Advances in Observational Studies of Galactic Bar Structure: Postprint

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Abstract

Galaxy bars are a ubiquitous morphological structure in the nearby universe. The interaction between galaxy bars and their host galaxies influences the physical properties of the host galaxies and drives long-term galactic evolution. This paper first introduces the influence of bars on galaxy evolution, with a focus on discussing the role of bars in star formation within galaxies; secondly, it analyzes the distribution of bars in galaxies, elaborating on the characteristics of barred spiral galaxies and the evolution of bars with redshift; subsequently, it discusses several primary methods for bar identification; and finally, it provides a summary and outlook for research on the relationship between bars and galaxies.

Full Text

Abstract

Galactic bars are a ubiquitous morphological structure in the nearby universe. There exists an interaction between the bar and its host galaxy that affects the physical properties of the host and drives its long-term evolution. This paper first introduces the influence of bars on galaxy evolution, focusing on the role of bars in star formation within galaxies. It then analyzes the distribution of bars in galaxies, elaborating on the characteristics of barred spiral galaxies and the evolution of bars with redshift. Next, several main methods for bar identification are discussed. Finally, the research on the relationship between bars and galaxies is summarized and future prospects are outlined.

Keywords: galactic bar; galaxy properties; galaxy evolution; galaxy morphology

1 Introduction

Barred spiral galaxies are a common type of galaxy in the nearby universe, possessing—like the Milky Way—a bright, large-scale bar composed of stars. A galactic bar (hereafter referred to as a "bar") is an elongated structure extending from the galactic center and represents one of the most prominent features of galaxy morphology, characterizing galactic form while simultaneously influencing evolutionary processes. It is generally believed that bars can form through internal physical processes such as intrinsic instabilities in the galactic disk [1-3], or through external processes like galaxy interactions, perturbations, and tidal effects [4-6]. Numerous theoretical studies and numerical simulations indicate that bars only form in kinematically cold disks dominated by baryonic matter [7-10], serving as the primary driver of secular evolution in disk galaxies. Once formed, bars interact with gas and other components of the galaxy, gradually altering the properties of the bar itself and affecting the evolution of the host galaxy [11]. As shown in Figure 1 [Figure 1: see original paper], Gao and Ho [12] presented a comparison between unbarred and barred galaxies, revealing significant morphological differences between the two, with the bar being a highly prominent galactic structure.

In recent years, advances in astronomical technology and observational facilities have enabled increasingly detailed observational studies of galactic bar structures. Research results demonstrate that, as an important internal factor driving galaxy evolution, bar structures can influence and redistribute the angular momentum of gas and stars in the galactic disk, causing material and energy to be redistributed across the disk, thereby affecting the physical properties and altering the morphological characteristics of galaxies. Observationally, these effects manifest as correlations between bars and various physical activities and features of galaxies (such as star formation, bulges, ring structures, metallicity distributions, nuclear activity, etc.), as well as in the distribution of bars within galaxies and their evolution with redshift. Therefore, a systematic understanding of these research advances helps us comprehend the formation and evolution of bars and galaxies, which this paper will briefly introduce.

Current research results on bars still contain considerable uncertainties, with many theories about bars yet to be observationally confirmed, and even many fundamental questions remaining unresolved. These discrepancies and disagreements arise primarily from two aspects: on one hand, the complex formation and evolution mechanisms of bars themselves and the physical processes of galaxy evolution; on the other hand, differences in the samples, data, and methods used for bar identification and measurement across various studies. Current research on bar identification and measurement primarily relies on qualitative or quantitative analysis based on one-dimensional or two-dimensional data, with different methods having distinct focuses, advantages, and disadvantages that directly affect the accuracy of research results. Therefore, we will also introduce the main methods for bar identification.

This paper will focus on two aspects: the influence of bars on galaxies and the distribution of bars in galaxies, while also presenting the primary methods for bar identification. The structure of this paper is as follows: Section 2 discusses the influence of bars on galaxies, with a focus on the impact of bars on star formation in host galaxies; Section 3 primarily introduces the distribution characteristics of bars in galaxies, including the main properties of barred spiral galaxies and the evolution of bars with redshift; Section 4 lists and discusses several mainstream methods for bar identification; Section 5 provides a summary of the entire paper and outlines future research directions.

2 The Influence of Bars on Star Formation in Galaxies

Bars in disk galaxies are important internal drivers of galaxy evolution in the nearby universe [13], and star formation is one of the key physical processes in galaxy evolution. Therefore, there must be direct or indirect connections between them. However, recent research on bars has shown considerable controversy regarding their influence on star formation in host galaxies. Although many studies have confirmed that bars significantly affect star formation activity in galaxies, the specific physical processes remain unclear. Two main viewpoints exist: (1) bars promote or enhance star formation in galaxies (particularly in central regions); and (2) bars suppress star formation activity in galaxies (either globally or in the disk) and cause quenching. These diametrically opposed conclusions arise not only from differences in sample data, research environments, and methodologies but also primarily from the complex evolution mechanisms and physical processes of bars and galaxies themselves. This section introduces these two viewpoints on the role of bars in star formation and summarizes the observational evidence.

In the late 20th century, astronomers began studying the influence of bars on star formation, but due to limited observational techniques and immature data processing capabilities, most studies were confined to small samples with simple analyses. In 1980, Heckman [14] used a sample of several dozen nearby galaxies, employing simple classification of galaxy types and spectroscopic observations, to find that barred disk galaxies were more likely to host star formation in their centers than unbarred disk galaxies. Hawarden et al. [15] similarly used a small sample and discovered that over one-third of barred galaxies in their sample exhibited enhanced emission at 25 (cid:22)m, likely resulting from bar-induced enhancement of central star formation. By today’ s standards, these studies lacked generality and precision, but in an era of limited research capabilities, they provided valuable guidance for researchers.

Subsequently, many researchers began using more observational techniques and wavelength bands to study the influence of bars on star formation. Roussel et al. [16] investigated the relationship between bars and mid-infrared radiation in 69 nearby spiral galaxies, suggesting that observed excess 15 (cid:22)m emission was likely caused by central starbursts triggered by the dynamical effects of bars. Knapen et al. [17] used B- and I-band broad-band observations along with

H(cid:11) narrow-band observations to study 73 nearby barred spiral galaxies, confirming that central region rings primarily exist in barred galaxies, indicating to some extent that bars can promote the formation of central rings. Allard et al. [18] supported Knapen et al.' s conclusions, studying the star formation history in the bar and central region of the barred galaxy M100 and confirming that the central region of M100 formed numerous massive stars from gas flowing inward under the influence of the bar, thereby demonstrating that central region rings can form under bar influence. Ho et al. [19] used spectroscopy to compare the detection rates and intensities of central HII regions and AGN in barred versus unbarred galaxies, confirming that bars in early-type galaxies can enhance galactic star formation rates. Huang et al. [20] conducted more detailed research using multiple detailed star formation indicators. They analyzed three galaxy samples using two relative star formation rate indicators, LFIR/LB and the IRAS color index S25/S12, confirming that the average specific star formation rate (sSFR) of strongly barred galaxies is significantly higher than that of unbarred galaxies, with this phenomenon being more pronounced in the infrared band. Moreover, this effect was limited to early-type galaxies (S0/a–Sbc) and was not evident in late-type galaxies (Sc–Sdm), with no enhancement of sSFR found in weakly barred galaxies.

2.1.2 Recent Progress

With continuous improvements in observational techniques and data analysis capabilities, researchers have obtained increasingly large datasets and enhanced their ability to conduct large-sample studies, leading to a growing body of large-sample research results on star formation in bars. Coelho and Gadotti [21] calculated stellar ages for a sample of 575 disk galaxies, finding that approximately 43% of the sample galaxies contained bars. They also concluded that the average stellar age of bulges in barred galaxies is lower than in unbarred galaxies, strongly supporting the model that bars trigger star formation activity in galactic centers. Ellison et al. [22] compared the stellar mass, star formation rate, and chemical abundance of galaxies with large-scale bars versus unbarred galaxies. They found that the central star formation rate of massive barred spiral galaxies is 60% higher than that of unbarred galaxies of the same mass, while the central star formation rate of low-mass barred spiral galaxies shows no increase. As shown in Figure 2c [Figure 2: see original paper], the difference in central star formation rate between barred and unbarred galaxies is small or even negative at the low-mass end, but substantially positive at the high-mass end. Wang et al. [23] further noted that whether central star formation is enhanced depends primarily on the bar ellipticity, not on bar size or host galaxy mass or structure, and that strong bars with ellipticity greater than 0.5 cause enhanced central star formation. Kim et al. [24] compared the physical properties of barred and unbarred galaxies with similar mass and redshift distributions, using g-r color, NUV-r color, and mid-infrared color to characterize star formation activity. They found that the star formation activity of strongly barred galaxies is on average lower than that of unbarred galaxies, while weakly barred galaxies show no such difference. They suggested that star formation activity in barred galaxies was enhanced in the past, but significant gas consumption has resulted in current star formation activity that is lower than or comparable to unbarred galaxies, with the degree of past star formation enhancement depending on bar strength.

With the popularization of integral field spectrographs (IFU) and the conduct of large-scale surveys, IFU data have gradually been applied to studies of galactic bars. Lin et al. [26] analyzed two-dimensional spectra of approximately 1,400 low-redshift nearby late-type galaxies, identifying 121 galaxies with ongoing or recent central star formation. Of these galaxies, (89$±$3)% are barred, with their central star formation activity potentially enhanced by an order of magnitude, and the size of the region tightly correlated with bar length. Chown et al. [27] studied the spatially resolved star formation history and molecular gas distribution in 58 nearby galaxies. They divided their sample into 17 barred galaxies, 24 unbarred galaxies, and 17 merging galaxies, finding that galaxies with enhanced central star formation are only barred or merging galaxies, and that they have relatively high molecular gas densities. Their findings provide substantial evidence for the theory that cold gas transported inward through bars or tidal interactions leads to increased and rejuvenated star formation in central regions.

2.1.3 Innovative Methods

Some unconventional studies have employed indirect and clever approaches to investigate star formation in barred spiral galaxies. For example, Fraser-McKelvie et al. [28] decomposed the structure of barred spiral galaxies, distinguishing between the bar center, bar ends, and the ridge region between the center and ends, measuring the star formation efficiency in each region. They found that star formation tends to occur along the bar, generally at the leading edge of the galactic bar, consistent with the scenario where gas is compressed and then triggered into star formation by shocks. Additionally, their spectral fitting results [31] showed that the star formation history of barred galaxies reaches its peak on average 1.7 Gyr earlier than that of unbarred galaxies, indirectly proving that barred galaxies have higher star formation rates than unbarred galaxies. Furthermore, researchers found that star formation efficiency is often high at the bar center and ends, while being systematically suppressed in the ridge region of the bar [29]. Other scholars have studied the influence of bars on host galaxy star formation in specific environments. Yoon and Im [30] studied 105 low-redshift galaxies in SDSS galaxy clusters to investigate the possible connection between the fraction of star-forming galaxies and bars in interacting clusters. They found that the increased fraction of star-forming galaxies in interacting clusters is primarily due to an increased number of barred galaxies, suggesting that star formation in interacting clusters is related to bars in galaxies.

In addition to actual observational results, numerical simulations also provide evidence for the influence of bars on host galaxy star formation. Renaud et al. [32] conducted a hydrodynamic simulation of a Milky Way-like galaxy, finding that material moves slower at the ends of the bar, causing orbital crowding that increases the probability of molecular cloud collisions and enhances star formation efficiency, similar to the mechanism in galaxy interactions. Carles et al. [33] compared the star formation history in barred versus unbarred spiral galaxies, finding that star formation is significantly enhanced by the presence of a bar. Barred galaxies of the same mass have stronger central star formation rates than unbarred galaxies, such that the most massive barred galaxies experience a starburst, with the star formation rate in the central 1 kpc region increasing by 30 times relative to unbarred galaxies of the same mass.

2.2 Suppression of Star Formation

In massive disk galaxies, the rapid and sustained decline in star formation rate is referred to as "star formation quenching," a process often thought to be related to the presence of bars. A series of studies have found that, on one hand, bars can cause quenching by rapidly consuming gas, leading to subsequent gas deficiency; on the other hand, large-scale shear induced by bars can transfer energy to turbulence, stabilizing the gas disk and making gas velocity dispersion too large for collapse into stars, thereby suppressing star formation and causing quenching [34]. Research has found that the lack of star formation in regions surrounding bars appears to be a fairly common property of strongly barred disk galaxies [35].

2.2.1 Strong Evidence Some studies on star formation quenching have yielded clear and robust conclusions. Kruk et al. [36] performed multi-band two-dimensional photometric decomposition of barred spiral galaxies. By comparing these galaxies with unbarred galaxies, they found that the disks of barred galaxies are significantly redder than those of unbarred galaxies, indicating that bars are associated with quenching of star formation in galactic disks. Additionally, they found that the bulges and bars in the central regions of barred spiral galaxies are redder than their disks, consistent with observations of inside-out cessation of star formation. Therefore, bars either influence star formation quenching or the processes that drive bar formation lead to quenching.

Cheung et al. [13] studied the relationship between bars and specific star formation rates in disk galaxies. They found that the likelihood of a galaxy hosting a bar is anti-correlated with specific star formation rate, regardless of stellar mass or bulge fraction. Vera et al. [25] found that strongly barred galaxies have lower star formation activity efficiency and older stellar populations compared to weakly barred and unbarred galaxies. As shown in Figures 2a and 2b, the sSFR is higher in unbarred galaxies whether varying with concentration (C, defined as R90/R50, indicating the concentration of galaxy brightness distribution) or stellar mass. James and Percival [37] studied the stellar populations in the central regions of four strongly barred galaxies, finding that all four showed strong star formation activity in their centers and outer rings, while star formation in the bar itself was strongly suppressed. In 2018, they [38] analyzed spectroscopic data for 21 barred spiral galaxies, focusing on "star formation desert" regions (where star formation activity is almost completely suppressed), confirming that galactic star formation rates are strongly suppressed in disk regions swept out by strong bars.

2.2.2 Indirect Evidence Other studies, while not providing strong direct evidence, have supported the conclusion that bars cause star formation quenching to some extent. Gavazzi et al. [39] found that the fraction of strongly barred galaxies increases sharply with galaxy mass, suggesting that strong bars may cause the decline in sSFR. They combined numerical simulation results to propose that strong bars significantly contribute to the star formation quenching observed in massive spiral galaxies, though other mechanisms may dominate in the outer regions of massive spirals. Masters et al. [40] found that the fraction of bars in red spiral galaxies is significantly higher than in blue spiral galaxies (70% versus 27%), suggesting that bar instability may be related to quenching of star formation in spiral galaxies.

George and Subramanian [41] divided galaxies with quenched star formation into centrally quenched and globally quenched galaxies, finding a possible correlation between bar length and star formation rate. Masters et al. [42] studied the relationship between atomic gas content in disk galaxies and the likelihood of hosting large-scale bars, finding that bars may reduce or prevent star formation in outer disk regions by preventing gas inflow outside the bar' s corotation radius, causing the overall color of outer disk regions to become redder. Emsellem et al. [35] conducted a Milky Way-like simulation showing that as stars move along orbits elongated by the bar, they induce shear motions in the interstellar medium, which in gas-rich regions suppresses star formation within the bar. Géron et al. [43] divided galaxies into quenching galaxies and star-forming galaxies, finding that quenching galaxies typically have a higher fraction of strong bars, while the fraction of weak bars is similar. Additionally, they found that strong bars drive the quenching process in star-forming galaxies, where local star formation rates are higher than in unbarred galaxies.

2.2.3 Simulation Studies Numerical simulations have also produced conclusions supporting the suppression of star formation by bars. Smethurst et al. [44] used a simple Bayesian method to model the star formation history of galaxies, performing Bayesian analysis on exponentially declining star formation quenching models. They found that the increasing fraction of bars is consistent with an increase in the average quenching timescale, perhaps indicating that bars bear some responsibility for quenching star formation in galaxy interiors. Khoperskov et al. [34] quantitatively simulated gas-rich disk galaxies, including star formation, stellar feedback, and the interstellar medium. They found that bars effectively quench star formation, reducing the star formation rate to one-tenth within less than 1 Gyr. In their simulations, bars increased the random motion of gas within the galaxy' s corotation radius, causing the star formation efficiency to decline rapidly. Moreover, in all models, bars quenched star formation in galaxies. Barred galaxies in the simulations had much lower star formation efficiency than unbarred galaxies, and bars formed more quickly, enabling faster quenching of star formation. Gavazzi et al. [39] proposed a numerical model simulating bar formation, finding that strong bars can rapidly quench star formation in the central few kpc of field galaxies. Spinoso et al. [45] simulated a Milky Way-like galaxy including radiative cooling, star formation, supernova feedback, and a central massive black hole. As the bar grew to its maximum length and strength, almost all infalling gas was consumed in star formation and, to a lesser extent, accreted onto the central black hole, leaving a gas-depleted region on small scales. This suggests that bar-driven star formation quenching may play an important role in all disk-dominated galaxies.

2.3 Sources of Disagreement

As mentioned earlier, the two different views on the influence of bars on star formation may arise partly from differences in sample data, research environments, and methodologies, with the former focusing on star formation activity in galactic central regions and the latter on overall galactic star formation. On the other hand, the complex evolution mechanisms and physical processes of bars and galaxies themselves are also primary reasons for these divergences, as different evolutionary stages and processes of galaxies and bar structures will inevitably exhibit different characteristics and effects.

Most evolution mechanisms regarding bars and disks are based on speculation from observational data or simulation studies. Jogee et al. [46] proposed that the large number of strong bars in the early universe implies that dynamically cold disks capable of forming large-scale bars had already formed by redshift 1, and that large-scale bars can exist for long periods, averaging over 2 Gyr. However, El-Zant and Shlosman [47] suggested that centrally concentrated dark matter halos can destabilize bars, making the evolution of bars in galaxies highly uncertain. The research results of Kim et al. [24] support this theory, showing that star formation activity in barred galaxies was enhanced in the past, but significant gas consumption has resulted in current star formation activity that is lower than or comparable to unbarred galaxies. In other words, the role of bars in galactic star formation likely differs at different stages of galaxy evolution. Bars most probably promote star formation in the early stages of galaxy evolution, leading to substantial gas consumption, which in turn suppresses star formation after gas depletion. As can be seen from the aforementioned studies, bars mostly promote star formation in galactic centers while suppressing it in disks. There are many such asynchronous evolutions and inconsistent effects between bars and disks, and these mechanisms collectively contribute to the divergence of research results.

3 The Distribution of Bars in Galaxies

Observations indicate that approximately two-thirds of nearby spiral galaxies are barred [40, 48–50], with about one-third hosting strong bars [46, 51, 52]. This demonstrates that bars are common in nearby galaxies. Is there a pattern to the distribution of bars in galaxies? Why do some galaxies have bars while others do not? How is the distribution of bars in the high-redshift universe? This section introduces the research progress on these questions.

3.1 Characteristics of Barred Spiral Galaxies

Bars and host galaxies interact with each other. Since galaxies can nurture bars, bars must also affect galaxies. In theoretical studies, the effect of bars on host galaxies primarily stems from the non-axisymmetric component introduced by bars into the gravitational potential, guiding large-scale gas flows and angular momentum transfer, thereby influencing the kinematic and chemical evolution of the host galaxy [49, 53, 54]. Galaxies with bars should differ from those without bars in terms of size, mass, age, metallicity, gas content, etc. [13, 22, 42, 55, 56], and bars in different barred spiral galaxies are not identical. As shown in Figure 3 [Figure 3: see original paper], bars exhibit clear and distinct distribution characteristics in galaxies at different redshifts and with different properties. The bar fraction increases with stellar mass across all redshift intervals and decreases with decreasing bulge dominance and galaxy brightness in most redshift intervals. At the highest redshift intervals, the fraction of bars is lower in later-type galaxies; however, at lower redshifts, the bar fraction does not change monotonically. Additionally, recent studies indicate that bars can play a crucial role in black hole feedback, particularly in galaxies with massive stellar disks [57], and that the formation of bar instability and bar evolution interact with dark matter halos and galactic stellar disks [58]. Many results show that bar properties are strongly correlated with the intrinsic properties of their host galaxies, independent of the external environment [59]. Therefore, the properties of galaxies hosting bars are key to studying the distribution of bars in galaxies. The following sections primarily elaborate on the correlations between bars and several important characteristics of galaxies.

3.1.1 Stellar Populations The most prominent characteristic of a galaxy is its stellar population, with properties including stellar color, age, and metallicity. Reviewing studies on the stellar populations of barred spiral galaxies reveals that most research supports the conclusion that bars exist in redder galaxies, though opposing conclusions occasionally appear. Observations indicate that bars are primarily composed of relatively old stellar populations [60, 61]. Fraser-McKelvie et al. [28] found that, at fixed stellar mass and galaxy morphology, barred galaxies are redder, older, and more metal-rich than unbarred galaxies, attributing this to barred galaxies having older and more metal-rich stellar populations. Vera et al. [25] classified and quantitatively studied barred spiral galaxies, finding that strongly barred galaxies have older and redder stellar populations compared to weakly barred and unbarred galaxies. Hoyle et al. [56] studied not only the distribution of bars but also the distribution of bar lengths, discovering a bimodal color distribution in bar length data—longer bars reside in redder disk galaxies, and the bars themselves are also redder, while the bluest galaxies host the smallest bars. They also found a clear correlation between bar and disk colors: on average, in galaxies with smaller bars, disks are redder than bars, while the opposite is true in galaxies with longer bars. Wang et al. [23] found that bar length depends primarily on galaxy color, consistent with many simulation results. Masters et al. [40] studied the bar fraction in low-redshift bright galaxies, classifying the sample by color, luminosity, and bulge fraction. They found that red disk galaxies have a higher fraction of bars (up to 50%). Aguerri et al. [59] reached seemingly opposite conclusions, finding significant correlations between the presence of bars and galaxy concentration and color, with bars mostly residing in less concentrated and bluer galaxies.

3.1.2 Metallicity Research results on metallicity in barred spiral galaxies are more consistent than those on stellar populations, almost uniformly supporting that barred galaxies have higher metallicity. The study by Vera et al. [25] also found higher metallicity in barred galaxies. Ellison et al. [22] compared the metallicity of large-scale strongly barred galaxies with unbarred galaxies, finding that at low masses and low redshifts, barred galaxies have higher central local metallicity than unbarred galaxies. Friedli and Benz [55] performed numerical simulations of star formation in barred spiral galaxies, finding that bar-induced gas flows enhance star formation in the bar and center, and this enhanced star formation activity increases the metallicity of gas in the central region.

3.1.3 Galaxy Morphology The morphology of barred spiral galaxies specifically refers to the distribution characteristics of bars in early-type and late-type galaxies. Overall, research results on the distribution characteristics of bars in different morphological galaxies are not uniform, with conflicting opinions on both bar fraction and the distribution of bar length and strength. Menéndez-Delmestre et al. [62] measured bar fractions in near-infrared images of nearby spiral galaxies and studied the relationship between bar fraction and bar length and strength, finding a weak correlation between bar strength and length. What is certain is that bars in early-type spiral galaxies are longer than those in late-type galaxies. Aguerri et al. [59] studied the relationships between galaxy morphology, size, central concentration, and color with bar fraction, bar length, and bar strength. They found that bars in late-type galaxies are relatively longer, while bars in lenticular galaxies are weaker. Whyte et al. [48] reached similar conclusions, while Martin [63] found that bars in early-type galaxies are stronger. Erwin [64] studied the sizes of bars in 65 nearby early-type galaxies and 70 nearby late-type galaxies published by Martin (1995), finding that bars in early-type galaxies are larger than those in late-type galaxies, and that this conclusion remains unchanged regardless of the method used to measure bar size. On average, bars in early-type galaxies are 2.5 times larger than those in late-type galaxies. Giordano et al. [65] studied in detail how the bar fraction in the Virgo cluster varies with luminosity, HI gas mass, galaxy morphology, and color. They found that the dependence of bar fraction on galaxy morphology is strongest, with a higher bar fraction in early-type disk galaxies. Their explanation is that the disks of early-type galaxies are more massive and therefore more susceptible to bar instability, and that environmental effects may destroy the spiral structure of late-type galaxies but leave the spiral structure of early-type galaxies intact. Lee et al. [52] found that in late-type galaxies, the number of strong bars is about 3.5 times that of weak bars.

3.1.4 Galaxy Luminosity and Mass Masters et al. [40] found that, at fixed color, the bar fraction decreases slightly with luminosity. In the sample of Cheung et al. [13], the bar fraction was approximately 1/4, with bar length measurements available for about half of the bars, and they found that bar length correlates with galactic stellar mass. Marinova et al. [51] studied a sample of 800 low-redshift bright galaxies in the Abell 901/2 supercluster, finding that the bar fraction increases with galaxy luminosity and stellar mass. However, Barazza et al. [66] studied large-scale bars in 3,692 low-redshift bright galaxies from SDSS, reaching the opposite conclusion that the bar fraction decreases with increasing galaxy luminosity and mass. Lee et al. [52] found that the fraction of strong bars in their sample increases with redder color and peaks at intermediate velocity dispersion, indicating that strong bars primarily exist in intermediate-mass systems, while weak bars tend to reside in less massive, less concentrated blue galaxies. Additionally, there have been studies on the star formation main sequence relationship in barred spiral galaxies. Willett et al. [67] found that, regardless of whether galaxies are barred or unbarred, the slope and scatter of the stellar mass-star formation rate relation remain constant, suggesting that the relationship between star formation rate and stellar mass appears unaffected by the presence of bars.

Mass in galaxies includes not only stars but also dark matter, leading to studies on the influence of dark matter halos on bars in galaxies. Skibba et al. studied 15,810 low-redshift galaxies from SDSS, finding that the likelihood of a disk galaxy hosting a bar or bulge increases when the galaxy has redder color and greater mass. They explained this by suggesting that more than half of bars can be explained by more massive dark matter halos hosting redder disk galaxies, making bars more likely to exist. They proposed that barred galaxies reside in slightly more massive halos than unbarred galaxies, with about 1/4 being grouped satellite galaxies [68].

3.1.5 Galactic Gas There have also been many studies on atomic gas in barred spiral galaxies. Masters et al. [42] studied the atomic gas content observed in 2,090 disk galaxies, finding that the bar fraction in gas-rich disk galaxies is significantly lower than in gas-poor disk galaxies, meaning bars are more common in gas-poor galaxies. They offered three possible explanations for this phenomenon: (1) bars in disk galaxies cause atomic gas to be consumed more quickly; (2) increased atomic gas content in disk galaxies suppresses bar formation; (3) both bar fraction and gas content are influenced by the same external environmental factors. Kim et al. [24] also found that strongly barred galaxies have less atomic and molecular gas than unbarred galaxies, while having higher gas metallicity.

3.1.6 Other Features In addition to the characteristics mentioned above, barred spiral galaxies have many other properties worth briefly listing. Generally, larger galaxies host larger bars, and bar length and strength are independent of local galaxy density [59]. Previous studies have also yielded secondary conclusions, such as bar length correlating with both the Sérsic index and central stellar surface density [13], galaxies with bulges possibly having longer bars than those without [56], and disk galaxies with larger bulges having a higher bar fraction [40]. Kruk et al. [36] performed multi-band 2D photometric decomposition of strongly barred galaxies, observing that disks are bluer than bars and bulges, and found that bars may lead to the formation of pseudobulges, subsequently affecting the evolution of their host galaxies. Martel et al. [69] conducted a series of chemodynamical simulations of disk galaxies, finding that the chemical evolution observed in the central regions of disk galaxies depends primarily on the dominance of the galactic bar, which evolves over time. López et al. [70], based on data from the TNG50 cosmological simulation, found that before bar formation, the ratio of stellar to dark matter mass in the inner regions of barred galaxies is higher, with higher initial gas content that promotes increased star formation rates and leads to faster central stellar mass growth over time compared to unbarred galaxies. They also found that barred galaxies have higher angular momentum transfer from disk to halo.

3.2 Evolution of Bars with Redshift

Observations to date have found bar fractions of 30%–70% in the nearby universe [40, 52, 71], with slightly lower values at higher redshifts [49, 72, 73]. This indicates that the proportion of bars in galaxies has changed across cosmic time, meaning bars exhibit clear evolution with redshift.

3.2.1 Recent Research Findings The earliest studies on the evolution of bars with redshift were based on numerical simulations of early-type and late-type galaxies. Combes and Elmegreen [74] used N-body numerical simulations to study bars and gas in early-type and late-type galaxies. The simulations showed that in low-mass late-type galaxies, bars stop growing early, while in massive early-type galaxies, bars continue to grow.

Before the advent of JWST, observational studies on the evolution of galactic bars with redshift were primarily based on analyses of HST data (as shown in Figure 4 [Figure 4: see original paper]). Sheth et al. [49] used HST data to analyze how the bar fraction in 2,157 bright spiral galaxies at redshifts 0.2–0.84 varies with redshift. They found that the bar fraction in their sample decreases rapidly with increasing redshift. In the local universe, about 65% of bright spiral galaxies host bars, while this proportion drops to about 20% at redshift 0.84, with the fraction of strong bars decreasing from about 30% to below 10%. In massive and red disk galaxies, the bar fraction remains essentially unchanged with redshift, while for low-mass blue galaxies, the bar fraction decreases significantly with redshift at z > 0.3. In other words, most of the observed evolution occurs in low-mass blue disk galaxies. Melvin et al. [75] measured the evolution of bar fraction with redshift in a sample of 2,380 disk galaxies classified by Galaxy Zoo in HST data. They found that the overall bar fraction decreased by half, from (22$±5)±$2)% at redshift 1. Their results also confirmed that the evolution of massive disk galaxies at redshift 1 began to be influenced by long-term internal evolution. Simmons et al. [73] used classifications of HST images from the Galaxy Zoo: CANDELS project to study the evolution of bar fraction across redshift range 0.5–2. They found that at redshifts less than 1, the bar fraction is consistent with previous studies, while at redshifts 1–2, the bar fraction remains stable at about 10% with no significant evolution, qualitatively consistent with predictions from cosmological simulations.

3.2.2 Latest Developments A turning point came with the advent of JWST, which enables us to see more distant objects in the universe and study properties at higher redshifts and earlier cosmic times. Recently, many scholars have discovered several high-redshift galactic bars at lookback times of 8–11 Gyr [76–79]. Costantin et al. [80] even discovered a Milky Way-like barred spiral galaxy at redshift 3, while Conte et al. [81] found bar fractions at z > 1 that are 3–4 times higher than earlier HST results. Since JWST has not been in operation for long, many studies are still ongoing, and definitive results are still limited, but more research on high-redshift galactic bars and the evolution of bars at even higher redshifts will undoubtedly emerge in the future.

4 Methods for Bar Identification

As previously mentioned, a fundamental prerequisite for studying galactic bars is their identification. Current mainstream identification methods include but are not limited to visual classification [83], machine learning [84], Fourier analysis [85], and isophotal fitting [86]. In past studies, the high bar fraction in early-type spiral galaxies has been obtained primarily through visual classification or Fourier analysis [13, 49, 59, 87], while contradictory results have been obtained mainly through isophotal fitting methods [59, 66]. Ghosh and Di Matteo [88] used several common research methods to measure the length and strength of simulated bars, finding significant differences in bar length and strength measured using different methods, with Fourier analysis yielding significantly smaller bar lengths than isophotal fitting. Therefore, adopting appropriate methods is crucial for research results in studies of galactic bars. Menéndez-Delmestre et al. studied bar length and strength from ultraviolet to infrared bands, finding significant differences in measured bar length and strength across different bands, with bars even being unobservable in some bands [89]. Consequently, selecting appropriate bands is also important when identifying bars, with the infrared band being the most important for bar research. This section will also briefly introduce the importance of infrared data [90].

4.1 Visual Classification

Visual classification, as the name suggests, involves observing the morphological features of galaxies with the human eye and classifying them—a method entirely dependent on subjective judgment. This is the simplest, most intuitive, and historically longest-standing method for galaxy morphological classification. In the early days of 20th-century astronomy, when observational techniques and computer technology were immature, astronomers naturally used telescopes or photographs from cameras to visually classify nearby visible galaxies and subsequently study the connections between galaxy morphological classification and other galactic features.

Currently well-known catalogs obtained through visual classification include RC3 [91] and Ann15 [92]. RC3 visually classified over 23,000 galaxies larger than 1 , with B-band magnitudes brighter than 15.5 mag and redshifts less than 0.05. Ann15 visually classified 5,836 galaxies with Petrosian radius magnitudes brighter than 17.77 mag and redshifts less than 0.01. The Ann15 classification system follows the RC3 classification method, dividing spiral galaxies into SA, SB, and SAB. RC3 classified 1,274 galaxies as 24% SA, 28% SAB, and 48% SB to identify whether they host bars. Ann15 discovered 361 strong bars and 365 weak bars among 1,163 disk galaxies.

With technological advancement and the development of the internet, large-sample visual classification has become possible. Although many automatic classification methods continue to emerge, given that most classification methods still have defects and visual classification retains irreplaceable advantages, citizen science projects such as Galaxy Zoo have emerged. Galaxy Zoo2 (GZ2), the second phase of the Galaxy Zoo project, is a citizen science project based on data from the Sloan Digital Sky Survey (SDSS), containing over 1,600 morphological classifications for 304,122 galaxies. In the current era of big data, the vast number of images obtained from astronomical observations makes detailed visual inspection of each galaxy impractical for individual astronomers or even small teams. GZ2 uses classifications from participants to identify large-scale galaxy morphologies, deriving the probability that a galaxy contains specific features based on participant identifications weighted by individual accuracy. GZ2 identifies galaxies as early-type, late-type, or merging, as well as finer morphological features including the shape and strength of bars, bulges, and disks. The vast majority of GZ2 classifications are consistent with those of professional astronomers, particularly for strong bars and the degree of spiral arm curvature [83].

Many of the aforementioned studies are based on Galaxy Zoo results, demonstrating its value and success. Galaxy Zoo employs a flowchart-like questionnaire for large numbers of participants to classify galaxy morphologies, compensating for its subjective influences and enhancing universality and accuracy. Galaxy Zoo classifications also include information on whether galaxies are barred or unbarred and the strength of bars, making it a reliable and significant research method for bar identification.

4.2 Isophotal Analysis

Isophotal analysis is often used to measure the surface brightness profiles of galaxies [46, 66, 93, 94]. Given that the isophotes of most galaxies, particularly early-type systems like elliptical and lenticular galaxies, are very close to elliptical in shape, we can fit a set of ellipses to the galaxy’ s isophotes using the iterative method of Jedrzejewski [95] to obtain the galaxy’ s surface brightness profile. Different types of galaxies and different galactic structures have completely different surface brightness profile curves. Sérsic proposed a multi-parameter exponential function form as early as 1963 to explain the surface brightness profiles of different galaxy types. Through generations of refinement, the parameter n can generally represent different galactic structures, with $n = 1$ representing the disk (also known as the exponential disk) and $n > 2$ generally indicating a bulge or elliptical galaxy.

Ellipses fitted to isophotes contain not only surface brightness but also useful information such as ellipticity, position angle, and ellipse center coordinates. Galaxies contain numerous structures of various sizes and shapes, so ellipses fitted at different positions in a galaxy can vary greatly, allowing us to distinguish different structures in galaxies based on changes in fitted ellipses. This method is highly suitable for identifying bar structures in galaxies.

The principle of ellipse isophote fitting is roughly as follows: first, set the initial parameters for the ellipse, which can also be free parameters; then sample the ellipse along the galaxy’s semi-major axis at a predetermined step size, increasing the radius of each ellipse; after reaching the outermost ellipse, reverse the fitting direction, moving toward the galaxy center with continuously decreasing ellipse radius.

The criteria for bar identification are often based on changes in ellipticity and position angle, as well as the magnitude of ellipticity. Research by Wozniak et al. [96] shows that bars are characterized by increased ellipticity and constant position angle. Jogee et al. [46] provided more precise criteria for bar identification: (1) the bar’ s ellipticity must be greater than or equal to 0.25, while the position angle variation along the bar must remain relatively constant within a \$±\$20° range; (2) in the transition region between the bar and disk, the ellipticity must decrease by at least 0.1, and the position angle variation must be at least 10°. This bar identification method is defined by four parameters: the bar ellipticity threshold, the position angle variation range across the bar region, and the thresholds for ellipticity and position angle changes during the transition between bar and disk. Bar ellipticity can distinguish bars from elliptical structures in galaxies, while relatively constant position angle can distinguish bars from spiral arms. Bar ellipticity can also serve as a criterion for bar strength, and the semi-major axis of the ellipse can reflect bar length to some extent, with other data capable of revealing deeper galaxy information after further processing. Figure 5 [Figure 5: see original paper] shows schematic diagrams of isophotal fitting for a barred spiral galaxy and an unbarred elliptical galaxy by Marinova and Jogee [97], clearly demonstrating the distinct features exhibited by barred and unbarred galaxies in isophotal fitting, enabling effective bar identification.

Isophotal analysis is significantly influenced by identification criteria and requires galaxy images with small inclination angles, preferably face-on, to obtain more accurate results. Therefore, when using isophotal analysis, datasets must be screened and research criteria must be applied cautiously. Currently, there are two main methods for implementing isophotal fitting: the ellipse package in IRAF and the photutils.isophote package in Python. Multiple geometric parameters can be set as needed, such as initial coordinates, initial ellipticity, initial position angle, and step size for fitted ellipses. After fitting, errors at each step are automatically provided, making the process convenient and efficient. Each method has its advantages and disadvantages, and different research requirements must be considered during use.

4.3 Fourier Analysis

Fourier analysis is an automatic method for classifying bars that directly uses Fourier coefficients to analyze images [98, 99]. The specific method involves using deprojected images and Fourier transforms to analyze angular luminosity profiles along concentric ellipses. Fourier analysis can directly and conveniently obtain bar strength and length. Using two-dimensional fast Fourier transforms to quantify the amplitudes of different-order Fourier moments yields bar strength, while bar length can be determined through changes in the second-order Fourier moment.

To identify bars, some studies [98, 99] use the ratio of bar strength to inter-bar strength as an indicator, where bar strength is defined as the sum of even Fourier components (I0 + I2 + I4 + I6), and inter-bar strength is I0 (cid:0) I2 + I4 (cid:0) I6. Other studies [59, 100] use the relative Fourier amplitude of the m-th component. Typically, even terms in bar regions, particularly the m = 2 term, are much larger than odd terms. However, other non-axisymmetric structures like spiral arms can produce the same effect. Therefore, some studies add an additional condition that the phase defined by the ratio of Fourier coefficients remains constant to distinguish bars from spiral arms. Fourier analysis is usually not used alone but combined with visual classification and isophotal analysis to complement or compare research results.

4.4 Machine Learning

Machine learning is a method that enables computers to automatically learn patterns and regularities in data for prediction and decision-making, allowing them to automatically correct errors and continuously improve accuracy. This highly efficient and convenient method is increasingly widely used across various industries, bringing great convenience to numerous research fields. Although machine learning has certain drawbacks, such as requiring large samples for training and having unclear internal mechanisms, its advantages are irreplaceable by other methods, and its application in various research fields is an inevitable trend. This is particularly essential in astronomy, an industry heavily reliant on big data analysis. Using machine learning for automatic classification of galaxy morphology and, relatedly, for bar identification, is the most efficient method, and its accuracy continuously improves with increasing observational data.

Cheng et al. [84] compared several supervised machine learning methods for automatic classification of galaxy morphology and studied their effectiveness. Using data from the Dark Energy Survey (DES) combined with Galaxy Zoo classification results, they compared 10 common supervised galaxy classification machine learning methods, including Convolutional Neural Networks (CNN), K-Nearest Neighbors, Logistic Regression, Support Vector Machines, Random Forests, and Neural Networks, identifying the optimal machine learning method. The results showed that CNN is the most successful method, achieving 0.99 accuracy in morphological classification of elliptical and spiral galaxies. They further discovered that low-probability spiral or elliptical galaxies are S0 galaxies, demonstrating that supervised learning can identify such galaxies as distinct from both elliptical and spiral galaxies. They also confirmed that more than 2.5% of galaxies were misclassified by GZ1, and after correcting the morphology of these galaxies, CNN accuracy improved to an average of 0.99.

In bar research, infrared band data occupies a very important position. Although a large portion of infrared observations must be conducted in space beyond the atmosphere, greatly increasing detection difficulty, infrared data remains irreplaceable. For example, infrared bands can penetrate cosmic dust to observe dust-obscured objects such as nebulae, planets, and star-forming regions; infrared bands also contain many important molecular spectral lines, enabling astronomers to study molecular compositions in celestial bodies; thermal radiation from celestial bodies is also largely concentrated in infrared bands. Additionally, since bars exhibit different properties in different bands, bars in infrared bands naturally have their own characteristics. As shown in the study in Figure 6 [Figure 6: see original paper], bars exhibit the smallest ellipticity and semi-major axis at 3.6 (cid:22)m, i.e., in the infrared band, primarily due to differences in the effects of stellar population composition and extinction compared to other bands. It is conceivable that infrared bands must reveal important information unattainable in other bands, making classification of galactic bars in infrared bands of significant research value. For example, Buta et al. [90] used data from the S4G survey, the Spitzer Survey of Stellar Structure in

Galaxies, currently the largest database of deep mid-infrared galaxy images, to perform morphological classification of galaxies. The S4G survey includes 2,352 nearby galaxies. They used the Comprehensive de Vaucouleurs Revised Hubble-Sandage (CVRHS) system for morphological classification to classify over 2,300 nearby galaxies in mid-infrared. The CVRHS system follows the classic de Vaucouleurs morphological classification, adjusted to identify additional features such as lenses, rings, bars, disks, spheroidal galaxies, boxy/peanut-shaped structures, etc. They found that bars in mid-infrared S0/a–Sc galaxies typically have different characteristics from those in Scd–Sm galaxies. Earlier-type galaxies display bars with features such as 3D boxy/peanut/X-shaped patterns, ring ridges, or "bar lenses," while bars in late-type spiral galaxies tend to be thin linear shapes along star-forming regions. This dichotomy in bar characteristics has long been recognized, and this distinction is important for estimating cosmological bar fractions.

5 Summary and Outlook

Galactic bars are a ubiquitous morphological structure in the nearby universe, composed of stars, gas, and dust, driving the dynamical and chemical evolution of their host galaxies. However, the question of how bars evolve remains unresolved, and how bars influence galaxy evolution is still undetermined. Recent research on bars has focused on these two questions. Bars affect various characteristics of their host galaxies, such as star formation, size, mass, morphology, color, and age, while host galaxies in turn constrain bar growth. Moreover, bars do not appear to be a permanent structure, exhibiting strong evolution across different cosmic epochs. In addition to research on the physical properties of bars, research methods continue to develop. Bar identification methods have undergone many years of development and 更迭, with several mainstream methods now available for practical application based on research needs and conditions such as wavelength band, efficiency, and accuracy. Most bar evolution research consists of theoretical speculation and simulation calculations, while research on the influence of bars on galaxies involves more actual observations and theoretical verification.

With advances in observational techniques and the birth of more advanced telescopes, observational data on bars have increased exponentially. More and more survey projects, such as SDSS, DESI, and HST, have also provided a solid foundation for statistical studies related to bars. However, limited by observational precision, the vast majority of observational studies can only focus on low redshifts. With recent JWST observations, bars at higher redshifts have been discovered successively, enabling scholars to resolve galaxy properties at higher redshifts. In the coming years, next-generation space and ground-based observational facilities (such as CSST, EUCLID, LSST, WFIRST, etc.) will be built successively and conduct large-scale imaging surveys, bringing new opportunities for the search and study of galactic bars. The properties of bars and galaxies at high redshifts will undoubtedly occupy an important position in future research and will certainly achieve breakthrough results.

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

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