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Analysis of corotation radii in spiral galaxies

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Abstract. The corotation radius is one of the key parameters of a galaxy, since it not only influences the course of the dynamical processes, but also allows to determine the nature of the spiral structure. A clearly defined corotation radius indicates the presence of a spiral density wave, while an uneven distribution of positions suggests a transient nature to the spiral structure. In this study, we collected measurements of the corotation radius from the literature for 547 galaxies, obtained using 12 different methods. After analyzing the collected data, we found that only a quarter of the galaxies had consistent measurements of the resonance positions within the error limits when at least two different methods were used. As an indicator of the consistency of the collected measurements, we considered two values for each galaxy: the fraction of total error coverage and a dimensionless parameter related to the separation of average values. These quantities were found to be independent of the number of measurements taken, the methods used, and the values of the rotation radius with large uncertainties. In addition, no relationship was found between our results and the distance to the galaxy or its morphological type. Furthermore, we have shown that the consistency measure between the corotation radii does not depend on the type of spiral structure or the presence of a bar. Therefore, the obtained results can be explained by the different nature of the spiral arms in galaxies from the collected sample, where a dominant number of objects have a transient structure. As an example, we have examined in detail three galaxies to which several methods for estimating the corotation radius were applied. After a detailed analysis, we found that all three galaxies may have different nature of spiral arms. NGC 3686 shows a density wave, while NGC 4321 has dynamic (transient) spirals. The spiral structure of NGC 2403, on the other hand, most likely consists of several different spiral modes.

Keywords: galaxies: spiral, kinematics and dynamics

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1 Introduction

More than 70% of the galaxies observed in the Local Universe have a spiral structure, which has long captured the attention of astrophysicists. Despite extensive research on these structures, a comprehensive understanding of their nature is still lacking. Currently, two opposing theories offer possible explanations for the nature of spiral structures. One of these, known as the quasi-stationary density wave theory (Lin & Shu 1964), has received significant attention. This theory proposes that spiral arms are manifestations of density waves propagating through the galactic disk. The key assumption of this theory is that the angular velocity of the spiral density wave remains constant relative to the distance from the galactic center. The specific point where the angular velocities of the disk and the spiral pattern coincide is called the corotation radius (R_c). In contrast, the transient spiral theory considers the spiral structure to be dynamic in nature (Sellwood & Carlberg 1984). According to this theory, the angular velocity of the spiral pattern changes in a manner similar to the angular velocity of the disk rotation. Consequently, the positions of the corotation radii can be found at multiple locations throughout the disk of the galaxy, rather than being limited to a single fixed position.

The aim of this study is to collect corotation radius measurements from the literature, obtained by different methods, and to analyze the consistency of the gathered R_c positions for each galaxy. This approach allows not only to find "reliable" positions of corotation resonances, but also to determine which mechanism of spiral formation is most common among disk galaxies. In addition, we have used several methods to estimate corotation for selected galaxies in this study. The measurements we obtained confirmed some positions and allowed us to draw conclusions about the nature of the spiral arms in these galaxies.

2 Data and methods

In this study, we gathered a dataset of 1711 corotation positions for 547 galaxies, estimated using 12 methods.[1] For 300 of these objects more than one corotation position was found. Note that a reliable determination of corotation requires at least two different methods to be used on the same object. This requirement was met for 161 of the galaxies in our sample.

The methods used to estimate corotation radii were divided into conditional groups, based on their main assumptions and techniques. Thus, according to the *P-D (Puerari–Dottori)* and *offset* methods (shown in dark gray and red in Fig. 1,

[1] This dataset is publicly available on GitHub https://github.com/ValerieKostiuk/CRs_dataset

right), there is an angular offset between stellar populations of different ages, and the corotation radius is located at the point where this value changes sign. The *width* method analyzes the azimuthal distribution of matter along the spirals. The *T-W (Tremaine–Weinberg)* (dark blue) method allows us to obtain the pattern speed directly, while the *model* (purple) method adjust this value until the simulated galaxy has the same morphological features as the real one. The *potential-density* (cyan) and metallicity (green) methods use the radial profiles of the phase shift and the abundances. R_c of gathered sample have also been estimated by analyzing residual velocities (*F-B (Font–Beckman)*: gray) and morphological features (*morph (morphological)*: yellow). Detailed descriptions of the listed methods are presented in Kostiuk et al. (2024).

3 Consistency analysis

We examined the distributions of corotation radii for galaxies with at least two measurements obtained by different methods (examples of such distributions are shown in the right panel of Fig. 1). About 25% of these galaxies have a visually consistent R_c, while the remaining galaxies show no consistency in their distributions. This can be explained by the recurrence of spiral structure in some galaxies. To investigate the other factors causing these results, we calculated the total coverage error Σ_err in determining the R_c position and the measure of consistency. The first quantity is defined as the sum of measurement uncertainties when R_c positions intersect within the error limits, otherwise as the addition of the error covers. To compare objects of different sizes, we normalized Σ_err to the optical radius (r_{25}). The second one is calculated as the ratio of the average difference between the measurements to the square root of the average variance. The larger this value, the greater the discrepancy in the corotation radius positions for a given galaxy. Note that the magnitude of this this dimensionless parameter can reach high values in some cases due to small error values.

Figure 1 (left) shows the distributions of the total coverage error and the measure of consistency for each object in our dataset. This figure visually separates the sample into different groups. Galaxies with a well-defined corotation radius are located in the bottom left corner of this plot. Distributions with an intermediate value of $\Sigma_\mathrm{err}/r_{25}$ may have multiple corotation radii (see the distribution for NGC 1042 on the right panel). Other points represent objects for which the estimated corotation radii from different methods do not agree. The top and bottom panels in Fig. 1 illustrate how measurements can be inconsistent with large and small coverage errors, respectively. Before drawing any serious conclusions about the dominant mechanism

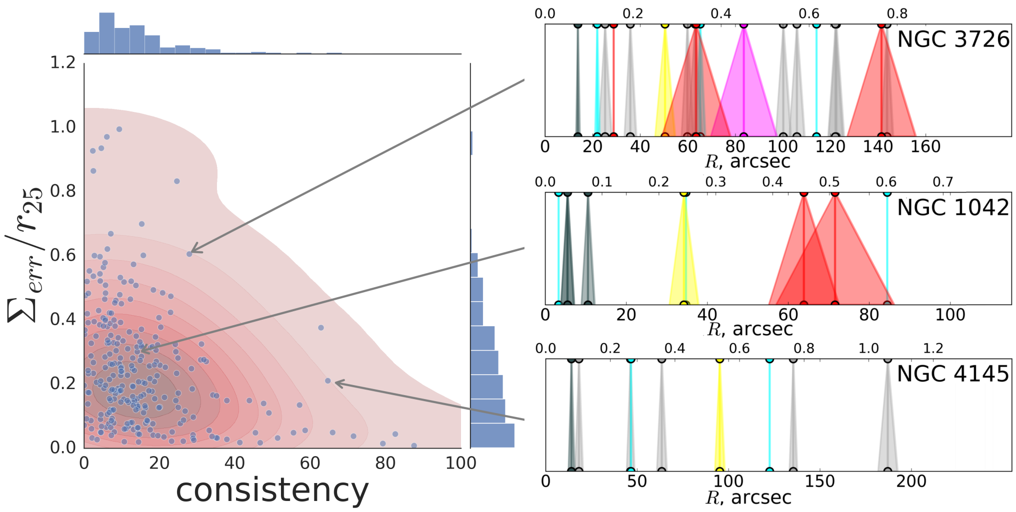

Fig. 1. The left panel shows the relationship between the error coverage fraction and the consistency measure. Each point represents a galaxy with at least two measurements. The histograms of the corresponding values are shown on the right and top. On the right panel are examples of R_c distributions for the objects indicated by the arrows. The shaded areas show the error of each value (base of the cone). Their color indicates the method used (see text for details). The lower scale indicates their positions in arcseconds, and the upper scale indicates their positions in units of the optical radius.

of spiral formation, we tested other reasons that might affect the obtained discrepancy. We found that the number of measurements did not affect the magnitude of the consistency. In addition, we examined the validity of the measurements and the correctness of the methods used, and found that the discrepancy did not disappear after excluding either measurements with high uncertainties or R_c values obtained by one method or another. Furthermore, we found no dependence on the Hubble type or the presence of a bar. Our analysis also showed that inconsistencies in the measurements were not related to the type of spiral structure, which challenges the idea that the type of spiral structure can determine its origin.

4 Investigation of individual galaxies

Although the results obtained can be better explained by transient spirals in a significant fraction of galaxies, it is still possible that a different combination of the above reasons could be realized for each object. Therefore, it would be more appropriate to study galaxies individually. For this reason, we selected three objects from our sample, NGC 3686, NGC 4321, and NGC 2403, which have completely different patterns of corotation radii distributions. We have not only verified each measurement to ensure its validity, but also implemented and applied the *offset*, *metallicity* and *F-B* methods to the observational data of the selected galaxies.

According to Fig. 2, the top panel shows that the combination of measurements of NGC 3686 obtained in this study and from the literature clearly shows consistent corotation positions estimated by 5 different methods. The estimate of the R_c position was made by fitting the distribution of the measurements with an asymmetric Gaussian function (see the blue line at the top). This is strong evidence for the existence of a spiral density wave. In contrast, the corotation positions for NGC 4321, shown in the bottom panel of Fig. 2, have an absolute discrepancy in distribution. In addition, we have not observed an angular offset between the young and old stellar populations as predicted by density wave theory. Taken together, this may indicate the dynamic nature of the spirals in this galaxy (Egusa et al. 2009).

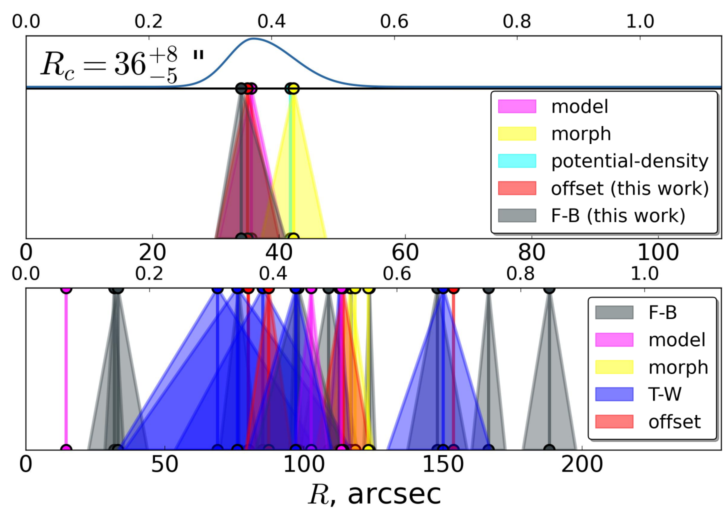

Fig. 2. The distributions of the corotations for NGC 3686 (top) and NGC 4321 (bottom) taken from the literature and obtained in this work (the same as in Fig. 1 right). The blue line at the top shows the fitted asymmetric Gaussian function.

The third analyzed galaxy, NGC 2403, is predicted to have multiple spiral modes rotating at different pattern speeds. In this study, we have confirmed the locations of several corotation resonances using measurements obtained by implemented methods. The top panel of Fig. 3 shows two reliable corotation positions at 140″ and 300″, confirmed by two and four independent measurements, respectively. In addition, according to the bottom panel of Fig. 3, we found the intersection of the corotation and outer Lindblad resonances for the second and first modes, respectively. This feature is expected for a galactic disk with multiple spiral modes. Furthermore, in this figure we see that the ultraharmonic resonance of the second mode is coupled within errors to the corotation of the third mode, proving the location of $R_{\rm c}$ at $390''$.

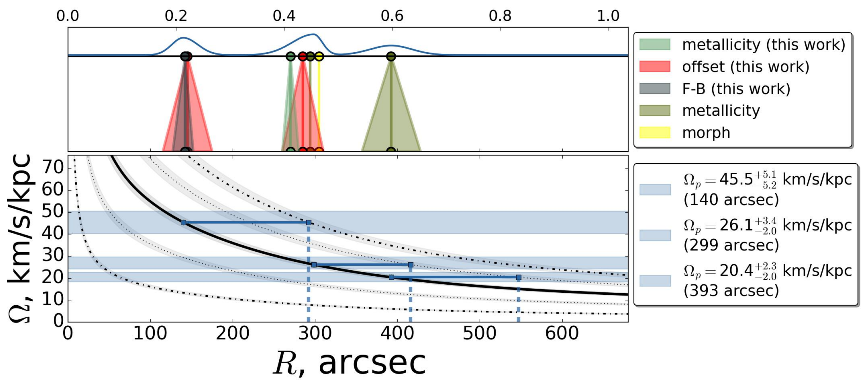

Fig. 3. *The top panel:* the same as in Fig. 2. *The bottom panel:* the black solid line shows the angular velocity profile of NGC 2403. To the left and right of it, dashed lines define the areas of inner and outer Lindblad resonances. Ultraharmonic resonances are represented by dotted lines. The blue horizontal lines connect the positions of the corotation radius and the OLR (or ultraharmonic resonance) for the angular pattern speed, whose value is given in the legend.

In summary, we have shown that the estimation of corotation radii is still a challenging problem in astrophysics due to discrepancies in their measurements. Using three examples, we have shown that the distribution of corotation measurements can be linked to the nature of the spiral structure. Furthermore, we have illustrated the coexistence of galaxies whose spirals may have different origins.

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