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Chorzów, 23.05.2018

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Report on the Doctoral Thesis of Mr. Grzegorz Gajda,
entitled
"Tidally induced bars in dwarf galaxies"

Recenzja rozprawy doktorskiej Grzegorza Gajdy
pod tytułem
„Pływowo indukowane poprzeczki w galaktykach karłowatych"

Rapport sur les travaux de Monsieur Grzegorz Gajda
en vue de la soutenance de doctorat
Intitulé: "Formation des barres par effet de marée dans les galaxies naines"

Prepared in the
Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
and
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Co-tutelle project supervised by
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The thesis of Mr Gajda is devoted to study of tidally induced bars in dwarf galaxies. Dwarf galaxies have now become a hot topic in extragalactic astronomy. One reason for this is that more detailed studies of dwarf galaxies orbiting large Milky Way-like galaxies are expected to shed light on the missing details of structure formation theory. In the ΛCDM model, which is currently assumed as the standard one, cosmic structure is seeded by primordial nearly scale-invariant adiabatic fluctuations and grows by gravitational instability in an expanding background. However, the highest-resolution cosmological simulations of Milky Way-size halos in the ΛCDM paradigm have demonstrated that dark matter clumps should exist at all resolved masses down to the numerical convergence limit. Hence, we expect thousands of subhalos, while only 50 satellite galaxies are known to orbit within the virial radius of the Milky Way. Moreover, observations indicate that a substantial fraction of satellite galaxies are part of highly flattened, planar arrangements. Available kinematic information furthermore supports the notion that these structures might be rotating. This is in stark contrast to the much more random distribution and motion exhibited by satellite sub-halos around their host galaxy halo in cosmological simulations. Resolution of these discrepancies is currently a great challenge.

The subject of the thesis is also important from the perspective of stellar systems dynamics. As it was always the case in the history of science, in particular Astronomy, theoretical works precede observations setting the framework – the fertile ground – within which future data could be understood and discussed. This is the case of Mr Gajda's PhD thesis, which albeit purely theoretical, could have a considerable impact in the future. Dwarf galaxies are intrinsically faint and it was only a matter of a last decade when the advent of large-area digital sky surveys with deep exposures and accurate star-galaxy separation algorithms has revolutionized the search for and discovery of faint stellar systems. One may expect that the findings presented by Mr. Gajda can be tested in the near future.

Thesis is well written, in good English. The style is transparent and easy to follow. Thesis consists of five chapters and an appendix. First chapter is the introduction, three middle chapters present original results obtained by Mr Gajda, while the last one concludes the thesis. The Appendix reveals mathematical details of the method used to calculate the pattern speed.

Chapters 2 and 3 describe the results obtained by the candidate, which have already been published in two corresponding papers in *the Astrophysical Journal* – a renowned, high-profile journal of the field. In both of these papers published together with his supervisors Mr Gajda is the first author, which marks his leading role. It is worth noticing that the full record of publications co-authored by him is much richer and comprises ten papers published in renowned journals. It is a very good result at this stage of scientific career.

Chapter 1 introduces the issues of barred galaxies, their abundance, underlying physics, bar instabilities, orbital structure and influence of bars on gas. Introduction of dwarf galaxies is a little bit too concise, in light of their importance in a context broader than merely stellar dynamics. However, from the perspective of purely dynamical considerations, which are the subject of the thesis, it is understood and fully acceptable.

Chapter 2 is based on the published paper: Gajda, Łokas, Athanassoula, *ApJ*, 830, 108 (2016).
It provides a detailed description and discussion of stellar orbits in tidally induced bar in a dwarf galaxy orbiting a Milky Way – like parent galaxy. The study was performed using the results of an *N*-body simulation of initially purely disky dwarf galaxy placed at the apocenter and then followed as it was moving on an elongated prograde orbit. After first pericenter passage bar developed and further evolved during subsequent pericenter passages, eventually developing buckling instability. In order to study stellar orbits in the bar Mr Gajda identified the period when the bar rotated with a constant pattern speed and focused on classification of orbits during this phase. He chosen one

particular method to classify the orbits, namely the Fourier transform used to identify dominant frequencies calculated in a Cartesian frame corotating with the bar. Besides the well-known x_1 orbits which turned out to contribute only 8% to the total, most of the other types (82%) had boxy shapes of various degree of elongation. Some of them being near-periodic, admitting frequency ratios of 4/3, 3/2 and 5/3. In the very center of the bar orbits known from the potential of triaxial ellipsoids were found. Technical details and discussion offered in this chapter are very thorough and fair.

Chapter 3 is based on the published paper: Gajda, Łokas, Athanassoula, *ApJ*, 842, 56 (2017). The same model of a disky dwarf galaxy orbiting a Milky Way-like host was studied concerning the impact of initial orbital parameters on the formation and structure of the bar. The orbital parameters tested were the size of the orbit (however with the same apocenter to pericenter distance ratio) and the inclination of dwarf's disk plane with respect to the orbital plane. In all cases a bar developed in the center of the dwarf during the first pericenter passage. Between subsequent pericenter passages the bars were stable, but at the pericenters they weakened and shortened. The important finding of this chapter is that details of the further evolution of bars depend strongly on the orbital configuration. The strongest bar is formed for the intermediate-size orbit. On the tighter orbit, the disc is too disturbed and stripped to form a strong bar. On the contrary the tidal interactions are too weak on the wider orbit. The dependence on the disc inclination is such that weaker bars form in more inclined discs. The bars experience either a very weak buckling or none at all. An important issue studied in this chapter was the angular momentum transfer from the bar to the dark matter component. Chapter was summarized with a comprehensive discussion and comparison with the results of other researchers.

Chapter 4 is the new, original and yet unpublished contribution of the candidate. Continuing and extending systematic study presented in the preceding chapters, Mr. Gajda investigated the impact of the interstellar medium on tidally induced bars in dwarf galaxies orbiting a Milky Way-like host. In order to accomplish this task, he combined the *N*-body code with Smoothed Particle Hydrodynamics. Then he performed simulations with various amounts of gas, that is with 0%, 30% and 70% gas fractions. The runs with gas were performed twice: with and without the star formation processes. All underlying assumptions were stated explicitly or proper references were given in cases when they were adopted from the papers published by the others. In all simulations, bars formed in the stellar component at the first pericenter passage. Despite different gas fractions, the bars had initially the same length and pattern speed. In the gas-poor models their further evolution was governed by the action of tidal torques at subsequent pericenters. The evolution of bars in the gas-rich dwarf galaxies was different. Namely, their bar strength decreased between pericenters leading to their complete disappearance. An important ingredient of this chapter was the discussion of temporal evolution of star formation rate in dwarf galaxies. It was shown that SFR was enhanced during first pericenter passage and later dropped significantly due to tidal stripping, staying constant until the next passage when it was enhanced again and then dropped.

Chapter 5 concludes the thesis. It summarizes the main findings and gives an outlook. It is very concise, but professionally written. In particular the outlook section demonstrated the author's awareness of the limitations of his work, where the initial conditions were chosen in a way that tidal effect of the host galaxy on the bar formation might be singled out.

Comments

1. The author did not state explicitly how was the orbital plane of the dwarf chosen. Presumably coplanar with the disk of the host galaxy. It would be interesting to study the influence of inclination of dwarf's orbit with respect to the disk plane of the parent galaxy. This may affect the

tidal effects exerted on the dwarf. I'm aware that this is easy to say for the reviewer and not so easy to perform before exascale supercomputers become a daily bread.

2. Two component model adopted both for the parent and the dwarf galaxy was described as comprising exponential disk and NFW dark matter halo. It would be good to give some justification for such a choice, especially the exponential disk. Why not Miyamoto-Nagai disk? While acceptable for the dwarf, the two component model seems too poor for the host spiral galaxy. The Milky Way-like galaxy should have central bulge as a third component. One may expect that tidal effects of the bulge could be important.

3. For the purpose of classification of orbits in the bar, the author used only the dominant frequency method. It is a pity that he did not independently analyzed the orbits using the surface of section method (which he mentioned in the discussion) and did not compared the results.

4. I am surprised that so little attention was given to chaotic orbits. What was the reason?

5. The thesis is focused on the structure and evolution of the stellar component. This is understood since it is the stellar component, which could eventually be tested observationally. However, the issue of dark matter component and how it is affected by subsequent pericenter passages is also interesting. A short information about this issue was given in Chapter 3, but for the completeness of the thesis it could be good to give some more discussion on this.

The above comments should not be perceived as criticism, but rather notification of minor drawbacks or expression of curiosity triggered by reading the thesis. The candidate may choose to reply to them during the public defense.

Summary

Thesis presented by Mr Grzegorz Gajda has demonstrated his deep knowledge of stellar dynamics and skills concerning numerical methods, in particular *N*-body and Smoothed Particle Hydrodynamics simulations. Moreover, it proves that Mr. Gajda is ready to continue his own unsupervised research.

Concluding my review, I declare that the dissertation meets the requirements of Art. 13 of the Polish "Act on academic degrees and academic title" (Ustawa Dz.U. Nr 65 poz. 595). It also meets the usual requirements posed on PhD theses by the academic community.

Hence, I am requesting the admission of Mr Grzegorz Gajda to the subsequent stages of the procedure including the public defense. I also propose the dissertation to be honored with distinction because of its scientific novelty, extensive research on a timely topic of dwarf galaxies, and a very good quality of the work done.

MBiesiada

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