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The dynamics of exoplanetary systems

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In this contribution I shortly review some basic features of recent theories of the formation of "Hot Jupiters". Models based on migrations, dynamical interactions and tides and in situ formation will be considered.

Keywords: Exoplanets, migration, celestial mechanics, tides, accretion

1 Introduction

3422 planets in 2560 planetary systems, including 582 multiple planetary systems, have been confirmed, as of 1 June 2016, see http://exoplanet.eu/. The least massive exoplanet is orbiting around a pulsar and has its mass roughly twice the mass of Moon, the most massive planet (which may be, however, classified as a brown dwarf) is about 29 times the mass of Jupiter. Orbital periods range from a few hours to thousands of years, and even to infinity (free floating planets) and eccentricities span from zero to ∼1. Many planets with close periods have large orbital inclinations with respect to rotational axes of their host stars, some are even retrograde. Several exoplanetary systems (e.g. Gliese 876, Kepler-223) have planets in mean-motion resonances. There are circumbinary planets, planets interacting with circumstellar debris discs, candidates to exoplanetary systems in other galaxies, etc. In general, there is a whole zoo of properties of exoplanetary systems, most of them are quite different from those that we have in the Solar System, see Fig. 1 for a distribution of e.g. exoplanets' eccentricities.

One of the most puzzling problems concerning possible formation mechanisms of exoplanetary systems consists in the presence of Hot Jupiters – giant gas planets with periods order of a few days. The first exoplanets discovered around a MS star (51 Pegasi b, Mayor & Queloz 1995) is a Hot Jupiter with orbital period ∼4d. The standard formation mechanisms of gas giants thought to operate in Solar System such as gas accretion onto cores formed from solid substances (the so-called ices), where these planets are born outside the so-called "ice line" with its size a few AU

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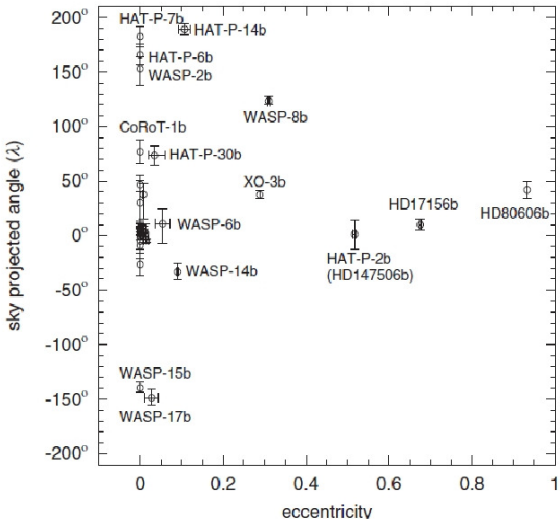


Figure 1 The dependence of eccentricities of exoplanets on orbital period in days taken from http://exoplanet.eu/. Size of the circles is proportional to planet's mass expressed in the units of Jupiter mass, while colour depicts their radii.

(e.g. Lissauer, 1993) or gravitational instability in outer regions of protoplanetary discs (e.g. Boss, 1997) are likely to be unable to explain their presence, see e.g. Bodenheimer, Hubickyj & Lassauer 2000.

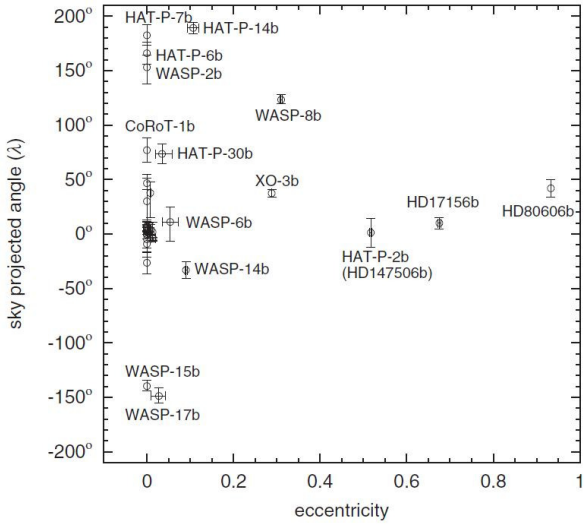


Figure 2 The dependence of angle λ showing orientation of inclination of planet's orbit with respect to equatorial plane of a host star on its eccentricity, for several planetary systems. When $|\lambda| > \pi/2$ orbital motion is retrograde (Nagasawa & Ida 2011).

They have very small eccentricities, some of them have inclined or even retrograde orbits, their host stars typically have larger metallicities*, see Fig. 2 for inclinations of Hot Jupiters with respect to rotations axes of their host stars.

In this contribution I briefly review some basic facts related to recent theories of the formation of Hot Jupiters.

2 Migration

Giant planets are thought to be formed either by accretion of gas onto seed cores made of solids or as a result of gravitational instability of protoplanetary discs. Both models favour large distances from central stars, say $\gtrsim$5 AU. It is, therefore, very important to consider mechanisms that are able to bring these planets to smaller distances.

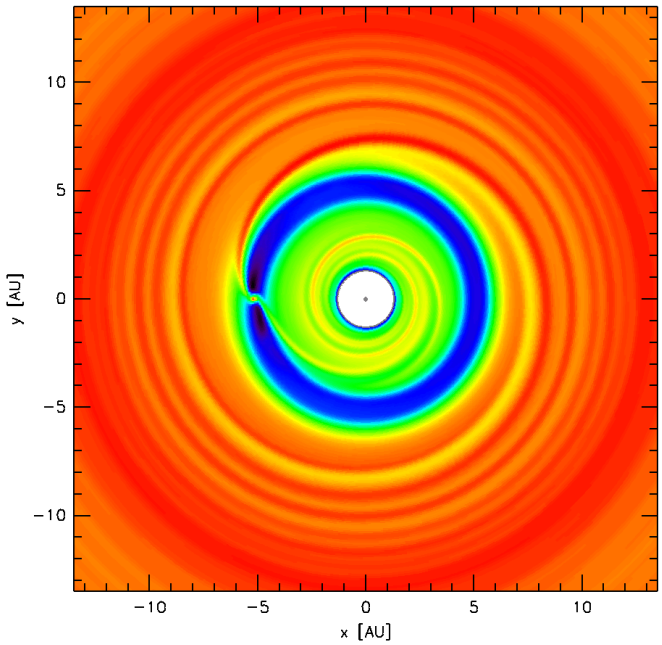


Figure 3 An example of numerical simulation of gap formation in a protoplanetary disc, see http://www.tat.physik.uni-tuebingen.de/ kley/research/planetform.html. The perturbing body has $q = 10^{-3}$.

When the ratio of mass of a planet to the mass of a host star, q, is sufficiently large: $q \sim 10^{-4}$, the planet opens a gap in the protoplanetary disc due to repulsive action of torques on the disc gas exerted by planet's gravitational potential at outer

*Note that an excess in metallicities of host stars is observed in planetary systems with planets having larger orbital periods as well, see e.g. Bond et al. 2006. It is usually interpreted as being of primordial origin, apprently the probability of planets formation is enhanced in metal rich molecular clouds.

and inner Lindblad resonances (e.g. Goldreich & Tremaine 1980, Lin & Papaloizou 1986), see Fig. 3.

When the mass of a planet is smaller than the mass of the disc material inside its orbit, the planet drifts in at "viscous" timescale of the disc, in the opposite case at an "accretion time scale" of the planet (Syer & Clarke 1994, Ivanov, Papaloizou & Polnarev 1999). This standard mechanism is called Type || migration.

Problems: 1) it is difficult to stop a planet to spiral into a central star[†]; 2) it is problematic to explain large eccentricities observed in Warm Jupiters; 3) within this scenario one must find a way to explain inclined and retrograde orbits.

3 Jumping Jupiters

The main idea: a system of massive planets formed beyond the ice line interacts gravitationally leading to strong perturbations of planet orbits. The outcome is similar to that in globular clusters, some planets are expelled from the system becoming free floating planets, while a few get significant eccentricities and/or inclinations. Then, tidal interactions with the central star circularise initially eccentric orbits of planets (e.g. Rasio & Ford 1996, Papaloizou & Terquem 2001). High orbital inclinations with

[†]Note that taking into account the loss of disc's mass, say, through a wind can alleviate this problem, see e.g. Armitage et al. 2002.

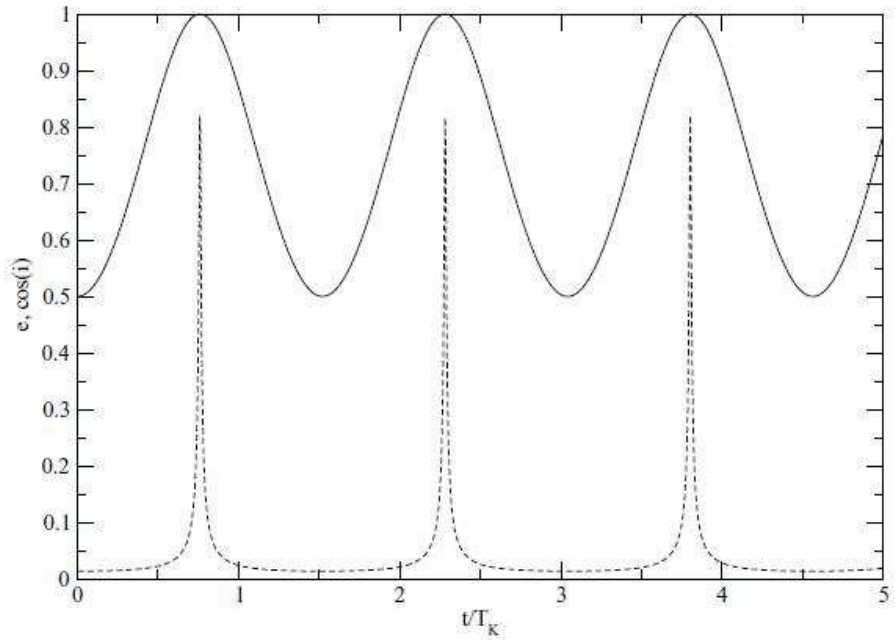


Figure 4 An example of Lidov–Kozai cycles. The dependencies of eccentricity e and $\cos(i)$, where i is the inclination angle are shown as functions of time in units of a characteristic time of secular evolution T_K (Ivanov, Polnarev & Saha 2005).

respect to outer perturbers (massive planets, brown dwarfs, stars, even massive outer gas disc) may facilitate the circularisation process through the so-called Lidov–Kozai effect (cycles of successive changes of orbital parameters between an orbit with high inclination and moderate eccentricity and low inclination and high eccentricity, see Fig. 4).

Two types of tidal interactions are considered: the so-called quasi-stationary tides and dynamic excitations of different normal modes of pulsations of rotating giant planets and stars (dynamic tides). Note that dynamic tides in planets having retrograde motion with respect to stellar rotation are amplified (e.g. Lai, 1997, Ivanov & Papaloizou, 2011). Thus, there is a natural bias towards retrograde orbits in the problem.

The Jumping Jupiters scenario is free from certain drawbacks of the migration scenario: it can easily produce planets with large eccentricities and inclinations, as well as, in principle, Hot Jupiters, see Figs 5 and 6.

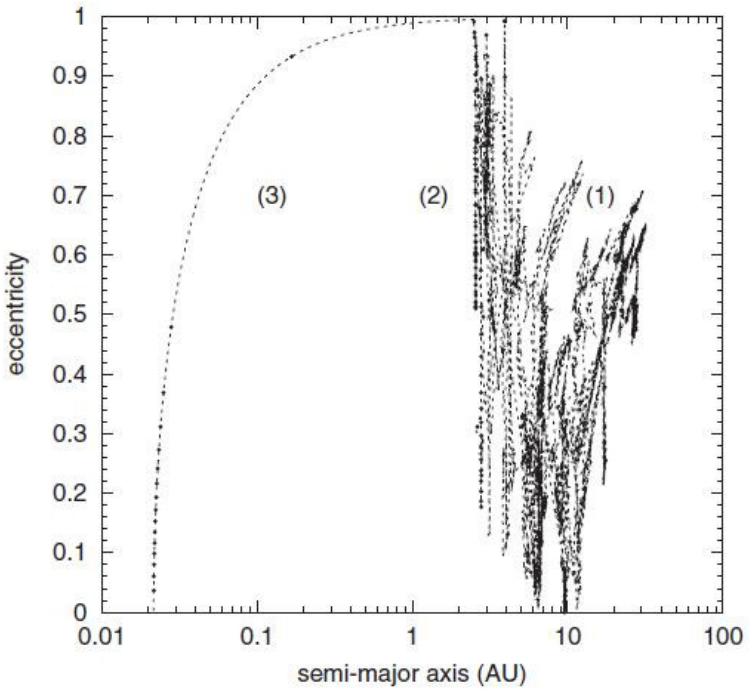


Figure 5 A typical orbital evolution of a close-in planet under the action of planet–planet interaction and dynamic tides, filled circles are plotted every 10^4 yr (Nagasawa & Ida 2011).

It has, however, its own problems: tides may be too weak to circularise a planet in a few Gyr. On the other hand, tides exerted on a planet may destroy it through a process known as "tidal runaway". Also, a planet spending a few Gyr on a highly eccentric orbit can expel all other planets within its apastron from the system. However, there are other planets within the ice line in some systems containing Hot Jupiters.

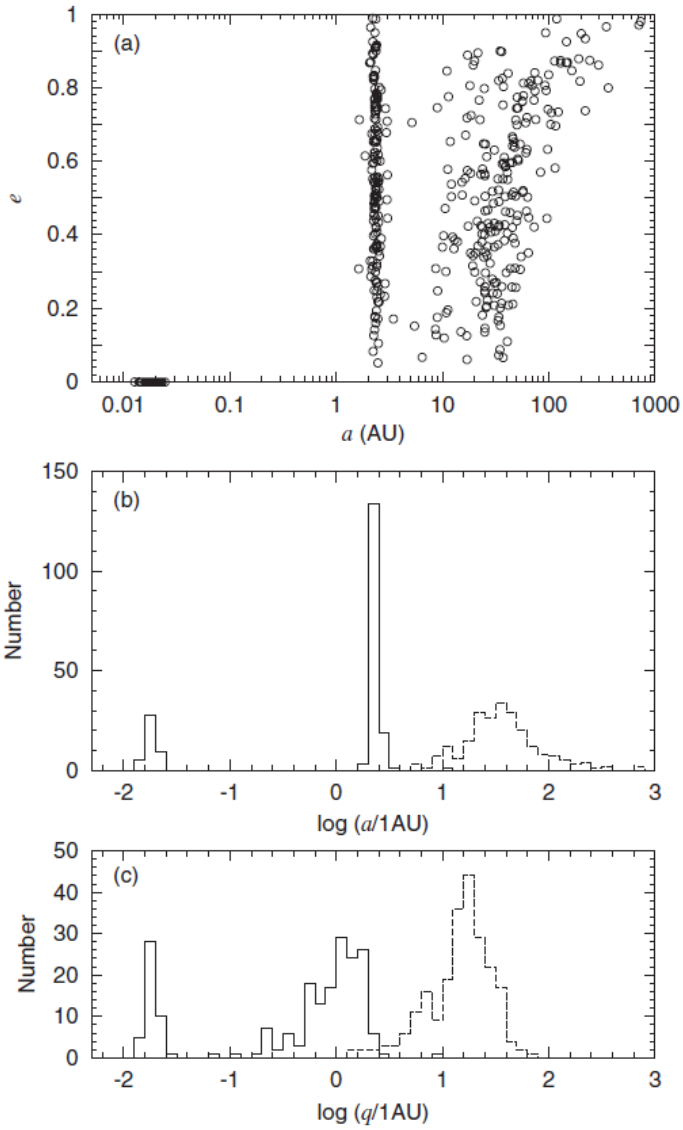


Figure 6 Distributions of planets at the end of numerical experiments of orbital evolution under the action of planet–planet interaction and dynamic tides. (a) Distribution of eccentricity versus semi-major axis, (b) histogram of semi-major axes and (c) histogram of pericentre distances (Nagasawa & Ida 2011).

4 In situ formation

Recently, it has been proposed that Hot Jupiters can form in place provided that a Super-Earth with mass ∼10–20 Earth masses is there. It plays the role of a core experiencing (core) accretion, which can be in the runaway regime (e.g. Batygin,

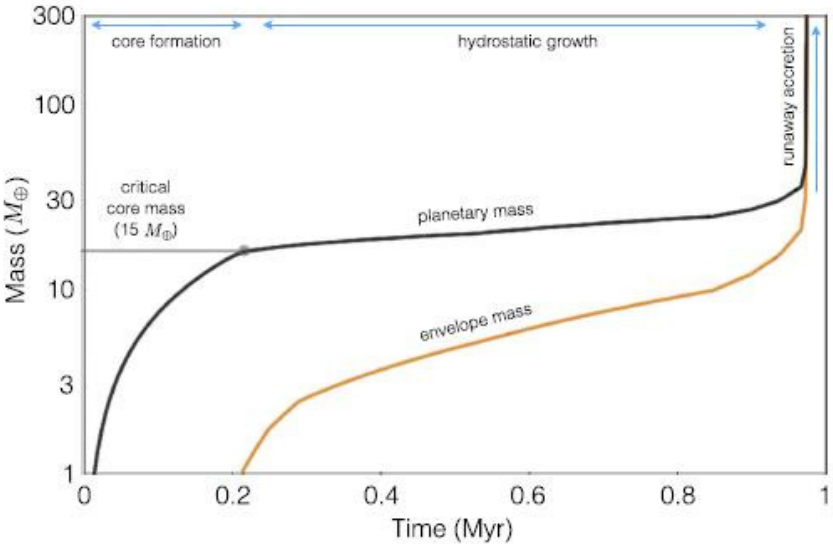


Figure 7 Evolutionary tracks of an in situ conglomeration of a Hot Jupiter at a close-in orbital distance. The orange and black curves show the evolution of gaseous envelope and total planetary mass, respectively (Batygin, Bodenheimer & Laughlin, 2016).

Bodenheimer & Laughlin, 2016), see Fig. 7 for an illustration, note also the early work of Tutukov, 1987, 1998. The model suffers, however, from the lack of available gas to build a Jupiter at such distances and certain other problems.

5 Conclusions

1) Systems of exoplanets demonstrate many intriguing properties totally absent in the Solar System, in particular, the phenomenon of the presence of Hot Jupiters.

2) Although there are certain more or less realistic scenarios of the formation of Hot Jupiters, they all have problems. More theoretical work and observations are needed due to the rather unexpected richness and complexity of exoplanetary systems.

3) Perhaps, a combination of these scenarios would eventually work. In particular, "Hot Jupiters" and "Warm Jupiters" may have been formed differently.

4) Our Solar System appears to be the exception rather than the rule. Note, however, that the ubiquity of similar systems may be underestimated due to observational bias towards systems containing massive objects at close orbits.

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