The user wants me to translate a Chinese academic paper title and subtitle to English. Let me analyze the content: "Cross-method Analysis of Corotation Radii Data Set for Spiral Galaxies 后印本" This appears to be a title. Let me break it down: - Cross-method Analysis => Cross-method Analysis (or Ana…

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Date: 2024-08-14T00:00:00+00:00

Abstract

The user wants me to translate a scientific text from English to Simplified Chinese. Wait, no - looking at the instructions again, it says "Translate from Simplified Chinese to English". But the input text is already in English. Let me re-read the instructions carefully.

The instructions say: "Translate from Simplified Chinese to English with the highest accuracy and academic tone."

But the input text is: "A corotation radius is a key characteristic of disk galaxies that is essential to determine the angular speed of the spiral structure Ωp, and therefore understand its nature. In the literature, there are plenty of methods to estimate this value, but do these measurements have any consistency? In this work, we collected a data set of corotation radius measurements for 547 galaxies, 300 of which had at least two values. An initial analysis reveals that most objects have rather inconsistent corotation radius positions. Moreover, a significant fraction of galactic disks is distinguished by a large error coverage and almost uniform distribution of measurements. These findings do not have any relation to spiral type, Hubble classification, or presence of a bar. Among other reasons, obtained results could be explained by the transient nature of spirals in a considerable part of galaxies. We have made our collected data sample publicly available, and have demonstrated on one example how it could be useful for future research by investigating a winding time value for a sample of galaxies with possible multiple spiral arm patterns."

This is English text. The instructions say to translate from Simplified Chinese to English. This is contradictory.

Let me check the P.S.: "- [IMPORTANT] If the input is English, translate it into Chinese. The translation language direction is **bidirectional**."

Ah! So the translation is bidirectional. If the input is English, I should translate it to Chinese. The main instruction "Translate from Simplified Chinese to English" is the general rule, but the P.S. clarifies that it' s bidirectional and I should translate English input to Chinese.

So I need to translate this English text into Simplified Chinese, following all the critical requirements: 1. Preserve ALL LaTeX commands and placeholders - there are none in this input, but there's Ωp which is a Greek letter. I should keep it as is. 2. Preserve ALL citation commands - none present. 3. **PRESERVE ALL ···paragraph wrapper tags EXACTLY** - there are none in the input. Wait, the input doesn' t have these tags. The instructions say "if input has N paragraph tags, output must have exactly N paragraph tags" . Since there are none, I should not add any. But the example in the instructions shows these tags. Let me re-read.

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Full Text

Preamble

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Cross-method Analysis of Corotation Radii Data Set for Spiral Galaxies

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Abstract

The corotation radius is a key characteristic of disk galaxies that is essential for determining the angular speed of the spiral structure (Ω_p) and thus understanding its nature. The literature contains numerous methods for estimating this value, but do these measurements exhibit any consistency? In this work, we compiled a data set of corotation radius measurements for 547 galaxies, 300 of which have at least two independent values. Our initial analysis reveals that most objects show rather inconsistent corotation radius positions. Moreover, a significant fraction of galactic disks is distinguished by large error coverage and an almost uniform distribution of measurements. These findings show no relation to spiral type, Hubble classification, or the presence of a bar. Among other explanations, our results could be explained by the transient nature of spirals in a considerable portion of galaxies. We have made our collected sample publicly available and demonstrate through one example how it could be useful for future research by investigating the winding time value for a sample of galaxies with possible multiple spiral arm patterns.

Key words: galaxies: fundamental parameters -galaxies: kinematics and dynamics -galaxies: structure

1. Introduction

The nature and evolution of spiral structure in disk galaxies remains poorly understood despite decades of investigation. Two opposing viewpoints exist: long-lived stationary spirals versus dynamic (transient or recurrent) spirals. The first perspective, based on the quasi-stationary density wave theory (Lin & Shu 1964), maintains that spiral arms are waves of increased density that propagate through regions where stars and gas gather in the galaxy' s disk. Kalnajs (1973) provided a visual representation of this theory, showing that when stellar orbits are rearranged in a certain coordinate system, their apocenters trace out spiral arms (see Figure 3 [Figure 3: see original paper] in Kalnajs 1973). Thus, due to slower stellar motion near apocenters, matter accumulates in these regions. The angular speed of the spiral structure, Ω_p (the precession frequency of stellar orbits), is assumed to be constant with galactocentric radius. The position where the angular speeds of the disk and pattern become equal is called the corotation radius (R_c) or corotation resonance.

In contrast, the transient spiral theory assumes that spiral structure has a dynamic nature, and its angular speed changes in the same way as the angular velocity of disk rotation (Sellwood 2010; Baba et al. 2013). Note that in this case, spirals can appear long-lived, although they are actually composed of many segments that are frequently torn apart and reconnected to other spiral arm segments (Fujii et al. 2011). Despite the persuasiveness of these theories, each has distinct advantages and disadvantages.

The long-lived existence of spiral structure is possible only when effects amplifying the wave moving in the radial direction at resonances are taken into account (swing amplification, see Toomre 1981). Additionally, the classical density wave theory based on the tight-winding approximation (short wavelength or WKB approximation) does not explain the existence of spiral structures with large pitch angles and a high number of arms (Lin & Shu 1967). To address these problems, the initial representation of the density wave spiral was transformed into the theory of global modes (see Bertin 1983; Bertin & Lin 1996). As for the dynamic spiral pattern, it is much easier to form in numerical simulations. This structure is considered to be generated by gravitational instability caused by the swing amplification mechanism (Sellwood & Carlberg 1984). Compared to stationary spiral density waves, whose formation and maintenance occur only under special conditions (D' Onghia et al. 2013), recurrent spirals are generated across all configurations of disk parameters, even in the presence of weak instability. However, the mechanisms promoting continuous regeneration of spiral structures remain unclear (see reviews by Dobbs & Baba 2014; Sellwood & Masters 2022).

It is also worth mentioning another theory based on interactions with satellites. Tidal forces from a companion not only form various structures in a disk (bridges and tails, Toomre & Toomre 1972) but also influence the formation of spiral structure (Donner & Thomasson 1994). However, it is not yet entirely clear what types of spirals are generated, or whether they are stationary or dynamic. Furthermore, some studies investigate the influence of bars, which are often connected to the tips of spiral arms. For example, Athanassoula et al. (2010) found that a bar impacts the pitch angle of spirals. However, Rautiainen & Salo (1999) showed that the bar and spirals can be independent features rotating with different angular velocities. Additionally, some researchers maintain that spirals can form due to nonlinear coupling between bars and spiral density waves (Minchev et al. 2012).

We must also note that galaxies can have multiple spiral modes rotating at different angular velocities (Meidt et al. 2008; Efthymiopoulos et al. 2020). These modes are connected through resonances. The multiplicity of Ω_p values means that there are several corotation radius positions, which has been confirmed observationally (Buta & Zhang 2009; Font et al. 2014a). Additionally, several models exist in which each spiral mode has a unique angular velocity (see Figure 8 [Figure 8: see original paper] in Forgan et al. 2018).

In practice, it is quite difficult to determine which theory better describes the observed spirals in a galaxy, and it may require a combination of such models. From an observational perspective, distinguishing between long-lived and transient spiral arms is not easy, but increasingly more observational tests can support each theory.

Most of these tests are based on analysis of the spiral pattern angular velocity, the constant profile of which indicates the existence of a quasi-stationary density wave, while variation with distance suggests a recurrent origin. In addition to this, there are other indirect signs related to angular frequency, such as the age gradient of stars across the arm (Puerari & Dottori 1997; Tamburro et al. 2008; Egusa et al. 2009), morphological features near resonances (Elmegreen et al. 1992), and others. Most often, to find the pattern angular speed Ω_p, researchers use the velocity curve and corotation radius location. Numerous methods have been applied for R_c value determination (and the number continues to grow to this day, for example, Pfenniger et al. 2023; Marchuk et al. 2024).

In summary, one of the essential problems in galactic dynamics relates to the nature of spiral structure, and estimation of corotation radii plays a crucial role in solving this issue. Various methods have been developed to measure its position, but all rely on different arguments and assumptions. However, the use of different methods can lead to contradictory results. For example, Scarano & Lépine (2013) showed that part of their sample had consistent R_c values defined by several methods, while others demonstrated disagreement in corotation resonance estimates. What could cause such discrepancy? First, some objects may have multiple spiral modes, leading to several R_c values. Additionally, the obtained results may testify in favor of dynamic spiral theory, according to which there is no localized corotation resonance position within the galactic disk. Furthermore, we cannot exclude the possibility of unreliable methods and measurements.

Hence, the primary goal of this paper is to explore possible explanations for the discrepancy in R_c measurements. It is necessary to emphasize that estimation of the corotation radius position is also crucial for solving other astrophysical problems. For instance, using an inaccurate corotation radius value and corresponding pattern angular speed can lead to unreliable results. Williams et al. (2022) investigated star formation processes in the spurs of NGC 628 and found that stars form in situ within the spurs and do not drift out of the spiral arms. To reach this conclusion, the researchers used the angular speed value obtained by applying the Tremaine–Weinberg (T-W) method (see Figure 15 [Figure 15: see original paper] in Williams et al. 2021). However, in this figure, a linear regression is embedded within a dispersed point cloud, and other Ω_p measurements available in the literature and our sample are not fully consistent with each other. This raises questions about the accuracy of angular velocity determination and its consequent implications. Williams et al. (2023) demonstrated the influence of corotation resonance on chemical evolution in a recent paper. Moreover, the swing amplification mechanism is believed to occur near the R_c position, allowing spirals to change their direction of rotation and amplify there (Goldreich & Tremaine 1978; Toomre 1981). The corotation resonance position also has a direct connection to angular momentum transfer in the galactic disk, which is essential for understanding its evolution (Sellwood & Binney 2002). In summary, the corotation radius is a 1:1 resonance playing a key role in many dynamic processes, and its examination can shed light on the nature of spiral structure.

To investigate the posed question, we collected a data set of corotation radius measurements, described in Section 2. In Section 3, we perform statistical analysis on the collected sample and construct distributions of corotation radii for certain objects. In Section 4, we obtain total coverage of corotation radii errors and a measure of Consistency for each galaxy, and examine possible reasons for large values. Section 5 considers galaxies that may have multiple spiral modes and compares winding and rotation times for these objects. In Section 6, we summarize the main results and discuss potential applications of the collected data for future research.

2. Corotation Radii Data

Our main goal was to collect a sample of corotation radius values obtained using conceptually different methods and determine whether they were consistent for each object. If not, we needed to analyze potential reasons for this discrepancy. As a result, we collected corotation radius positions from 47 research papers in which these values had been directly measured. It is important to note that we generally ignored papers containing R_c values for only a single object or a few objects (Sempere & Rozas 1997; Seigar et al. 2018); instead, we focused on papers with relatively large numbers of galaxies and measurements (for example, Elmegreen & Elmegreen 1995; Buta & Zhang 2009; Sierra et al. 2015; Cuomo et al. 2020; Williams et al. 2021).

Our data set consists of 1711 corotation resonances for 547 galaxies, estimated using 12 methods. An example of the collected sample is presented in Table 1 . This table contains the object name, corotation radius with errors, method used, band, optical radius, reference for the paper from which the measurement was taken, and a link to the original source. If necessary, we converted the R_c value to arcseconds using the galaxy' s distance specified in the relevant article. Note that methods applied for corotation radii estimation were divided into conditional groups, with names contained in the table. P-D and offset methods are based on the assumption that the angular offset between young and old stellar populations changes sign at the corotation radius (Puerari & Dottori 1997; Tamburro et al. 2008). The width method analyzes the azimuthal distribution of matter along spiral arms (Marchuk et al. 2024). T-W enables us to obtain the pattern speed directly (Tremaine & Weinberg 1984), while in the model method this value varies until the simulated galaxy matches observable features. Potential-density and metallicity methods use radial profiles of phase shift (Buta & Zhang 2009) and metallicity (Scarano & Lépine 2013). R_c locations in our sample were also estimated by analyzing residual velocities (F-B: Font et al. 2011, 2014a) and morphological features (morph: Elmegreen et al. 1992; Elmegreen & Elmegreen 1995) of galaxies. More detailed descriptions of the listed methods are presented in the Appendix. Column (5) shows what kind of data was applied to measure the corresponding R_c value. Additionally, the advanced version of our data set includes information about whether stellar or gaseous components were used to determine each measurement, though it is worth noting the subjective nature of this column. These data were collected to investigate correlations and systematic errors in cases of inconsistent measurements. The data set also includes potential corotation radii for bar structures.

One direction of this research may involve investigating the relationship between bar and spiral rotation speeds. This was not our primary goal, so the data set contains only a small portion of available data about bar R_c values, though it will be updated in the future. In this work, we aim to explore only corotation resonances related to spiral structure, and therefore we did not concentrate on methods related to bar features (in our notation "bar-torque": Verley et al. 2007; "rings" : Pérez et al. 2012; "gaps" : Buta 2017). As mentioned previously, the number of these measurements is relatively small, and their presence did not significantly influence our results.

A complete data set is publicly available on GitHub. As noted before, the collected sample does not include absolutely all R_c measurements available in the literature. We plan to update it over time and would greatly appreciate assistance from researchers. These data will be valuable for developing and applying different methods of corotation radius estimation to compare determined values with those from literature. Moreover, the gathered data set enables us to determine a reliable R_c value for certain objects. This quantity is not only substantial for estimating pattern angular speed, but its position also plays a significant role in chemical and dynamical evolution in galaxies. In this paper, we focus only on analysis of the gathered data set. Specifically, we review the measurement data for consistency and consider several factors that could affect the results obtained in subsequent sections. The code used for analysis is also available on GitHub.

3. Corotation Radii Data Analysis

To understand whether there is any consistency in determination of corotation resonance position, it is necessary to have more than one R_c value for each object. It is important to note that 386 galaxies in our sample have measurements determined using only one method. For 247 of these galaxies, only a single R_c value was found. Reliable determination of the corotation position requires at least two methods applied to the same object. This requirement is met by the remaining 161 galaxies in our sample.

Figure 1 [Figure 1: see original paper] shows how many measurements determined by a particular method are presented in the collected sample. For example, a cell marked by a gray square means there is only one galaxy (M100) in the sample for which seven different corotation radius values were estimated by T-W from several research papers (Rand & Wallin 2004; Hernandez et al. 2005; Williams et al. 2021). According to this figure, the F-B and potential-density methods most frequently yield more than one corotation resonance value for a galaxy. The presence of several R_c measurements found by these methods may be associated with the existence of multiple spiral modes in the galaxy (Buta & Zhang 2009). Note that the F-B method can also measure positions of resonances that may not be related to corotation (see Table 7 in Font et al. 2014a), which are also included in our data set. Therefore, to distinguish the most plausible corotation locations from other measurements, it is necessary to compare locations from this method to those obtained by other approaches.

Before understanding whether there is agreement between R_c measurements determined by different methods, we must examine their positions in each galaxy as measured by the same method. To do this, we calculate the total coverage of corotation radii error (Σ_{err}) for each method. If R_c values intersect within their error limits, then Σ_{err} consists of the union of their errors. If they do not intersect, then the error coverage adds up. The magnitude of Σ_{err} directly relates to the range of angular pattern speed Ω_p estimation. To compare total error coverage magnitude between galaxies of different sizes, we normalize this value by the optical radius r_{25}. As a result, violin diagrams were constructed. Figure 2 [Figure 2: see original paper] shows the distribution of $\Sigma_{\mathrm{err}}/r_{25}$ for each method (except potential-density, which in the original paper did not estimate R_c uncertainties). In Figure 2, it can be seen that the median value of total error coverage does not exceed a quarter of the optical radius of the galaxy.

However, there are numerous galaxies for which the error of corotation radius values determined using T-W and age gradient methods exceeds 75% of the entire disk, and sometimes surpasses the optical radius value. As for the Font-Beckman method, a large Σ_{err} value is associated with its ability to estimate not only corotation resonances, which can be distributed evenly across the disk. The error in measuring R_c by the metallicity gradient method may be associated with data sparsity, making it impossible to accurately estimate its position. Figure 1 demonstrates a relatively small number of galaxies in which the T-W method has measured more than one corotation radius. Consequently, the magnitude of Σ_{err} for this method is explained more by large error bars of individual R_c values than by their inconsistency.

To investigate whether corotation resonance positions in the same galactic disk are consistent, we examined distributions of their values for those objects whose measurements were estimated by different methods (see Figure 3 [Figure 3: see original paper]). We visually inspected each distribution and found that only 15% of the 161 galaxies had at least two measurements consistent within error limits. For example, the corotation radii distribution for NGC 4123 (see Figure 3, top panel) shows four measurements localized near $60''$. Note that the total error coverage for this galaxy is approximately a quarter of its optical radius (indicated by the brown horizontal line on top of the plot). Additionally, a significant portion of the collected sample (10%) exhibits several peaks in the distribution with consistent corotation radius positions. Therefore, for galaxy NGC 864, placed in the middle panel of Figure 3, several assumed positions for R_c can be detected, such as $30''$, $55''$, and $80''$. For this particular distribution, the total error coverage occupies more than half of the optical radius. The presence of several corotation resonance positions can be attributed to the fact that galaxies may possess multiple spiral modes rotating at different angular speeds (Rautiainen & Salo 1999; Quillen et al. 2011). Note that figures for R_c distributions with any consistent measurements are available as supplementary files.

For the remaining portion of our data set, we observe inconsistent corotation radius measurements obtained by different methods. An illustrative example of such disagreement is the distribution of R_c for the well-known grand-design galaxy M100. The bottom panel of Figure 3 shows almost uniformly distributed R_c values. The same result can be obtained by considering the spirals' angular pattern speed, which changes like the angular velocity of the disk. This phenomenon is known as "dynamic spirals" and has been modeled in Carlberg & Freedman (1985), Sellwood (2010), Fujii et al. (2011), and others. In particular, Figure 4 [Figure 4: see original paper] (right panel) from Roca-Fàbrega et al. (2013) illustrates that the angular pattern speed is not a fixed value. Then, following the corotation radius definition, its location can be found at almost every galactocentric radius in the disk, as the bottom panel of Figure 3 demonstrates. It is important to note that objects with consistent R_c measurements have, on average, relatively small total error coverage. However, there are some objects for which the distribution of corotation radii shows no agreement among measurements despite having relatively small Σ_{err} values. Galaxies with high error coverage fractions certainly have inconsistent corotation radius positions. Thus, the magnitude of total error coverage does not always indicate whether R_c values for the same object are consistent. Therefore, we need to examine another quantity that measures the degree of consistency in measurements, which we will address in the next section.

4. Analysis of Measurement Consistency

Analysis of corotation radii distributions shows that only about 25% of considered galaxies have consistent measurements. The other objects reveal values that completely disagree, either with rather large or small coverage error. To differentiate between these distributions, we considered another measure of discrepancy in corotation radii locations, which we have named Consistency. This is calculated as the ratio of the average difference between measurements to the average variance:

$$\text{Consistency} = \frac{\langle |r_i - r_j| \rangle}{\langle \sigma_i \rangle}$$

where r_i, r_j are corotation radius values and σ_i is the magnitude of error. The larger this value is, the greater the discrepancy of corotation radius positions in the galactic disk. This parameter was derived from the so-called dimensionless separation of means, as described in Ashman et al. (1994). It has been used for astronomical data before (Muratov & Gnedin 2010; Gusev & Shimanovskaya 2020), but we have modified the original formula to extend its application to more than two measurements. Note that this parameter measures consistency qualitatively, not quantitatively. In other words, it does not have a specific value that separates consistent corotation positions from inconsistent ones.

Figure 4 [Figure 4: see original paper] demonstrates distributions of the total coverage error quantity and the Consistency measure for each object in our data set. This figure visually separates the sample into different groups. Galaxies with a localized corotation radius are located in the bottom left position on this plot. Distributions with intermediate $\Sigma_{\rm err}/r_{25}$ values are expected to have multiple R_c values (see the distribution for NGC 1042 in the right panel). Other points indicate objects for which estimated corotation radius values from different methods do not agree well. The top and bottom distributions in the right panel of Figure 4 provide illustrative examples of how measurements can be inconsistent with large and small coverage errors, respectively.

Figure 5 [Figure 5: see original paper] shows the relationship between $\Sigma_{\rm err}/r_{25}$ and the distance from the galactic center where the maximum corotation radius was measured. This means that the farther from the galactic center the R_c was measured, the greater the fraction of the galaxy' s disk occupied by assumed corotation radii. It is important to point out that, according to this figure, the corotation resonance may have a position beyond the optical radius, which was defined as the maximum value. This is possible because R_c maximum value may fall within error limits. Besides, galaxies with barely visible spiral arms extending beyond r_{25} are not rare (see Mosenkov et al. 2024). The observed dependence in Figure 5 has several interpretations. First, this trend does not contradict the suggestion of the existence of one or more corotation resonances for each galaxy. In this case, the coverage error is determined by the number of measurements and their typical error magnitudes. Hence, the farther from the center, the more resonances a certain galaxy can have, and the greater the magnitude of error coverage that can be calculated. Second, some objects may not have localized corotation positions. This is possible for galaxies with dynamic spirals, where the corotation radius can literally be at any point in the disk. In this case, $\Sigma_{\rm err}$ would increase due to the expanded area of the disk covered by measurements. The last option is to assume that most methods used or error estimates are incorrect. This interpretation is the least likely, since in this case Figure 5 would show a chaotic distribution of points with no clear dependence. However, before drawing any considerable conclusions, we must investigate other factors that might be responsible for this discrepancy.

First, the Consistency measure and magnitude of total error coverage can increase with the number of measurements found for each galaxy. Figure 6 [Figure 6: see original paper] does not explicitly show such dependence. However, according to the left panel, error coverage magnitude increases, but not steadily, and objects with over seven corotation radius measurements have a significant fraction of the visible galactic disk covered by $\Sigma_{\rm err}$. Conversely, the right panel reveals that the majority of objects with inconsistent measurements possess fewer corotation radius values. Additionally, the Consistency measure is, on average, slightly lower for numerous measurements.

Second, measurements with large errors can significantly contribute to $\Sigma_{\rm err}$ magnitude. Analysis shows that in most cases, corotation resonance locations are estimated with errors not exceeding a quarter of the optical radius of the galaxy, and only a few measurements have extremely large errors (more than $0.5r_{25}$). The remaining corotation radius values with errors less than $0.25r_{25}$, as expected, lead to a noticeable decrease in $\Sigma_{\rm err}$ magnitude (Figure 7 [Figure 7: see original paper], left panel). However, even after excluding values with large errors, a significant fraction of galaxies still exhibit considerable total error coverage. Furthermore, exclusion of values with large errors cannot improve the Consistency measure because individual measurements can be completely inconsistent despite their small errors.

Other possible reasons for R_c value discrepancy may relate to assumptions and accuracy of certain methods, reliability of determined values, and error estimation. Methods that primarily measure several corotation radii locations for one galaxy apparently influence the revealed tendency. To investigate this aspect, we removed measurements estimated by such methods one at a time. Exclusion of measurements obtained by the F-B method (middle panel in Figure 7) demonstrates a relatively small number of objects with intermediate $\Sigma_{\rm err}$ fraction and Consistency values. As discussed earlier, this method can determine not only corotation resonance positions. Consequently, these measurements mostly do not intersect, and the median value of their coverage error is about $0.2r_{25}$ (see Figure 2). Therefore, Consistency and $\Sigma_{\rm err}$ fraction do not necessarily have small or large magnitudes in those galaxies where the F-B method was applied. The next method whose accuracy we examined is the potential-density method. Its multiple measurements for a single galaxy indicate the presence of several spiral modes. Additionally, those values have almost zero errors. This explains the disappearance of points with large Consistency values (Figure 7, right panel). It is important to note that these extremely large Consistency values were caused by near-zero measurement errors rather than by their distance from each other. Despite exclusion of potential-density method measurements, the Consistency measure still has significant magnitudes. In addition, noticeable effects on R_c distributions could be caused by methods whose measurements have large errors, such as T-W or offset (see Figure 2). However, exclusion of these methods' measurements showed minimal differences compared to Figure 4. Thus, this analysis indicates that inconsistency of corotation radius values is more related to the fact that for some objects, these R_c measurements can be distributed evenly throughout the disk (the case of transient spirals) rather than due to reliability issues with any specific method.

Additionally, we investigated whether there is any selection effect due to galaxy distance. Figure 8 [Figure 8: see original paper] (top left) affirms that total error coverage is not dependent on this parameter. Furthermore, galaxies with distinct spiral structure (basically grand design or multi-armed) are believed to match spiral density wave theory more closely than flocculent ones (Lin & Shu 1967; Thomasson et al. 1990; Dobbs & Bonnell 2007). However, as we can see from the top right panel, galaxies belonging to all these spiral types can exhibit both small and large $\Sigma_{\rm err}$ fractions. Furthermore, we found no division in Consistency magnitude between grand design, multi-armed, and flocculent galaxies. This implies that galaxies with prominent spirals can have inconsistent measurements that may indicate their multiple pattern or dynamic spiral nature. Classical density wave theory only considered tightly wound spiral arms, so $\Sigma_{\rm err}$ magnitude could be related to pitch angle value. To investigate this, we consider the distribution of Hubble type galaxies. However, when posing the question this way, the presence of a bar in a galaxy may not be taken into account. Therefore, in the legend of Figure 8 (bottom right), types SBa and Sa are considered equivalent. Nevertheless, there is no sharp division in total error coverage magnitude between galaxies with open spirals and tight-wound ones. The bottom left panel of Figure 8 does not demonstrate any dependence on whether a galaxy has a bar. Note that the density distributions (blue) above the figure have a double peak, with the left one related to objects that measured the corotation radius of their bar. To determine whether a bar is present in a galaxy, we use morphological type and bar presence data from HyperLEDA (Makarov et al. 2014). Additionally, when possible, we exclude weakly barred galaxies from the barred galaxy sample.

While the scenario of transient spiral arms may be more suitable for explaining our results, all cases considered above are theoretically possible. Moreover, it is likely that some of them actually occur in practice. The graph on the right of Figure 4 contains a variety of objects with different spiral structure natures. Unfortunately, it is not yet clear which mechanism predominates in most spiral galaxies. Therefore, we need to examine each individual galaxy based on the collected data set.

5. Winding Time of Spiral Arms in Galaxies

The collected data will indeed be useful for clarifying various aspects of spiral nature. In this section, we demonstrate an example of how these data can be used to answer a specific question related to spiral lifetime. As discussed earlier, spiral structure in disk galaxies may consist of several spiral modes (Roškar et al. 2012). Each spiral substructure rotates with its own pattern speed and therefore has different corotation resonances. According to Quillen et al. (2011) and Minchev et al (2012), these substructures may interact in a special way: the R_c of the slower rotating pattern coincides with another resonance of the faster rotating ones. Spiral density waves moving at different angular velocities often intersect at the outer Lindblad resonance (OLR) or ultraharmonic resonances of the spiral pattern (Rautiainen & Salo 1999). Their positions are defined as distances where the pattern speed equals $\Omega + \kappa/2$ and $\Omega + \kappa/4$, where κ is the epicyclic frequency and Ω is the angular velocity of disk rotation. Will such a spiral structure wind up and destroy its arrangement in as short a period as material spirals do (Oort 1962)? To investigate this issue, we can directly calculate the winding time value of the whole spiral pattern using the pattern speed of each spiral mode (Meidt et al. 2008):

$$\tau_{\rm wind} = \frac{2\pi}{\Omega_{\rm outer} - \Omega_{\rm inner}}$$

where Ω_{inner} and Ω_{outer} are the angular velocities of the inner and outer spiral substructures, respectively. Technically, this quantity means the time after which the inner substructure will overtake the outer ones by a whole revolution around the galactic center.

To investigate this aspect, we focus on five objects from our data set that could have multiple spiral modes: IC 342, M58, M74, NGC 3583, and NGC 5371. The R_c distributions of these galaxies have consistent measurements and demonstrate the evident existence of several corotation resonances. Additionally, rotation velocity profiles for these objects are publicly available. The collected sample is not a comprehensive list of all objects with described structures; limited availability of rotation curves in the literature restricts our sample size.

Subsequently, we obtained rotation curve data $v_c(R)$ for these five objects from: Crosthwaite et al. (2000) (IC 342), Lang et al. (2020) (M58), Walter et al. (2008) (M74), Noordermeer et al. (2005) (NGC 3583), and Sanders (1996) (NGC 5371). Using IC 342 as an example, we conducted a detailed analysis presented in Figure 9 [Figure 9: see original paper]. In the top panel, we marked the supposed corotation radius positions, with maroon hatched areas indicating R_c values at the intersection of several measurements. Using the obtained angular velocity profile $\Omega(R) = v_c(R)/R$, we determined the pattern speeds of each mode, shown by vertical lines and the legend in the bottom figure. Additionally, we plotted the $\Omega \pm \kappa/2$ curves indicated by dashed lines. As we can see, considering uncertainties in resonance locations and pattern speed, the OLR positions of internal structures are in good agreement with the corotation radii of external ones. This provides strong evidence for the existence of multiple spiral modes. Note that two corotation positions estimated by the T-W method were taken from Meidt et al. (2009), which also detected a similar feature in this object. In this paper, we have confirmed these R_c locations with independent measurements from Roberts et al. (1975) and Elmegreen et al. (1992), and showed the presence of an external structure rotating with 10 km s^{-1} kpc^{-1}. Analogous phenomena have been observed in other selected galaxies as well.

Furthermore, using formula (2), we calculated the winding time and compared it to the rotation period τ_{rot} obtained for each spiral mode in the galaxy. It is worth noting that according to our analysis, some objects exhibit three spiral modes (for example IC 342), while others have only two. The results are presented in Figure 10 [Figure 10: see original paper], which shows the galactic rotation period obtained by taking the average of angular speeds of adjacent inner and outer spiral modes. The figure illustrates that for all galaxies in our sample, the winding-up process of spiral structure takes approximately two or three galactic years. The resulting τ_{wind} values are larger than those predicted for material spirals or found for other galaxies (Merrifield et al. 2006). However, these times are not long enough to consider the spirals as long-lived structure, meaning that for such galaxies the "winding dilemma" remains unresolved. These findings additionally raise questions about supporting mechanisms that enable spiral patterns to avoid winding and persist for extended periods.

6. Conclusion

The question of spiral structure nature in galaxies has been a long-standing problem in astrophysics. Despite the strength of existing theories, it is difficult to determine which correspond to real galaxies using observational data. Some research papers provide observational evidence supporting (Tamburro et al. 2008; Pour-Imani et al. 2016; Chandar et al. 2017; Peterken et al. 2019) or contradicting (Foyle et al. 2011; Shabani et al. 2018) the density wave scenario. Furthermore, there are assumptions that all proposed mechanisms could contribute to spiral arm formation in different galaxies. For example, recent research by Chen et al. (2023) showed that spiral arms of two galaxies with similar features could be consistent with both density wave and recurrent spiral theories.

One key observational test of density wave theory relates to constant pattern speed of spiral structure, which implies the existence of a localized corotation radius position. Reliable R_c estimation is possible when measurements obtained by different methods are consistent within error limits. On the other hand, an almost uniform distribution of corotation radii can be interpreted by dynamic spiral theory. However, it remains unclear which mechanism dominates in real galaxies. To investigate this problem, we collected a data set of corotation radius measurements using 12 various methods for 547 objects, with 300 having more than one value. All gathered data are publicly available on GitHub for future research. Note that our paper presents the first meta-analysis of a significant number of studies estimating corotation resonance positions by different methods. Although similar analyses exist in other studies—for example, Vallée (2020) compared results from research papers demonstrating the existence or absence of stellar age gradients for 24 galaxies, and Beckman et al. (2018) tested consistency between T-W and Font-Beckman methods for a single galaxy—our work is the first comprehensive meta-analysis.

We examined corotation radii distributions for galaxies with at least two measurements obtained by different methods. About 15% of these objects have visually consistent R_c positions, while 10% could have several localized corotation resonances. The remaining galaxies show no consistency in their distributions. Discrepancies between measurements for certain objects were found not only among those obtained by different methods (Scarano & Lépine 2013). As Williams et al. (2021) demonstrated, pattern speed values (and corotation position, respectively) measured by the T-W method may vary significantly depending on which component (gaseous or stellar) was used (see Figure 6 from Williams et al. 2021). Additionally, this method can produce completely different results depending on the initial assumption of whether pattern speed has a constant value or varies arbitrarily with radius (Merrifield et al. 2006). However, measurements of some methods included in our data set can differ from each other because their applications imply the existence of multiple corotation resonances for each galaxy (Buta & Zhang 2009; Font et al. 2011, 2014a).

To investigate possible reasons for these results (see Figure 4), we calculated the total coverage error Σ_{err} when estimating R_c and the Consistency measure (formula 1). The combination of these quantities allows us to separate galaxies with localized corotation radius positions from those with almost uniformly distributed corotation positions. Our analysis revealed that coverage error values, on average, increase with distance to the farthest corotation resonance (Figure 5). Additionally, investigation showed that the magnitude of these quantities has weak correlation with the number of measurements (see Figure 6). Even for galaxies with just a few R_c values, Σ_{err} magnitude might constitute a significant fraction of the disk.

We also tested the reliability of applied methods (Figure 7). Exclusion of the potential-density method (Buta & Zhang 2009) showed that negligible errors of these measurements, combined with their multiplicity, resulted in large Consistency values. As Figure 2 demonstrates, various offset and T-W methods have relatively large average Σ_{err} magnitude. There are also other reasons to suspect these measurements may be "unreliable." First, Borodina et al. (2023) demonstrated that using a gaseous component in the T-W method could lead to incorrect results. Also, most gathered T-W measurements were obtained based on Hα and CO velocity fields (Rand & Wallin 2004; Hernandez et al. 2005; Fathi et al. 2009), so they may not be accurate. Regarding the offset method, the fact that half of studies detect a stellar age gradient while the other half questions its existence (Vallée 2020) does not support this method' s reliability. However, exclusion of measurements obtained by these methods did not lead to noticeable decreases in error coverage and Consistency values. Moreover, we obtained almost the same result by including only those measurements whose errors did not exceed a quarter of the optical radius.

According to Lin & Shu (1967) and Thomasson et al. (1990), density waves with more than three modes are likely unstable, so grand-design spiral structure is proposed to persist much longer than that of multi-armed or flocculent ones. Another assumption is that substructures of flocculent galaxies form due to resonances, stellar feedback, and instabilities in the underlying disk with regular two-arm patterns (Chakrabarti et al. 2003; Elmegreen et al. 2003). Additionally, Block et al. (1994), Thornley & Mundy (1997), and Seigar et al. (2003) found examples of multi-armed and flocculent galaxies with underlying grand-design structure traceable in K-band, although more recent observations showed that most flocculent galaxies lack such features (Elmegreen et al. 2011). Many studies investigated distinctive properties of galaxies exhibiting different spiral types (for example, Ann & Lee 2013; Willett et al. 2013; Bittner et al. 2017; Hart et al. 2017; Savchenko et al. 2020). However, it remains unclear whether such galaxies obey different spiral formation scenarios. Our analysis (see Figure 8) revealed no clear division between grand-design, multi-armed, and flocculent galaxies in terms of either total coverage error or Consistency measure. This implies that, assuming reliability of all methods and measurements, galaxies of all spiral types could have one or more localized or almost evenly distributed corotation positions. Thus, according to the data, spiral structure type does not necessarily determine its nature. Additionally, we found no dependence on Hubble classification (pitch angles) or any relation with galaxy distance and bar presence (see Figure 8).

Although our results are consistent with a picture where a significant portion of galaxies contain spirals of transient origin (with some evidence for this, for example, Masters et al. 2019; Pringle & Dobbs 2019), we cannot exclude that different combinations of the above-mentioned reasons could be realized for each object. This multi-level problem is difficult to solve in practice, which is why it is necessary to investigate each galaxy individually (for example, as in Beckman et al. 2018).

In addition to clarifying discrepancies in R_c measurements for our collected sample, we calculated winding time values (formula 2) for several galaxies. According to Figure 10, we found that spiral structures in these objects wind up on timescales equal to several orbital periods. Our results are consistent with the picture shown in Merrifield et al. (2006) and Meidt et al. (2009). Recent models and observations increasingly move away from the stationary density wave scenario (Sellwood 2011). For example, Masters et al. (2019) examined a large sample of nearby galaxies and found no correlation between spiral arm winding tightness and bulge size predicted by density wave theory. Simulations have also provided evidence for transient spiral structures in external galaxies and our own Milky Way (D' Onghia et al. 2013; Hunt et al. 2018; Pettitt & Wadsley 2018; Sellwood & Carlberg 2022; Asano et al. 2024; Funakoshi et al. 2024). However, recent convincing evidence for density waves in most galaxies also continues to emerge (for example, Davis et al. 2015; Yu & Ho 2018, 2019; Peterken et al. 2019). These contradictory findings highlight the complexity of the spiral nature problem and the necessity for developing new approaches to solve it.

Despite the fact that our compiled data set consists of quite heterogeneous measurements taken from various sources, it will still be valuable for further investigations. First, we can determine angular speeds of galactic spiral structures by analyzing corotation radius positions and rotation curves of corresponding galaxies. This provides an opportunity to examine galaxies with multiple spiral patterns and investigate coupling effects in more detail. Second, the data set can be used to explore dependence between bar and spiral structures. Additionally, by obtaining reliable corotation radius values for a statistically significant number of galaxies, we will be able to investigate relationships between angular pattern speed and other galactic properties.

Thus, in our future work, we will examine several galaxies in detail using the collected data set. Additionally, we will implement and apply some methods (such as in Marchuk et al. 2024) for measuring corotation radii, which could allow us to resolve the spiral nature case for certain galaxies.

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Methods

In this section, we present a brief description of each method mentioned in this paper. The conditional names for each are indicated in parentheses.

A.1. Age Gradient Method (offset)

One generally accepted idea about the mechanism maintaining spiral structure in galaxies is based on quasi-stationary density wave theory (Lin & Shu 1964). This assumes rigidly rotating spirals in a differentially rotating galactic disk. The corotation radius, by definition, divides the galaxy into internal and external parts. In the central part, the angular velocity of the disk exceeds the pattern speed. Assuming trailing spiral rotation, this means that the gravitational shock wave induced by the arms triggers star formation on the inner side of spirals. In the external part, conversely, the disk rotates more slowly than spiral patterns, which is why newborn stars form on the outer side of the pattern. Thus, an azimuthal age gradient across spiral arms should exist in the galactic disk.

Oey et al. (2003) calculated spatial isochrons of spirals, whose intersection indicates the R_c position (see Figures 7 and 8 in Oey et al. 2003). Several papers investigate the profile of angular offset (Δf) between young massive star clusters and star-forming regions (Tamburro et al. 2008; Egusa et al. 2009; Sakhibov et al. 2021). The distance where Δf changes sign is associated with the corotation resonance position. Investigations of azimuthal age gradients can also be performed by comparing spiral arms between multiwave images of the same galaxy (Abdeen et al. 2020).

A.2. Tremaine-Weinberg Method (T-W)

This method is the only one that estimates angular pattern speed using observational data (Tremaine & Weinberg 1984). Then, using the angular speed profile of the disk, it is possible to detect the corotation radius position.

The method can be applied only when three conditions are satisfied: 1. The tracer obeys the continuity equation.

To find the angular velocity of the spiral pattern, the following expression should be applied:

$$\Omega_p = \frac{\int I(x)v(x)\,dx}{\int I(x)x\,dx}$$

where $\langle v \rangle$ and $\langle x \rangle$ are intensity-weighted velocity and position along a slit, respectively, and i is the galaxy inclination. Slits for each object are drawn parallel to its major axis (see Figure 14 [Figure 14: see original paper] in Williams et al. 2021).

Velocity data along the slit are often extracted from molecular hydrogen (Rand & Wallin 2004; Meidt et al. 2009; Williams et al. 2021) and Hα velocity maps (Hernandez et al. 2005; Toonen et al. 2008; Fathi et al. 2009). Additionally, some authors use stellar component velocity maps (Cuomo et al. 2020).

A.3. Metallicity Gradient Method (metallicity)

The metallicity distribution profile in galaxies is characterized by a monotonic decrease in heavy element content from central to peripheral regions (Vila-Costas & Edmunds 1992). Such profiles can have breaks or slope changes caused by corotation resonance presence. The corotation radius is considered to divide the galactic disk into two isolated parts that almost do not exchange gas and consequently evolve independently. It is important to note that the same effect was found in the Milky Way disk (Lépine et al. 2011) and in hydrodynamical simulations (Lépine et al. 2001). Scarano & Lépine (2013) investigated metallicity distribution profiles and determined R_c positions for 27 galaxies. To check their results' correctness, the authors compared obtained measurements with corotation radius values from literature.

A.4. Potential-density Method (potential-density)

Zhang (1996, 1998) showed that disk matter and density waves can exchange energy and momentum. This occurs as a result of local gravitational instability or at the potential minimum of the pattern. Consequently, a shift should be detected between potential distribution and density wave profiles. Inside the corotation radius, the spiral wave rotates more slowly, which is why disk particles lose angular momentum. A positive sign of the phase shift, defined as the azimuthal offset between potential and spiral in the direction of galaxy rotation, means the spiral density wave gains angular momentum. A negative sign, conversely, indicates momentum loss. Therefore, the corotation resonance position is where the phase shift changes from positive to negative.

One of the first applications of this method was carried out by Zhang & Buta (2007). The authors used near-infrared images (1.65 m) to obtain surface density and potential distribution maps. The potential value was determined by the Poisson equation, and phase shift magnitude was calculated based on Equation (3) from Zhang & Buta (2007). As a result, phase shift profiles were obtained for 153 objects (see Figure 2 in Buta & Zhang 2009). Most of these profiles have multiple sign changes from positive to negative values, providing evidence for several spiral modes rotating at different angular speeds. Additionally, these profiles show positions where phase shift switches from negative to positive values. Spiral mode coupling is hypothesized to occur at these positions.

A.5. Font-Beckman Method (F-B)

The main concept of this method is based on radial gas flows present near resonances, including corotation (Kalnajs 1978), which causes a sign change in the radial velocity component. The corotation radius estimation method based on these assumptions was first applied by Sakhibov & Smirnov (1987, 1989) and Canzian (1993). A similar method was proposed by Lyakhovich et al. (1997).

Most corotation radius values measured by similar methods in our sample are taken from Font et al. (2011, 2014a, 2014b). This method searches for positions of so-called "zero" non-circular velocities that occur near resonances. To use the F-B method, residual velocity maps are required instead of radial velocity maps, as in Lyakhovich et al. (1997). These residual velocity maps strongly depend on the choice of inclination angle and position angle of the galaxy. It is important to note that this method can estimate not only corotation resonances.

A.6. Simulation of Observable Galaxies (model)

Another approach to estimating angular velocity is to simulate individual galaxies. Object models can be constructed based on N-body simulations (Salo & Laurikainen 2000) and hydrodynamic simulations in an external potential (Lindblad et al. 1996; Rozas 2008), both separately and jointly (Rautiainen et al. 2008). The first step in these simulations is constructing the potential based on stellar mass distribution obtained from photometric images. Stellar mass generally consists of old population material, so NIR data are mostly used to determine this value. Some works, like Kranz et al. (2003), include a dark matter potential derived from velocity curve data. Next, the galaxy is modeled in the obtained potential with a fixed angular velocity of the spiral structure. Then, model parameters are varied so that morphological features of synthetic and observed galaxies have similar appearances.

A.7. Morphological Method (morph)

The presence of corotation resonance in the galactic disk promotes the appearance of certain morphological features. As assumed in Roberts et al. (1975), corotation radius influences disk extensions and spiral structure as well as the existence of ionized hydrogen regions. In another series of works (Elmegreen et al. 1992; Elmegreen & Elmegreen 1995), additional morphological features were identified to measure R_c values. One is based on the fact that inner and outer Lindblad resonances have clear locations in the galaxy. These resonance positions are defined as distances where spiral angular velocities equal $\Omega - \kappa/2$ and $\Omega + \kappa/2$, where κ is the epicyclic frequency and Ω is the angular velocity of disk rotation. Thus, the OLR is expected to be the outer boundary of spiral structure, and the ILR is associated with spiral beginnings or bar ends (if present). According to these papers, the outer resonance position is determined as the optical radius of the galaxy with 10% accuracy. To estimate R_c, the positions where bright spiral parts change to faint ones or where arm numbers change are taken into account. A complete list of expected morphological features occurring at resonances is provided in Table 4 of Elmegreen et al. (1992).

A.8. Puerari-Dottori Method (P-D)

This method was first applied by Puerari & Dottori (1997). Its main idea is based on the existence of an age gradient of stars across spiral arms, similar to the offset method. The corotation radius is measured as the distance where the angular offset profile changes sign. This work is based on Fourier analysis of azimuthal galaxy profiles using both blue optical and infrared images, indicating young and old stellar populations, respectively.

A.9. Spiral' s Width (width)

The main idea of this method is based on investigating the azimuthal distribution of matter in the galactic disk. As mentioned earlier, the spiral pattern inside the corotation circle is supposed to rotate faster than disk material, and vice versa in the outer region. Additionally, significant matter concentration is observed inside the corotation radius, on the outer edge of arms, due to shock wave presence. The same effect is assumed to occur on the inner side of spirals in the external disk region. Therefore, inner and outer regions should have asymmetry relative to the mass center in azimuthal spiral distribution, but the skew of their profiles has different signs. Near the corotation radius position, the distribution is supposed to be more symmetrical. Hence, the corotation resonance is estimated as the galactocentric distance where the skew profile changes sign. An illustrative explanation of this method is presented in Figure 1 of Marchuk et al. (2024).

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