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Encounter flybys between two solar systems

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Abstract

Typical open clusters contain hundreds to thousands of member stars spanning a few parsecs [1]. In such an environment, the component stars may encounter one another at close distances. Here we study the close encounters that result in the capture of a planet by another planetary system. Capture occurs in 1/3 of encounters that remove a planet from the original star. The capture of a planet can lead to long-term destabilisation of the system. However, many captured planets can be retained on wide orbits for Gyr and may be observable as retrograde planets.

1. Introduction

Stars often form giant molecular clouds with tens to tens of thousands of siblings. Born out of these, open clusters can hold together for hundreds of millions of years. There, 10-20% of solar-type stars are expected to fly by another star within 100 au [2]. Such events strongly shape the planetary systems, e.g., planets can be ejected from a star or transferred from one star onto the other. In addition to the instantaneous disruption, an encounter may induce long-term instability in that though a planetary system is stable during the encounter, planet loss may still occur during the post-encounter evolution long afterwards [3].

In this work, we study the two effects in detail. Different from previous work, here we model the encounters between two solar systems. As such, the interplanetary interactions can be examined. Full details can be found in Li, Mustill and Melvyn [4].

2. Numerical simulations

Our simulation consists of two phases: (1) encounter and (2) post-encounter.

In (1), two solar systems, each of a Sun and the four giant planets, from Jupiter to Neptune, are encountering each other from random directions. We exclusively consider the encounters <100 au because only those may make instantaneous ejection and capture of planets [3]. The encounter velocity is 1 km/s, typical of young open clusters [5]. 5×10^3 such encounters are simulated, thus the number of planetary systems is 10^4. This phase is brief, lasting only 10^4 yr.

In (2), we track the long-term evolution of the planetary systems post-encounter. Particularly interested in the captured planets, we pick all the planet-capture systems and integrate them in isolation for 1 Gyr.

3. Results

Out of the 10^4 planetary systems, 3×10^3 immediately lose at least one planet during the encounter. Neptune, as expected, is the most vulnerable while Jupiter, deep down in the solar potential well, is the most resistant against the flyby. Many systems lose more than one planet, and as a result, a total of 5×10^3 planets are removed from these 3×10^3 systems. While most of those lost are directly ejected, turning into free floaters, a significant fraction, $\sim$ 1/3, i.e., 1.8×10^3 in absolute number, are captured by the encountering star. These planets are transferred to 1.4×10^3 systems, so a flying-by star can capture more than one planet.

Planet capture occurs in various ways. In Figure 1, we show how the number of planets of the planet-capture systems evolves.

There, each label consists of two numbers: the first has two digits, i.e., the number of the original planets and that of the captives while the second number shows the number of such systems observed in our simulations. Before the encounter, all 1390 systems have 4 originals and 0 captives, thus all being 40. During the encounter, all capture at least one planet. Most frequently, a system captures one planet not losing any of the originals and this happens over 400 times. The second most likely situation is that the loss of one original planet accompanies the capture, resulting in a configuration 31 at an occurrence rate of 283/1390=20%. In extreme cases, a full planet swap is realised in that a star loses all four original planets and captures all four from the encountering star; this is recorded 12 times.

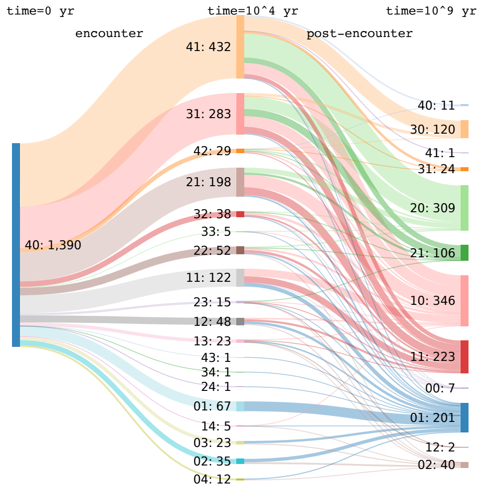

Figure 1: Evolution of number of the original and captured planets in each system (the first and the second digit of the first number of each label) and the number of such systems (the second number) during the encounter and during the post-encounter evolution. Here we only consider planet-capture systems.

However, capturing a planet does not mean keeping it. And in a similar sense, retaining a planet during the encounter does not guarantee its stability later. Our post-encounter phase simulations show that most of the captured planets, and a large fraction of the originals, are later lost owing to the interplanetary interactions. Take the system state 41 for example. Among 432 such systems, nearly 200 evolve to 20, meaning that they lose the captive as well as two originals. Only a few tens of such systems are able to keep the captive, ending up in, for example, 21 or 11.

The captured planets surviving the post-encounter evolution often have wide orbits decoupled from the inner planets. Their distribution in inclination is wide and prograde and retrograde orbits are similarly probable.

4. Summary

We have simulated flyby encounters between two solar systems. Concentrating on the close encounters <100 au, we show that $\sim 30\%$ of the systems immediately lose at least one planet during the encounter. About 1/3 of the planets lost from one system are captured by the other.

Post-encounter, we have picked all those planet-capture systems and further propagate them for 1 Gyr. We find that most of the captured planets are destabilised during this phase and also, a great extent of loss of the original planets is observed.

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