UNIWERSYTET
MIKOŁAJA KOPERNIKA
W TORUNIU
Wydział Fizyki, Astronomii
i Informatyki Stosowanej

Toruń, 29.08.2022

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Review of the doctoral dissertation of Ms. Zijia Cui, entitled "Disk-Planet Interactions: Formation of Mean-motion Resonances in a Gaseous Protoplanetary Disk".

The PhD Thesis by Zijia Cui deals with the formation of mean motion resonances in early stages of the evolution of planetary systems, when the forming planets are still embedded in gaseous protoplanetary disks. The resonance capture phenomena are investigated in two-dimensional gaseous disks with the aid of numerical and analytical methods. The Thesis is based on two refereed papers:

1. Zijia Cui, John C. B. Papaloizou, and Ewa Szuszkiewicz, "On the 9:7 Mean Motion Resonance Capture in a System of Two Equal-mass Super-Earths", published in The Astrophysical Journal, 872:72 (15pp), 2019.
2. Zijia Cui, John C. B. Papaloizou, and Ewa Szuszkiewicz, "On the importance of wave planet interactions for the migration of two super- Earths embedded in a protoplanetary disk", published in The Astrophysical Journal, 921:142 (28pp), 2021.

The dissertation consists of six chapters. The introduction (Chapter 1) presents general astrophysical aspects of the subject together with the goals of the Thesis. In Chapter 2. the author introduces basic elements of theoretical description of protoplanetary disks and three different types of planetary migration. Chapters 3, 4, and 5 describe the main achievements of the dissertation and Chapter 6 contains summary and conclusion. The Thesis is equipped with References section containing 225 references.

Chapter 3 describes two-dimensional simulations that have been used to investigate the circumstances favoring the formation of second-order mean-motion resonances and the conditions for the planets to be trapped in the resonant migration.
The author studied the 9:7 second order resonance capture in a system of two equal-mass super-Earth. The disk parameters were adopted in such a way that the planets were not able to open partial gaps, so the migration of planets in a protoplanetary disk

was identified as type I migration. The main results of this chapter include detailed analysis of the process of the planets capturing in the resonant migration supplied with discussion of various "capture" and "failed" cases for different choices of initial orbit parameters such as semi-major axes and eccentricities.

Chapter 4 extends the studies to the case of non-equal masses of the planets, covering the cases of a planet pair represented by a super-Earth migration in the presence of an interior Jupiter-mass planet, which is able to induce a gap around its orbital position. The author finds that the migration of super-Earth is dominated by the disk-planet interactions. In this case the density waves of the giant planet are sufficiently strong to perturb the disk in the vicinity of the super-Earth, which finally reverses from the state of inward-migration to outward-migration. This interesting phenomenon is interpreted and explained in a clear way: The outward propagating density waves excited by the inner planet dissipate in the co-orbital region of the outer planet. During this process, the angular momentum carried by the density waves is transferred to the horseshoe region of the outer planet and then to the planet itself through the horseshoe drag. Therefore, an additional torque is supplied, which is able to affect the migration direction of the outer planet in the disk. Further studies of the role of the giant planet mass demonstrate different outcomes of the migration process. For reduced masses of the inner planet the reversals of the outer planet migration occur at lower and lower values of semi-major axis ratio, and the effect takes place near one of the first-order resonances – 3:2, 4:3, etc. When the inner planet mass is low enough (near the super-Earth masses) the outer planet is trapped in the Mean Motion Resonance migration with the inner planet.

The subsequent Chapter 5 analyzes the wave-planet interaction in a pair of super-Earth, which are more massive than the planets discussed in Chapter 3 and are able to form partial gaps. The wave-planet interactions are examined carefully to estimate separately the torques resulting from the Lindblad and corotation resonances acting on the outer planet. It has been found that the repulsion between planets, leading the outward migration takes place also for the case of two super-Earth. An important result of this chapter is the uncovering the nature of the repulsion between planets. The wave-planet interaction has been attributed to density waves, emitted by one planet, being absorbed in the horseshoe region of the other planet and transmitted to it.

The main achievement of the PhD thesis by Zijia Cui is discovery of the repulsion mechanism operating in the system of two planets embedded in the gaseous disk. The mechanism can change from convergent to divergent migration of planets if they are massive enough to form a partial gap. The gap should not be too deep to ensure that the amount of material in horseshoe regions is sufficient to transfer the angular momentum transported by waves to the associated planet.

My overall impression on the PhD Thesis by Msc. Zijia Cui is very good. The strength of the work presented is that the results obtained by numerical simulations have been thoroughly analysed and interpreted with the aid of analytical methods. I find the results presented in the PhD thesis very robust and convincing.

Conclusion

The results of the original research by Msc. Zijia Cui, presented in the dissertation, represent an original solution to a scientific problem in the study of Formation of Mean-motion Resonances in a Gaseous Protoplanetary Disks. The doctoral dissertation demonstrates the candidate's general theoretical knowledge and ability to conduct independent research in the discipline of astronomy. The Doctoral Dissertation of MSc. Zijia Cui meets the requirements of Article 187 of the Law on Higher Education and Science of 20.07.2018. I therefore request that it be admitted to the public defence.

Moreover, to my opinion the doctoral dissertation of Msc. Zija Cui deserves distinction for achieving a deep understanding of the complex hydrodynamic interactions between migrating planets and the gaseous disk.

Michal Hanasz