GLOBAL ORBITAL INTEGRATION FOR TEMPORARY CAPTURE OF PLANETESIMALS BY A GIANT PLANET: IMPLICATION FOR THEIR SOURCE REGION

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Introduction: Gravitational interaction between planets and planetesimals plays an important role not only in planet formation but also in the origin and dynamical evolution of small bodies in the Solar System. When planetesimals encounter with a planet, in most cases they experience either gravitational scattering by the planet or collision onto it. However, in some cases planetesimals can be captured by the planet's gravity and orbit about the planet for an extended period of time, before they escape from the vicinity of the planet. This phenomenon is called temporary capture, and may have played an important role in the origin of irregular satellites and Kuiper-belt binaries, as well as dynamical evolution of short-period comets.

In most previous works on temporary capture or permanent capture with some energy dissipation, orbital stability of planetesimals in the vicinity of a planet was examined numerically. In these studies, orbital integration was started within or near the Hill sphere of a planet to study capture orbits. Although such orbital calculation started in the vicinity of a planet is suitable for the study of orbital stability around a planet, it is difficult to discuss relationship between temporary capture orbits and pre-capture heliocentric orbits based on such calculation. It is also difficult to evaluate the likelihood of such capture events from those numerical results.

Rates of temporary capture of planetesimals by a planet from heliocentric orbits can be obtained using three-body orbital integration [1, 2]. In the case of planetesimals initially on circular orbits [1], it was shown that planetesimals undergo a close encounter with the planet before they become temporarily captured. When planetesimals are scattered by the planet into the vicinity of one of periodic orbits around the planet, the duration of temporary capture tends to be extended. The rate of temporary capture was evaluated, and it was found that it increases with increasing semi-major axis of the planet, because the size of the planet's Hill sphere relative to its physical size increases with increasing distance from the sun.

Recently, we investigated temporary capture of planetesimals initially on eccentric orbits [2], and found that temporary capture orbits can be classified into four types. Their orbital size and direction of revolution around the planet change depending on planetesimals' initial eccentricity and energy. When initial eccentricity is so small that Kepler shear dominates relative velocity between planetesimals and the planet, temporary capture typically occurs in the retrograde direction in the vicinity of the planet's Hill sphere, while large retrograde capture orbits outside the Hill sphere are predominant for large eccentricities. Long prograde capture occurs in a very narrow range of eccentricity and energy of planetesimals. We obtained rates of temporary capture of planetesimals and found that the rate of long capture increases with increasing eccentricity at low and high eccentricity but in intermediate values of eccentricity decreases with increasing eccentricity.

In the above study [2], we performed three-body orbital integrations under Hill's approximations, where the masses of the planet and planetesimals are assumed to be much smaller than the solar mass. In this case, the effect of the curvature of their guiding-center orbits are neglected. This assumption is valid for the case of low mass planets, but the effect of curvature may be important for temporary capture by a high mass planet, like Jupiter. Previous global orbital integration that investigated temporary capture focused on long-term evolution of small bodies under the influence of multiple giant planets [3, 4].

In the present work, we use a simple three-body system that consists of the Sun, a planet, and a test particle, and perform global orbital integration to examine effects of a high mass planet on temporary capture.

Numerical Method: We examine temporary capture using three-body orbital integration. When the masses of planetesimals are much smaller than the other two bodies' masses and the planet orbits about the Sun in circular orbit, the problem of motion of planetesimal is called restricted three-body problem. We integrate equations of motion for planetesimals with various initial orbital elements, using the forth-order Hermite integrator.

In previous works [1, 2], the duration for temporary capture $T_{\rm cap}$ was defined by the time interval between a planetesimal's first passage of the x-axis and its last passage of the same axis during an encounter, where (x, y, z) is the local coordinate system centered on the planet and rotating with it. We also adopt this definition in the present work.

We calculate the number of revolutions around the planet during temporary capture, and we call it the winding number N_w [e.g. 1-3]. When a planetesimal crosses the x- or y-axis in the prograde direction around the planet (e.g. when it crosses the $y > 0$ part of the y-axis from the region with $x > 0$ to $x < 0$), 0.25 is added to N_w, while the same amount is subtracted from N_w when it crosses the axes in the retrograde direction. Finally, after the planetesimal's last passage of the x-axis, N_w is re-defined by its integer part, so that it represents the number of revolutions around the planet. If N_w is positive (negative), temporary capture is called prograde (retrograde).

We also define the signed mean orbital period $\mathcal{T}_\mathrm{m}$ about the planet during temporary capture as $\mathcal{T}_\mathrm{m} = T_\mathrm{cap}/N_\mathrm{w}$, where $\mathcal{T}_\mathrm{m}$ is positive or negative, depending on the sign of N_w. Numerical results of previous works [1, 2] suggest that planetesimals with initially on heliocentric circular orbits are captured into orbits in the vicinity of the planet's Hill sphere with a short mean orbital period ($|\mathcal{T}_\mathrm{m}| < T_\mathrm{K}$, where T_K is the planet's orbital period), while those initially on eccentric orbits can be captured into orbits outside of the Hill sphere with $|\mathcal{T}_\mathrm{m}| \simeq T_\mathrm{K}$.

Results: We found four types of capture orbits by our present global integration (Fig. 1), as we did in our local three-body integration [2]. The orbital shapes in the case of capture in the vicinity of the planet (Figs. 1(a)-1(c)) are consistent with those found in our previous work [2]. However, the shape of temporary capture orbits which revolves outside of the planet's Hill sphere (Fig. 1(d); this was called type-E orbits in [2]) was found to be bent due to the effect of the curvature of the guiding-center orbits. On the other hand, the other three types of capture orbits are located in the vicinity of the planet, thus the effect of the curvature was negligible. The size of the region swept by the planetesimal trajectory during temporary capture increases with increasing mass of the planet; thus the above curvature effect becomes significant when the size of temporary capture orbits is comparable to the planet's orbital radius. Therefore, this curvature effect needs to be taken into account when we examine the source region for planetesimals that undergo temporary capture by a giant planet. We will discuss the rates of temporary capture obtained by our global calculation and compare them with our previous results of local three-body calculation.

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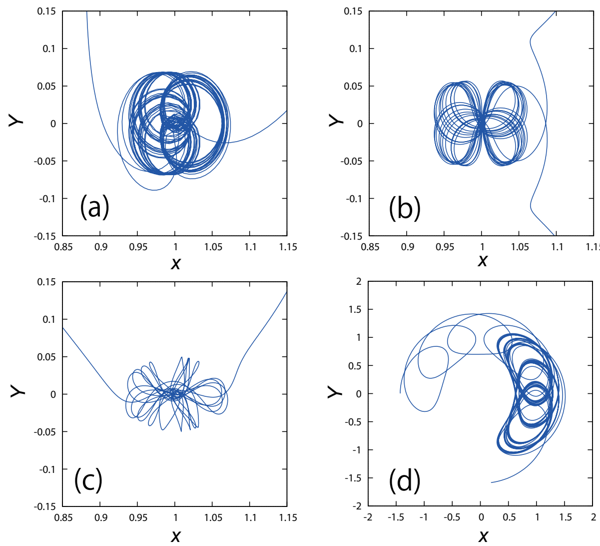

Figure 1: Example of temporary capture from heliocentric eccentric orbits obtained by global orbital calculation. These figures show planetesimals' orbits on a coordinate system that rotates with the planet. Values of the coordinates are expressed in units of the planet's semimajor axis. The planet is located at $(X, Y) = (1, 0)$, which is the center of Panels (a) to (c). The Sun is located at $(X, Y) = (0, 0)$, which is the center of Panel (d).

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