Abstract

In this thesis, we investigate the formation of mean-motion resonances at the early stages of the evolution of planetary systems, when the forming or newly formed planets are still embedded in a gaseous protoplanetary disk. We focus on the systems containing the most numerous planets known till now, called super-Earths or mini-Neptunes. The planets evolving in a gaseous environment are subjects to the orbital migration due to disk-planet interactions. It is expected that, when the relative migration of two planets is convergent, than the capture into a mean-motion resonance can occur. Is this expectation always met? To answer this question, we employ a full two-dimensional hydrodynamic treatment of the disk-planet interactions, accompanied where possible with the analytic estimates, based on a simplified description of the interactions.

The first series of simulations, motivated by the observed orbital configuration of planets in the Kepler-29 system, is conducted with the aim to determine disk properties that favor a capture of two equal-mass super-Earths into the 9:7 second-order mean-motion resonance. We find that, a resonance trapping occurs during the convergent migration of planets, if one of the resonance angles at the moment of arrival at the commensurability assumes values in a so called window of capture. The width of such a window depends on the relative migration and circularization rates that are in turn determined by the disk parameters. The window is wide, if the relative migration rate is low, and it becomes narrower as the relative migration rate increases. If the migration rate is sufficiently high than the window will be closed and the capture will not take place. Here, we confirm the results of the previous studies and thanks to our full two-dimensional hydrodynamic treatment of the problem, applied to the second-order resonances for the first time, we are able also to extend the conclusions to the wider range of the initial eccentricities and the initial orbits of the planets. The masses of the super-Earths and the disk properties are chosen to ensure that the planets are not able to form the partial gaps along their orbits, and their migration can be regarded as classical type I migration.

The second series of simulations is motivated by the observational trend, seen in the distribution of the period ratios of planet pairs in the confirmed multi-planetary systems, that the period ratios prefer slightly larger values than the resonant ones. This trend is present regardless of the distance from which a planet pair orbits its parent star. We propose that, one of the reasons for what is seen in the distribution of the period ratios of planet pairs, may be the repulsion between planets due to wave-planet interactions. In the proposed picture, the transfer of the angular momentum carried by the waves to the other planet can lead to divergent migration, thus preventing the planets from being closely locked into any mean-motion resonance. Similar picture has been described in the literature in the case of the system of an inner giant planet and a super-Earth migrating in the exterior orbit, as well as in the case of pairs of Saturn-like and Uranus-like planets. In this thesis, we confirm those findings, and demonstrate that repulsion between planets is effective also in the case of two super-Earths, if they are able to form partial gaps in the disk (their migration is not of type I) and if those gaps contain enough material to support angular momentum exchange with the planet. These two conditions for the effectiveness of the mechanism are formulated by us using simple analytical estimates describing wave-planet interactions. Using two-dimensional hydrodynamical simulations, we verify these conditions for a wide range of planetary masses and disk properties. Our results indicate that, if conditions favor the repulsion between two planets, we expect to observe planet pairs with their period ratios greater, often only slightly greater, than resonant values. Another possibility is that the commensurabilities will not form at all and therefore the resonances are not necessarily common.