difference in bar formation across groups, clusters, and field environments, and Barazza et al. observed similar bar fractions, lengths, and widths in clusters and the field. Sarkar et al. argued that bar formation is more strongly influenced by internal galaxy processes than by environment.

While the connection between bars and environment remains unclear, the relationship between star formation and environment is well-established. Ram-pressure stripping in clusters can remove gas from galaxies, reducing SFR and transforming them into quenched systems, thereby explaining the redder colors of galaxies in massive halos. Galaxy mergers similarly drive gas toward the center, triggering starbursts that subsequently deplete gas and lead to quenching.

Given these complexities, if bar formation and evolution are indeed environment-dependent, the observed correlations between bars and global star formation properties must be re-examined. Moreover, due to the difficulty in identifying weak bars, detailed studies separating the causal relationships among bars, 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. This study leverages the GZD sample to analyze the interplay among bars, SFR, and environment while improving our understanding of weak-bar galaxies. The GZD sample’s unprecedented size enables more detailed analysis than previously possible.

2 Data and Sample Selection

This chapter details the galaxy samples and data used in our work. Section 2.1 describes the GZD data, while Section 2.2 covers star formation and environmental parameters.

2.1 Bar-Related Information

Our barred galaxy sample derives from the GZD project data released by Walmsey et al. Originating from the Sloan Digital Sky Survey (SDSS), Galaxy Zoo engages public volunteers to classify galaxy images, addressing the challenge of processing vast image datasets. DECaLS, one of three sub-surveys in the DESI photometric program, offers photometric depth more than one magnitude deeper than SDSS, enabling clearer resolution of detailed morphological features. The GZD project comprises three phases (GZD-1, GZD-2, and GZD-5), with volunteers classifying 313,789 galaxies from the SDSS main galaxy sample ($r < 17.77$ mag). The classification includes votes on the presence and properties of substructures such as bars, spiral arms, and bulges. GZD-5 employs a more detailed decision tree than its predecessors. Due to its larger sample size, an active learning algorithm prioritized “information-rich” galaxies for volunteer analysis, with Bayesian deep learning subsequently trained on these votes to predict classifications for all galaxies across all three phases. This study utilizes these deep learning-predicted classifications.

To analyze bar features, we first selected face-on spiral galaxies from the sample. We identified galaxies as suitable for bar analysis when the product of vote fractions for “spiral galaxy (Features or Disk)” and “face-on (Not Edge On)” exceeded 50% in the GZD-5 decision tree. This “Morph” sample contains 56,912 sources.

Within the Morph sample, we classified galaxies as “non-barred” (33,486) if the predicted vote fraction for “no bar” exceeded 50%. Among the remaining galaxies, those with higher vote fractions for “weak bar” than “strong bar” were classified as “weak-bar” (16,703), and the rest as “strong-bar” (6,723). Figure 1 [Figure 1: see original paper] illustrates this selection process.

2.2 Additional Galaxy Parameters

For star formation parameters, we used data from 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_*) were derived from spectral energy distribution (SED) fitting combining UV/optical photometry with infrared luminosity. We computed sSFR as SFR/M_* . Cross-matching the Morph sample with GSWLC-X2 yielded 43,221 sources, designated the “Morph-SFR” sample.

For environmental parameters, we employed the galaxy group catalog of Yang et al., which provides group properties including coordinates, redshift, luminosity, stellar mass, and dark matter halo mass (M_h) for SDSS DR7 galaxies. The catalog offers six variants based on different redshift combinations and magnitude systems. We adopted the subsample using SDSS redshift + 2df redshift + model magnitude, cross-matching with the Morph sample to obtain halo information for 35,807 galaxies (the “Morph- M_h ” sample). Unmatched sources primarily result from the group catalog’s magnitude limit of $r < -19.5$ mag. We

used halo masses derived from group stellar mass.

We calculated the group radius at 180 times the cosmic mean density (r180) as the virial radius:

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

where r180 is in Mpc, zgroup is group redshift, and $h = 0.73$. We defined the most massive galaxy as the group center and computed normalized projected distances r/r_{180} for other members. We also calculated line-of-sight velocity differences $|\Delta V|$ relative to the group velocity and velocity dispersion σ using the gapper estimator for groups with ≥ 3 members. This reduced the Morph-Mh sample to 8,142 galaxies with both halo mass and σ (the “Morph-Mh/ σ ” sample).

Note that 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 of $z \approx 0.1$, we ignore differences in Ω_m and Ω_{Λ} but correct SFR and stellar masses to $h = 0.73$.

2.3 Sample Summary

Table 1 summarizes our samples: Morph (56,912 galaxies), Morph-SFR (43,221), Morph-Mh (35,807), Morph-Mh/ σ (8,142), Morph-Mh-SFR (31,754), and Morph-Mh/ σ -SFR (7,127). The table lists the numbers of strong-bar, weak-bar, and non-barred galaxies in each sample. For comparative studies, we construct control samples by matching parameters (e.g., stellar mass, halo mass) within a 0.1 dex threshold in log space.

3 Statistical Results

This chapter presents our findings: Section 3.1 examines bar galaxies and star formation, Section 3.2 analyzes their environment, and Section 3.3 investigates star formation after controlling for environment.

3.1 Barred Galaxies and Star Formation

Figure 2 [Figure 2: see original paper] shows the stellar mass and sSFR distributions for the three bar types in the Morph-SFR sample. Strong-bar galaxies (red) exhibit higher masses and lower sSFRs than weak-bar (green) and non-barred (blue) galaxies. Following Salim, we define star-forming (SF) galaxies as $\text{sSFR} > 10^{-10} \cdot 8 \text{ yr}^{-1}$, green valley (GV) galaxies as $10^{-11} \cdot 8 < \text{sSFR} < 10^{-10} \cdot 8 \text{ yr}^{-1}$, and quenched galaxies as $\text{sSFR} < 10^{-11} \cdot 8 \text{ yr}^{-1}$.

To isolate the effect of bars, we constructed mass-controlled samples by matching stellar masses within 0.1 dex, yielding 5,151 galaxies of each type. Figure

3a [Figure 3: see original paper] shows the sSFR distributions for these control samples. Barred galaxies, particularly strong-bar galaxies, exhibit sSFR distributions skewed toward lower values. The median sSFR values (with errors from 1,000 bootstrap resamplings) confirm this systematic offset.

Since quenched galaxies represent a relatively small fraction, we introduce the quench fraction parameter:

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

Figure 3b [Figure 3: see original paper] shows F_{quench} for the mass-controlled samples, binned by stellar mass. While F_{quench} increases with mass for all types, barred galaxies exhibit systematically higher quench fractions, with strong bars showing the most significant enhancement.

3.2 Barred Galaxies and Environment

We analyzed environmental parameters including halo mass (Mh), normalized group position (r/r_{180}), and normalized line-of-sight velocity ($|\Delta V|/\sigma$). Figure 4a [Figure 4: see original paper] presents Mh distributions for mass-controlled samples from Morph-Mh-SFR (4,273 galaxies per type). Strong-bar galaxies clearly prefer more massive halos, with median Mh values confirming this trend.

Phase-space diagrams effectively trace galaxy orbital histories and group formation. Figure 4b [Figure 4: see original paper] shows the phase-space distribution for mass- and halo-controlled samples from Morph-Mh/ σ -SFR (1,031 galaxies per type). Using the Jaffe et al. division:

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

we identify virialized and infalling regions. The virialized fractions are 0.81, 0.77, and 0.79 for strong-bar, weak-bar, and non-barred galaxies, respectively. While strong-bar galaxies show the highest virialized fraction (consistent with their preference for dense environments), weak-bar galaxies surprisingly show the lowest fraction, though differences are not statistically significant given the sample size.

These results demonstrate that barred and non-barred galaxies inhabit systematically different environments, particularly in halo mass. Since dense environments suppress star formation, the higher quench fractions and lower sSFRs observed in barred galaxies may reflect environmental bias rather than bar-driven effects.

3.3 Star Formation in Barred Galaxies After Environmental Control

Using the Morph-Mh/ σ -SFR sample, we simultaneously controlled for stellar mass and halo mass, then separated virialized and infalling regions to eliminate phase-space-related environmental biases. This yielded control samples of 786 galaxies per type in the virialized region and 138 per type in the infalling region.

Figures 5a and 5b [Figure 5: see original paper] show sSFR distributions for these environments. In both regions, barred galaxies exhibit lower median sSFRs than non-barred galaxies, with the difference being more pronounced in the virialized region. Figures 5c and 5d display Fquench trends: in all sub-environments, barred galaxies show higher quench fractions than non-barred galaxies, with strong bars having the highest fractions.

However, when examining only star-forming galaxies ($\text{sSFR} > 10^{-10} \cdot 8 \text{ yr}^{-1}$), the sSFR distributions become remarkably similar. Figures 5e and 5f show sSFR distributions for SF galaxies (1,503 in the virialized region, 300 in the infalling region). The median sSFR values are consistent across bar types, and Kolmogorov-Smirnov tests confirm no significant differences in their distributions.

These findings demonstrate that the systematically lower average sSFR in barred galaxies results from their higher quench fractions, not from reduced star formation efficiency in actively star-forming systems. After accounting for mass and environment, the star formation properties of SF galaxies are independent of bar presence or strength. This represents our primary conclusion.

If bars drive the elevated quench fractions, the quenching process must be rapid, leaving the sSFR distribution of SF galaxies unaffected. Alternatively, quenched galaxies may more easily develop bars. Our statistical analysis establishes correlations but cannot determine causality; disentangling these scenarios requires numerical simulations beyond our current scope.

4 Summary and Outlook

This work utilizes GZD data combined with GSWLC-X2 star formation measurements and Yang et al.'s group catalog to assemble the largest sample of strong-bar and weak-bar galaxies to date. After controlling for mass and environment, we systematically analyzed correlations between bars and star formation. Our main conclusions are:

1. Barred galaxies exhibit larger stellar masses, lower sSFRs, residence in more massive halos, and greater preference for virialized regions compared to non-barred galaxies, with strong bars showing more pronounced differences.
2. At fixed mass and environment, barred galaxies have higher quench fractions, again with strong bars showing stronger effects.

3. At fixed mass and environment, star-forming galaxies on the main sequence show no significant sSFR differences between barred and non-barred galaxies.

Our study is the first to systematically remove environmental biases, providing clearer insight into the physical connection between bar features and star formation properties.

Our sSFR measurements describe global star formation, which may be insensitive to local processes. Bar effects might be localized rather than global. For instance, Lin et al. demonstrated that bars only suppress central SFR. If the central region contributes minimally to the total SFR, this suppression would not significantly reduce global sSFR, explaining our null detection in SF galaxies. Future work should quantify bar strength more precisely and perform spatially resolved SED fitting across multiple bands to analyze how bars influence internal star formation processes.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.