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Review report on the PhD Thesis submitted to the Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

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Title: „Disk-Planet Interactions: Formation of Mean-motion Resonances in a Gaseous Protoplanetary Disk''

Supervisor: Prof. dr hab. Ewa Szuszkiewicz

Introduction

The Dissertation of Zijia Cui contains 167 pages, and includes abstracts in English, and in Polish, acknowledgements, 6 chapters, one Appendix, and an extensive list of references. It is well illustrated with multiple figures. The language of the Thesis is clear, which proves both fluency in English, and good understanding of the scientific background of the field covered by the Thesis.

The topic of the Thesis is well defined, and concerns a very contemporary research area of planet - disk interactions in early stages of planetary systems formation. In the era of massive exoplanet detections, and direct observations of protoplanetary disks, our understanding of planetary systems formation is challenged with discoveries of objects like hot Jupiters, super Earths, or hot Neptunes, which are not present on our Solar System. Processes, that lead to formation of such planets are not clear yet, therefore detailed studies of early stages of planetary systems formation are one of key topics in contemporary astronomy.

Most of results obtained by Zijia Cui in the presented Thesis were published in two papers in the Astrophysical Journal.

Structure of the Thesis

The Thesis starts with an Introduction, in which a wider perspective of the research problem is presented. General properties of protoplanetary disks are reviewed, and the problem of planet migration and formation of mean motion resonances as a consequence of migration of planets is introduced. The Introduction contains an overview of the Thesis as well.

In Chapter 2 the formalism and numerical setup of the adopted approach of 2D hydrodynamical modeling of disk evolution with planets as perturbers is presented.

The scientific results of the Thesis are presented in Chapters 3-5. Chapter 3 contains results of the modeling, that leads to a capture of two super-Earths into the second order mean motion resonances (MMR) 9:7. In the following Chapter 4 the problem of migration of a super-Earth in the presence of a more massive planet is addressed. Chapter 5 is devoted to detailed modeling of the wave-planet interactions in a young two super-Earth planetary system. A summary of the results is presented in Section 6.

The structure of the Thesis is logical, and each of Chapters 3-5 contains a solution to a well defined scientific problem.

The Review

The scientific results of the Thesis are presented in Chapters 3-5. In Chapter 3 disk properties, that favour a capture of two equal mass super-Earth planets into the 9:7 mean motion resonance are determined. The research is motivated by a presence of planets in orbits close to such a commensurability in several exoplanetary systems detected within the Kepler mission. In specific, the Kepler 29 b, c system is invoked as the best example ($M_\star/M_\odot$=0.76, Pb=10.3397 d, Pc=13.2861 d). Simulations are performed for a young planetary system, composed of a solar mass star (a point mass), gaseous disk with a locally isothermal equation of state, and two super-Earth planets (m_1=m_2=$3M_\oplus$). The inner planet (with e=0.005) is initially located at r_1=1 AU. The outer planet initial position is chosen such, that the orbital period ratio of two planets equals to 1.2865, slightly larger than 9:7. It is assumed, that both planets arrived at these positions during the previous stage of the evolution. After a short period of covergent migration two planets arrive at 9:7 resonance near their initial positions, in the protoplanetary disk with surface density $\Sigma_0 = 2 \times 10^{-5}$ and kinematic viscosity $\nu = 1 \times 10^{-6}$. In turn of multiple (82) full 2D hydrodynamical simulation runs disk properties (Σ_0, ν), initial eccentricities, and initial location of the outer planet, that allow for at least temporary trap in 9:7 mean motion resonance were determined and extensively discussed.

In Chapter 4 the problem of wave-planet interactions is studied in detail, in the case of a planet pair, composed of a massive inner one [$8M_{\oplus}$, M_{Jup}], and a super-Earth (m_2=$5.5M_{\oplus}$) as an outer one, migrating in a gaseous disk. In this chapter the problem previously studied in Podlewska-Gaca et al. 2012 is revisited, and extended to the systems with the inner component less massive than Jupiter. Again, the disk accompanies a solar-mass star, and the inner planet is initially located at 5.2 AU. The outer planet is initially located slightly beyond the 2:1 mean motion resonance. Such a configuration is again assumed to be an outcome of previous evolution. The results of Podlewska-Gaca et al. 2012 are confirmed and somewhat generalised: for the cases of $m_1 \geq 40M_{\oplus}$, the outer planet migrates outward, and the planets are not trapped in any long lasting MMR, as a result of the relative divergent migration. When $m_1 \leq 20M_{\oplus}$, the planets arrive at and stay in the 5:4 ($m_1 = 20M_{\oplus}$) or 6:5 ($m_1 = 8M_{\oplus}$) MMRs till the end of the calculations.

Results presented in Chapter 4 lead to Chapter 5, where the repulsion mechanism in a system with a pair of super-Earths is studied in more detail. This case is motivated by a presence of such super-Earth pairs with period ratios slightly larger than the first order resonance in the Kepler sample. The example of Kepler-59 is invoked ($M_{\star}/M_{\odot}$=1.04, Pb=11.8715 d, Pc=17.9742 d) among several others. Simulations were done for a young planetary system, composed of a solar mass star, and two super-Earth planets initially located at r_1=1 AU and r_2=1.48 AU. The disk initial surface density profile was chosen, that guarantees the convergent migration of the pair of planets at the beginning of the simulations. Various cases were studied leading to convergent or divergent migration, and criteria for the effective repulsion between two planets were elaborated.

Chapters 3-5 present a mature, consistent original science case, with rising degree of complexity. All three stages are well justified, and described. Sophisticated 2D hydrodynamical simulations of a planet pair migrating in a gaseous protoplanetary disk were presented for a multitude of disk properties and planetary orbit choices. Numerous interesting conclusions are reached.

Summary and Conclusion

Mean motion resonances are not particularly common among known extrasolar planetary systems. Several exoplanets locked in such resonances or near resonances are known, however, including those mentioned in the Thesis. Even, if the conditions adopted for the presented simulations are not very close to those in real short-period planetary systems, we learned from the Thesis a lot about the physics of the young protoplanetary disk, and planet migration process of planet pairs at early stage of planetary system formation. No doubt the doctoral dissertation constitutes an original solution to a scientific problem, and demonstrates the candidate's general theoretical knowledge in exoplanet astronomy, 2D hydrodynamic modeling of planet-disk interactions in young planetary disks in specific, as well as her ability to independently conduct scientific work.

Summing up, I consider the doctoral thesis of Zijia Cui to be a valuable contribution, and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defence.

A. Niedzielski