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The capture rate of free-floating planets in our galaxy

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Abstract

Free-floating planets were detected through direct imaging and microlensing surveys. However, their population remains a mystery due to detection limitations of such faint objects. It was proposed that planetary nebulae and supernova remnants may constitute a significant source of free-floating planets, as many of them exhibit outflows of planetary-mass gas blobs. With a large population of free-floating planets, the rate at which these planets get captured by planetary systems may be non-negligible. To evaluate this rate, we constructed a three-dimensional scattering simulation between a free floating planet and a star accompanied by a Jupiter-mass bound planet. We tested different masses of the free floating planets and stars, impact parameters, inclination angles and approach velocities. With the use of the resulting capture statistics, we analytically approximated the cross section of such captures, and predict that about one out of every 100 sub-solar stars are expected to experience a capture of a free-floating planet during their lifetime.

1. Introduction

Observations of nearby supernova remnants and planetary nebulae revealed outflows of thousands of high-speed and planetary-mass gas blobs [2, 5, 6]. Some of these blobs may escape into the interstellar medium (ISM), where they cool and slow down by accretion of interstellar ambient matter, and collapse if their mass reaches the Jeans mass. As a source for free-floating planets, we may expect hundreds of them per cubic parsec in our galaxy, that were originated through this mechanism [1] .

With a large population of free-floating planets wandering through the ISM, some may get captured by planetary systems, where they will not share the same characteristics that are inherited from the host star. Since free-floating planets can encounter planetary systems at different inclination angles, captured planets may explain a considerable fraction of the hot Jupiters whose orbital axis is misaligned with the spin axis of their host star.

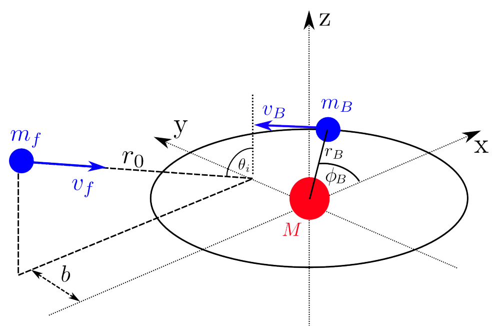

Figure 1: The scattering simulation involves a free floating planet m_f that approaches a star M accompanied by a Jupiter-mass bound planet m_B with a velocity v_f, inclination angle θ_i and impact parameter b. The bound planet orbits around the host star with a constant distance of r_B from the star.

2 Numerical Method

Our simulation is an extension of the work carried by Varvoglis et al. [7], which was restricted to coplanar scatterings. We included an unbound planet and star-planet binary, which are represented as point-mass objects. The free-floating planet approaches the binary with some initial velocity v_f and inclination angle θ_i, and interacts with a Jupiter-mass bound planet that is on a circular orbit of $r = r_B$ around the host star (see Fig 1). The dynamical system is described by a simple Lagrangian that includes the kinetic term of each body and the interaction terms between them,

$$\mathcal{L}_{kinetic} = \frac{1}{2}m_f v_f^2 + \frac{1}{2}m_B v_B^2$$
$$\mathcal{L}_{interaction} = G\frac{Mm_f}{r_f} + G\frac{Mm_B}{r_B} + G\frac{m_f m_B}{|\mathbf{r}_f - \mathbf{r}_B|}.$$

Simulations are performed for different inclination angles, masses, and approach velocities. 175 values of impact parameters (b) and 125 initial orbital phases of the bound planet (ϕ_B) are tested; a total of 21,700 runs for each simulation. Once the free-floater travels out approximately twice its initial distance from the star, the simulation stops, and the total energy of the free-floating planet (E_f) and the bound planet (E_b) is calculated. Captures ($E_f < 0, E_B < 0$), flybys ($E_f > 0, E_B < 0$) and exchange ($E_f < 0, E_B > 0$) are distinguished.

3 Results

The fraction of simulation runs that led to a capture (Fig 2), as a function of inclination angle, masses and the approach velocity, is used to construct an analytical approximation of the cross section. As received by Varvoglis et al. [7], about 50% of the coplanar simulation runs led to captures. This percentage drops as the approach velocity becomes higher and less aligned with the orbital plane of the bound planet.

Using our analytically approximated cross section, and assuming the predicted number densities of free-floating planets that originated from explosive death of stars, we evaluate that a capture will occur every ~ 200 years in our galaxy. Since low-mass stars have a longer lifetime and dominate the stellar population, most of the captures are expected to involve such stars. We estimate that $\sim 1\%$ of all $0.1M_\odot < M < 2M_\odot$ stars are expected to experience a capture during their lifetime.

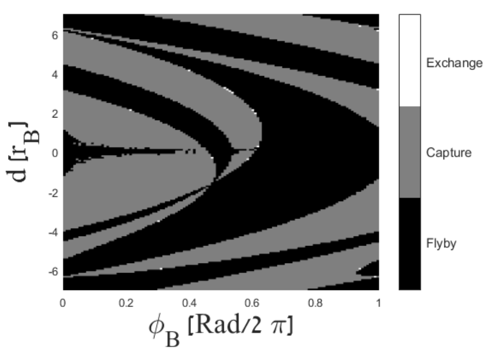

Figure 2: The outcomes of a coplanar scattering simulation between a Jupiter-mass free-floating and bound planets, and a solar-mass host star. Pixels correspond to different values of impact parameters of the free-floating planet and orbital phases of the bound planet.

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