Publ. Astron. Obs. Belgrade No. 98 (2018), 167 - 173 *Progress Report*

BAR DETECTION IN N-BODY SIMULATIONS USING FOURIER ANALYSIS

A. MITRAŠINOVIĆ[1], M. MIĆIĆ[1], N. MARTINOVIĆ[1], M. SMOLE[1] and S. MILOŠEVIĆ[2]

[1]*Astronomical Observatory, Volgina 7, 11000 Belgrade, Serbia*
E–mail: amitrasinovic@aob.rs

[2]*Department of Astronomy, Faculty of Mathematics, Studentski trg 16, 11000 Belgrade, Serbia*

Abstract. Bars are considered to be a common feature in disk galaxies. Since their formation and evolution can be fully studied only using N-body simulations, it is important to refine and improve methods for bar detection and determination of its properties. The most practical and frequently used method is based on Fourier analysis of the face-on density distribution of disk particles. However, criteria for positive bar detection and determination of its parameters are usually biased toward long and strong bars or cases where no other feature is present in the disk (e.g. spiral structure, tidal tails). We propose a new criterion which enables positive bar detection for both weak and short bars, and also successfully distinguishes bar region from other possibly present features.

1. INTRODUCTION

Measurements of the fraction of barred galaxies can vary depending on the definition of the bar, methods of its detection, and the sample of observed galaxies, but it is undoubtful that bars are a common feature in disk galaxies. Moreover, bar can play a major role in secular evolution of its host galaxy (e.g. Cheung et al. 2013, and references therein). For these reasons, there is still ongoing research, both observational and theoretical, focusing on different aspects of bars in galaxies: their formation, evolution and effects they have on host galaxy (e.g. Galloway et al. 2015; Cheung et al. 2015; Berrier & Sellwood 2016; Gajda et al. 2017).

Observational studies can provide useful information about statistical properties of barred galaxies, or detailed analysis of specific galaxies. However, in depth and temporal analysis of bar and its host galaxy is only possible using N-body simulations. Large amount of data acquired by simulations dictates that the method for analysis must be fully automated and efficient in usage of resources. Since method based on Fourier analysis satisfies these requirements, it is frequently used for detection of bars in N-body simulations. We will briefly review common criteria for bar detection using this method, and propose a new, more general criterion with appropriate examples.

2. FOURIER METHOD

When disk is decomposed in Fourier modes, prominent features (like bars and two armed spirals) contribute the most to second mode C_2. Relative (mass normalized, since zeroth mode C_0 yields total mass) second Fourier mode $m = 2$, in general, is calculated as:

$$\frac{C_2}{C_0} = \frac{1}{M}\sum_{j=1}^{N} m_j e^{2i\phi_j} = C_{21} + iC_{22} \tag{1}$$

where M is total mass, and summation is performed over all particles with masses m_j and angles ϕ_j in $x-y$ plane. With C_{21} and C_{22} representing real and imaginary part respectively, of its complex form, amplitude A_2 and phase ϕ_2 are then calculated as:

$$A_2 = \sqrt{{C_{21}}^2 + {C_{22}}^2} \quad \text{and} \quad \phi_2 = \arctan\left(\frac{C_{22}}{C_{21}}\right) \tag{2}$$

This calculation can be done globally (for all disk particles) but high amplitude A_2 will, in that case, indicate that some kind of axisymmetric feature or more of them are present, and phase ϕ_2 will give rough estimate of position angle for the most prominent feature or its part.

In order to get more detailed information about the feature type and its region, this calculation must be performed locally, by slicing the disk in annuli in $x-y$ plane.

2. 1. COMMON CRITERIA FOR BAR DETECTION

Strength of the bar is characterized by local maximum value of amplitude A_2. Determining whether that local maximum really indicates that the bar is present is a bit more complicated. The most common method is to set lower limit for maximum amplitude to 0.2. Since this can be biased toward strong bars, usage of some lower value for the limit is not uncommon. Position angle of the bar is determined either by phase angle of the local amplitude maximum, or by mean phase angle in the bar region.

Determination of the bar length is the most complicated part of bar detection procedure. It is usually determined by the radius where amplitude A_2 drops to half maximum value after detected maximum, or by the end of region where phase angle ϕ_2 does not deviate more than some fixed value (either 10° or 20°) from the mean phase in the region (e.g. Aguerri et al. 2009). In ideal cases where there is only strong long bar present in the disk, all of these methods will give similar bar length as a result. However, if another feature (e.g. spiral arms, rings) is present, measuring bar length using half maximum amplitude is not viable due to amplitude not dropping to its half maximum value or not dropping fast enough. Introducing condition for fixed phase deviation must be done with caution and some prior knowledge of the bar. For example, choosing lower value for phase deviation will give realistic length for longer bars but shorter bars can go undetected. Alternatively, choosing higher value will make it possible to detect shorter bars but it will overestimate length of longer bars. All of these problems make it clear that the process of bar detection cannot be fully automated using these common criteria.

2. 2. NEW ALGORITHM OUTLINE

Basic concepts of our bar detection algorithm are presented on the flowchart (Figure 1). We start by identifying all local peaks of $A_2(R)$ profile as $A_{2,\max}$ with respective radius $R_{\max}$, and run the procedure for each of them.

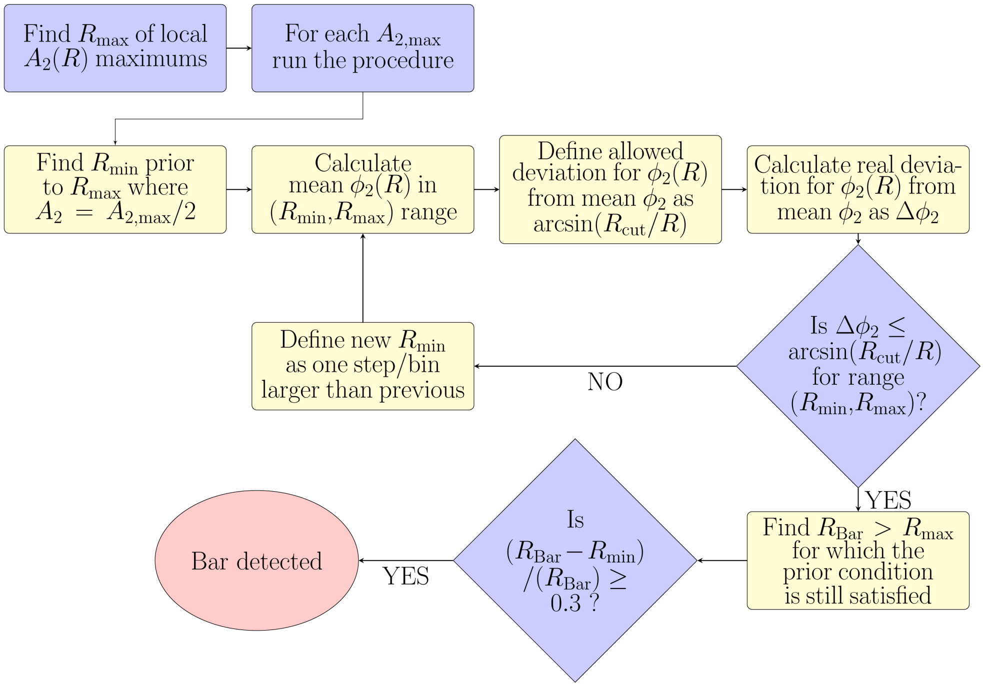

Figure 1: Our bar detection algorithm.

We use $A_{2,\max}$, $R_{\min}$, R_{bar} and $\phi_{2,\mathrm{mean}}$ as measures of bar strength, width, length and position angle, respectively. Allowed deviation of $\phi_2(R)$ from mean phase $\phi_{2,\mathrm{mean}}$ is defined and calculated as $\arcsin(R_{\mathrm{cut}}/R)$ where R_{cut} is a free parameter. Generally, R_{cut} can take any fixed value, either arbitrary chosen or estimated based on some characteristics of amplitude and phase profiles. It represents fixed maximum allowed distance from fixed angle at any given radius, resulting in variable allowed angle distance on different radii. That way we can get rid of the bias toward long or short bars raised by fixed allowed angle deviation, and detect bars regardless of any prior assumptions about bar length. Additional condition examines flattening (or ellipticity) of the bar. We chose rather high value of 0.3 for the second condition in order to avoid getting false positives for bar as much as possible.

3. RESULTS

As mentioned previously, in ideal cases with strong long bar every criterion for bar detection will give similar results for bar strength and length. We will present two special cases where every common criterion fails to either detect the bar, or determine its properties but our algorithm detects the bar and gives decent rough estimate of its properties.

3. 1. TWO ARMED SPIRAL WITH SHORT BAR

Amplitude and phase profiles for the case of two armed spiral with short bar are presented on Figure 2. Red dashed line on amplitude profile plot represents bar width and red solid line represents bar length. Dashed red lines on phase profile plot represent allowed deviation from fixed phase angle (black solid line). Method based on amplitude half maximum value would, in this case, give significantly larger bar length, whereas method based on fixed phase deviation would fail to detect the bar (if not set to higher value, e.g. $> 40°$).

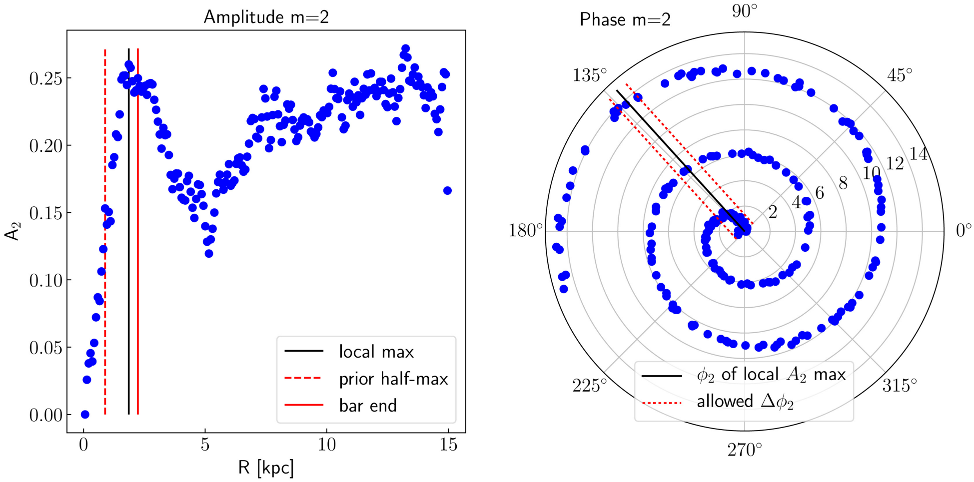

Figure 2: Amplitude and phase profiles for the case of two armed spiral with short bar. Left (amplitude) panel: solid black line represents radius of local A_2 maximum, dashed red line radius of prior half maximum (i.e. bar width), and solid red line radius of the bar end (i.e. bar length). Right (phase) panel: solid black line represents phase angle of local A_2 maxium, and dashed red lines allowed deviation.

Disk surface density map is given on Figure 3. Radius of solid circle is equal to determined bar width, and radius of dashed one to bar length. Solid line corresponds to bar position angle. It is clear that these parameters are estimated quite precisely and bar region is cut from spiral region successfully.

3. 2. BAR WITHIN BAR

Dispositioned shorter bar within larger bar is a quite interesting and unique feature. Amplitude and phase profiles are presented on Figure 4. with the same line notation like in previous example. Solid lines on phase profile plot correspond to phase angles of local amplitude peaks. However, as a final estimate of bar position angle we use mean phase angle in the bar region. Inner, shorter bar cannot be detected by any of the common criteria. For outer, larger bar method based on amplitude half maximum value gives slightly shorter bar length, and method based on fixed phase deviation

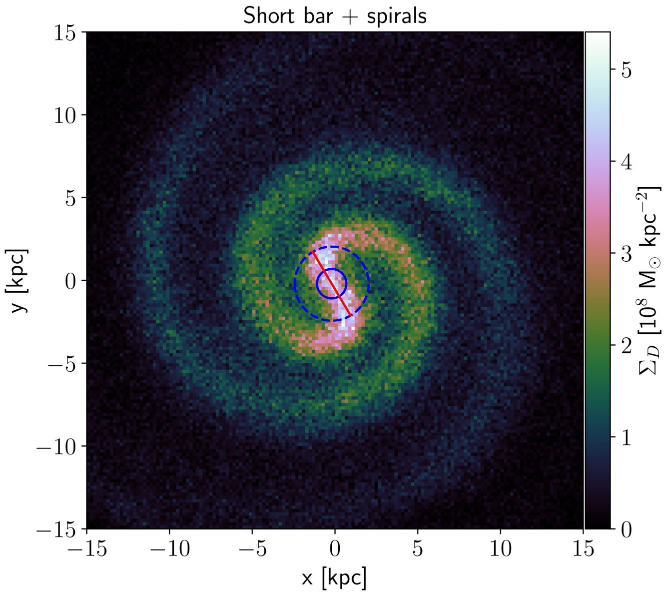

Figure 3: Disk surface density for the case of two armed spiral with short bar. Radius of solid blue circle is equal to determined bar width, and radius of dashed blue circle to determined bar length. Solid red line represents determined bar phase angle.

requires allowed deviation to be set to somewhat higher value (20°) in order to detect bar due to a few scattered points in the bar region.

Disk surface density maps are given on Figure 5. In order to avoid confusion, determined parameters are shown separately for inner bar (left panel) and outer bar (right panel). Due to overlap between bars regions, inner bar phase angles are highly affected by outer bar so inner bar position angle cannot be estimated by mean phase angle in the region. We encountered this issue in every similar case with dispositioned overlapping bars. However, *ad hoc* fix for this particular issue - simple subtraction of the angles in question seems to give more accurate estimate of inner bar position angle (dashed line on left panel).

4. SUMMARY

We modified the conditions for bar detection based on the analysis of amplitude and phase profiles of relative second Fourier mode. Instead of using maximum of amplitude, with a lower limit, in some radial range as a measure of bar strength, we detect all local peaks of amplitude and wrap our further analysis around those. For every of those peaks, we use position of half maximum amplitude prior to every local maximum as a measure of bar width. With determined width we define the condition for allowed deviation of phase from mean phase angle in the possible bar region. Upper radial limit of the region where the condition for phase deviation is satisfied is used as a measure of bar length and if the two measures (width and length) satisfy the ellipticity condition, we conclude that the bar is detected.

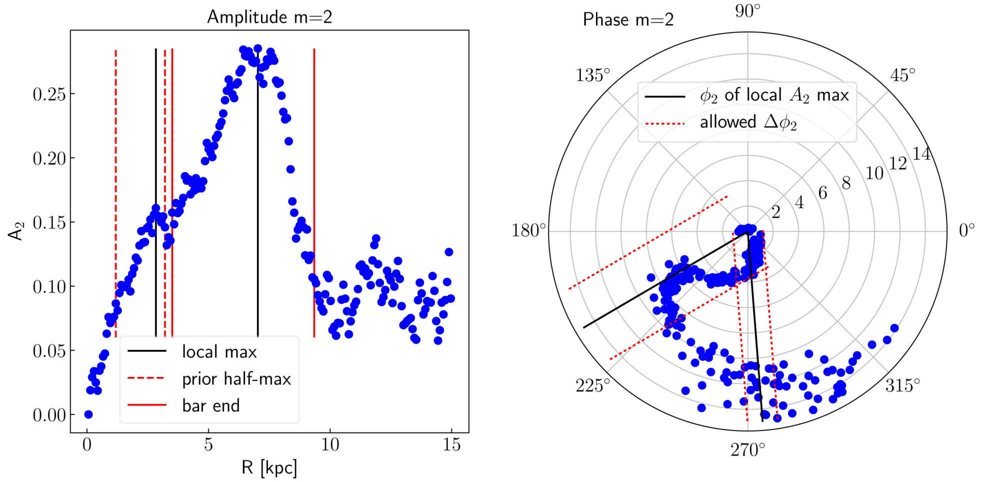

Figure 4: Amplitude and phase profiles for the case of short bar within larger bar. Left (amplitude) panel: solid black lines represent radiuses of local A_2 maximums, dashed red lines radiuses of prior half maximum (i.e. bar widths), and solid red lines radiuses of the bar ends (i.e. bar lengths). Right (phase) panel: solid black lines represent phase angles of local A_2 maxiums, and dashed red lines allowed deviation.

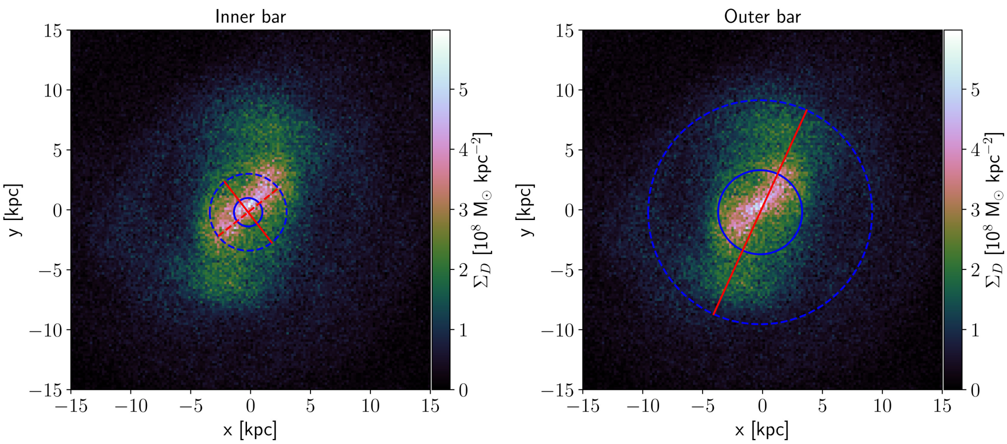

Figure 5: Disk surface density for the case of short bar within larger bar. Left panel shows detailed line plots for inner, short bar, and right panel shows detailed line plots for outer, larger bar - radiuses of solid blue circles are equal to determined bar widths, and radiuses of dashed blue circles to determined bar lengths. Solid red lines represent determined bar phase angles, and dashed red line *ad hoc* fixed phase angle for inner bar.

These changes enable bar detection for both short and long, weak and strong bars, and algorithm successfully distinguishes bar region from spirals. In addition, unique and short lived structures like dispositioned short bar within larger bar can also be detected.

Applied to over 8000 snapshots of galaxy flyby simulations, done using GADGET2 code (Springel 2005), we had less than 2% of false positives for bar, all of which were the cases with either inner region of tightly winded spirals or thick rings. Discarding those cases is possible with additional analysis of disk surface density profiles. Compared to the results of other bar detection methods and criteria, we did not have false negatives. Lowering the value for ellipticity condition in our algorithm might show that the value we chose to use results in some amount of false negatives. However, it is questionable whether low ellipticity bar-like features can be considered as bars.

Analysis and plotting scripts were written in `Python` but simplicity of our algorithm allows it to be written and executed in any programming or scripting language. Our full method, currently in testing, will be able to detect regions of different features present in the disk and recognize them as bars, spirals and rings or arcs.

Acknowledgment

This work was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia through project no. 176021, 'Visible and Invisible Matter in Nearby Galaxies: Theory and Observations'.

References

Aguerri, J. A. L., Mendez-Abreu, J. and Corsini, E. M.: 2009, *Astron. Astrophys.*, **495**, 491.
Berrier, J. C. and Sellwood, J. A.: 2016, *Astrophys. J.*, **831**, 65.
Cheung, E. et al.: 2013, *Astrophys. J.*, **779**, 162.
Cheung, E. et al.: 2015, *Astrophys. J.*, **807**, 36.
Gajda, G., Lokas, E. L. and Athanassoula, E.: 2017, *Astrophys. J.*, **842**, 56.
Galloway, M. A. et al.: 2015, *Mon. Not. R. Astron. Soc.*, **448**, 3442.
Springel, V.: 2005, *Mon. Not. R. Astron. Soc.*, **364**, 1105.