Interaction of free-floating planets with a star–planet pair

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Abstract The recent discovery of free-floating planets and their theoretical interpretation as celestial bodies, either condensed independently or ejected from parent stars in tight clusters, introduced an intriguing possibility. Namely, that some exoplanets are not condensed from the protoplanetary disk of their parent star. In this novel scenario a free-floating planet interacts with an already existing planetary system, created in a tight cluster, and is captured as a new planet. In the present work we study this interaction process by integrating trajectories of planet-sized bodies, which encounter a binary system consisting of a Jupiter-sized planet revolving around a Sun-like star. To simplify the problem we assume coplanar orbits for the bound and the free-floating planet and an initially parabolic orbit for the free-floating planet. By calculating the uncertainty exponent, a quantity that measures the dependence of the final state of the system on small changes of the initial conditions, we show that the interaction process is a fractal classical scattering. The uncertainty exponent is in the range (0.2–0.3) and is a decreasing function of time. In this way we see that the statistical approach we follow to tackle the problem is justified. The possible final outcomes of this interaction are only four, namely flyby, planet exchange, capture or disruption. We give the probability of each outcome as a function of the incoming planet’s mass. We find that the probability of exchange or capture (in prograde as well as retrograde orbits and for very long times) is non-negligible, a fact that might explain the possible future observations of planetary systems with orbits that are either retrograde (see e.g. Queloz et al. Astron. Astrophys. 417, L1, 2010) or tight and highly eccentric.

Keywords Planetary systems · Numerical methods · Planet exchange · Temporary capture
1 Introduction

The three-body problem has been a topic of active research since the seventeenth century, initially most of the effort focusing on bound solutions and their long time stability. This problem was “solved” through the work of (a) Poincaré (1993), who showed that the general solutions of even the simplest variant of the problem (apart from highly symmetric configurations), the restricted planar circular three-body problem, cannot be written in the form of convergent series, and (b) Marchal and Bozis (1982), who showed that in the general three body problem zero velocity curves do not exist, so that one of the bodies can always escape to infinity. However the “inverse” problem, i.e. the interaction of a body coming from “infinity” with a binary pair, has attracted less attention. From the astrophysical point of view, there are three distinctive special forms of this problem: (a) the binary members and the incoming body have similar masses (interaction of a “passing” star with a binary star), (b) the binary consists of a massive and a small body and the incoming body is massive (a passing star interacting with a planetary system) and (c) the binary consists of a massive and a small body and the incoming body is small (a passing planet interacting with a planetary system). The first two forms have already been discussed in the literature (e.g. see Boyd and MacMillan 1993; Mikkola 1994; Donnison 2008 for the first, Astakhov and Farrelly 2004 for the second). However the third one has attracted limited interest up to now (e.g. see Donnison 2006), probably because planets were considered always to be bodies revolving about stars. The discovery of free floating planets (FFPs) a few years ago changed this picture.

The initial report by Zapatero Osorio et al. (2000) on the observation of free-floating planets with masses $m_J < m < 3m_J$ (where $m_J$ is Jupiter’s mass) was regarded initially with scepticism, since it was not consistent with the generally accepted definition of a planet. However subsequent microlensing observations (Sumi et al. 2011) showed that celestial bodies with masses $m \approx m_J$ really do exist in the Milky Way, and for that in numbers exceeding those of its stars, making the interaction of FFPs with already existing planetary systems a noteworthy process. In any case, recent publications (e.g. see Adams et al. 2006; Malmberg et al. 2007) have shown that the probability of such an interaction is non-trivial within clusters of newborn stars, where a planet ejected from a young planetary system (or condensed independently) may remain within the cluster for long time intervals. In the present paper we study numerically the simplest possible model of such an interaction, namely a bound planet (BP) on circular orbit around a star, scattering a FFP approaching from “infinity” on a coplanar orbit.

The interaction of a FFP with an existing star–planet binary system has only four possible outcome states: the incoming body (a) goes to infinity, probably exciting the planet (flyby), (b) replaces in orbit around the star the BP, which in turn goes to infinity (exchange) (c) is captured by the star–planet binary system, forming a two-planet planetary system (temporary capture) or (d) the system is disrupted (disruption) (Fig. 1). If the initial total energy of the system is negative, as in our numerical experiments, the fourth outcome is ruled out and we are left with only three possible outcomes.

From the purely dynamical point of view, however, the situation is more complicated. The interaction can be distinguished into “single-” and “multiple-encounter” events. In a single-encounter event the FFP interacts only briefly with the BP (e.g. for a time interval less than one unperturbed period of the BP) while in a multiple encounter event the FFP enters in orbit around the star and interacts for an extended period of time with the BP (typically much more than one unperturbed period). Therefore a single encounter event can result only in flyby or exchange, which may be thought of as “direct” outcomes. To the contrary, a multiple encounter event (temporary capture) is not a “definitive” outcome, since after some time interval one