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Simulating late stages of the formation of giant planet systems

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Abstract

Dynamical processes leading to the formation of multiple giant planet systems with various orbital characteristics are investigated. The model includes gravitational interactions of planets and migration of planets due to the presence of a gas disc. For the system of four giant planets like the Solar system, we show how capture of all planets into resonances occurs at the type I migration. The resonant motion can remain after transition to the type II migration as well as after dissipation of gas. For the GJ876 system, it is shown how planets can migrate to orbits located inside the orbit of the most massive planet. Features of subsequent capture of planets into low-order resonances are investigated too. For the system HD102272, capture of planets into high-order resonances and subsequent evolution to high-eccentricity orbits are studied. We explain also how planetary systems similar to the GJ 581 system form. We conclude that different planetary systems similar to the observed ones can be simulated by varying parameters of the suggested model.

1. Introduction

After the discovery of more than 500 extrasolar planets, it is clear now that the formation of planets is a typical process in circumstellar discs. On the other hand, the observed planets have diverse dynamical characteristics (http://exoplanet.eu). Semimajor axes of the observed extrasolar planets spread from a few percent of the astronomical unit to hundreds astronomical units. The extrasolar planets move in both near-circular and near-parabolic orbits. Moreover, all the discovered multiple planet systems are different from the Solar system. First, while all the planets in the Solar system move in the near-circular orbits, there are orbits with much larger eccentricities in extrasolar systems. Secondly, librations near commensurabilities of planetary periods are typical for extrasolar systems, and it is not the case for the present Solar system. In addition, the tendency to the decrease of giant planet masses with heliocentric distances in the Solar system is often violated in extrasolar systems.

The aim of this work is to study dynamical processes at late stages of the formation of systems with planets moving finally in stable orbits. For this purpose, we consider a simple model based on known properties of dynamical evolution of planets in discs of gas and dust. The model described in Section 2 includes effects of the planetary interaction and migration. Are simple assumptions of this model sufficient to explain basic features of the observed extrasolar systems? In Section 3, we consider a few observed extrasolar systems with various dynamical characteristics to handle this problem. We conclude that it is possible to simulate systems similar to the different observed planetary systems by varying parameters of the model.

2. Model

The model includes gravitational interactions of giant planets and migration of these planets due to the presence of a gas disc. The dynamical evolution of the planets is calculated using the symplectic integrator [1]. In addition to gravitational interactions of the planets, the acceleration

$$\mathbf{F}=-\mathbf{v}/(2\tau^{(a)})-2\mathbf{r}(\mathbf{rv})/(r^2\tau^{(e)}) \qquad (1)$$

is introduced for every planet, where **r** and **v** are the position and velocity vectors relative to the star, $\tau^{(a)}$ and $\tau^{(e)}$ are the parameters determining changes of semimajor axes and eccentricities, correspondingly [2], [3].

For every planetary system, two stages of evolution are considered. We assume that the innermost planet reaches its final mass more rapidly than the other planets of the system, and it has the largest mass in the system. Except for this planet, all the planets undergo the fast type I migration at the first stage of evolution. Later, all the planets reach their final masses, and they undergo the relatively slow type II migration at the second stage until the gas disc disappearance.

3. Dynamical simulations of observed planetary systems

3.1 The Solar system

We assume that Jupiter has the present-day mass and Saturn, Uranus and Neptune have masses of $10m_E$ at the first stage of evolution, where m_E is the Earth mass. We have found that the planetary system is captured in the resonant configuration at different values $\tau^{(a)}$ and $\tau^{(e)}$ during the type I migration. The resonant motion remains at the typical type II migration with the present-day masses too.

3.2 The GJ876 system

The planets c and *b* of the system move in the resonance 2:1, and the planets *b* and *e* move in the resonance 2:1 too. The unusual feature of this system is also that the largest planet *b* is located further from the star than the planet *c*. We explain the observed properties of the GJ876 system in the framework of our model (Figure 1).

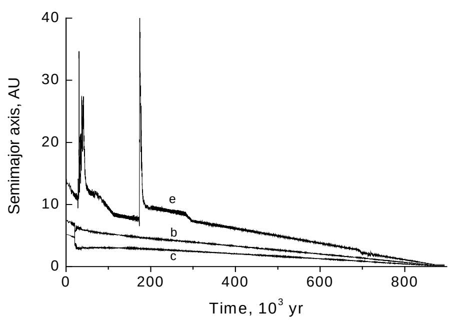

Figure 1: Evolution of semimajor axes for the planets *b*, *c* and *e* of the GJ876-type system.

3.3 The HD102272 system

The unusual features of this two-planet system are a high-eccentricity orbit of the planet *c* and a high-order resonance motion of planets (4:1). We show how such a system can form (Figure 2).

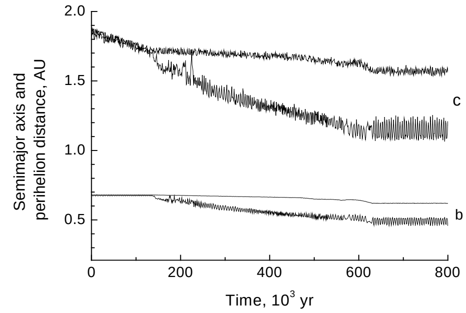

Figure 2: Evolution of semimajor axes and perihelion distances for the planets *b* and *c* of the HD102272-type system.

3.2 The GJ581 system

We studied the origin of the GJ581 system using also the two-stage model of evolution.

4. Conclusion

It has been shown that various features of the observed multiple giant planet systems can be explained by the unified model of late stages of planetary system formation.

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