# On the Orbital Evolution of Planetary Embryos Under the Influence of Giant Planet Scattering

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**Introduction:**

Many of observed extrasolar planetary systems have planets with orbital characteristics significantly different from our Solar System. Among such characteristics is large orbital eccentricities of giant planets, which suggests that they underwent dynamical instabilities after their formation. Systems with two planets are known to be stable if their separation is large enough, but those with three or more planets undergo dynamical instability, and the time required for the onset of the instability depends on the masses and initial orbital separation of the planets [1]. When the masses of the planets are large, the instability would lead to even ejection of one of the planets, leaving other two planets on rather eccentric orbits [e.g., 2, 3]. This ”jumping Jupiter” model has been offered as an explanation for the origin of the so-called eccentric planets in extrasolar planetary systems.

Such dynamical instabilities of giant planets should inevitably influence dynamics of smaller bodies in the system, i.e., planetesimals and planetary embryos in the stage of planet formation, or even already-formed terrestrial planets in the system [e.g. 4-7]. During and immediately after the dynamical instability of the giant planets, planetesimals or planetary embryos initially in orbits interior to these giant planets tend to be almost entirely thrown into the central star. This is caused by a rapid increase of these small bodies' eccentricities mainly by secular resonances caused by the scattered giant planets [5, 7]. Most of small bodies initially placed in orbits exterior to the giant planets tend to be ejected from the system through interactions with the scattered giant planets, but some of these bodies initially in the outer part of the system also collide with the central star [7].

In previous numerical simulations investigating such giant planet instabilities and their effects on small bodies, it is often assumed that any body whose perihelion distance ($q$) became less than $0.1 \sim 0.2$AU eventually collides with the central star, thus bodies are removed immediately when $q < 0.1$AU (or 0.2AU) is satisfied [e.g. 6, 7]. If small bodies are in secular resonance with giant planets on stable orbits, such small bodies' eccentricities would monotonically increase and thus their perihelion distances would monotonically decrease; in this case, the above assumption would be a reasonable one. However, in systems of giant planet scattering where the orbits of the perturbing giant planets are still evolving, locations of their secular resonances are expected to change, thus influences on small bodies would also change.

In the present work, we investigated orbital behavior of test particles under the influence of three giant planets that undergo dynamical instability. We focus on orbital evolution of small bodies whose perihelion distances become rather small ($\mathcal{O}(q) \sim 0.1$AU) due to interactions with the scattered giant planets.

**Numerical Method:**

We performed orbital integration for systems of three giant planets and test particles. We use the fourth-order Hermite integrator with hierarchical individual time steps. The giant planets have Jupiter mass, and both the giant planets and test particles are placed initially on circular orbits with small orbital inclinations. The giant planets are initially placed in a marginally unstable configuration, and test particles are initially placed on orbits both interior and exterior to the giant planets. Unlike the assumption adopted in some of the previous works as mentioned above, we continue orbital integration even when $q < 0.1 \sim 0.2$AU. Particles are regarded as colliding with the central star only when their distance from the central star became smaller than the solar radius ($4.65 \times 10^{-3}$AU). We did not take into account effects of tidal interaction with the central star in the present work.

As shown by previous works, secular resonances with the giant planets play an important role in orbital evolution of test particles in systems considered here. The locations of secular resonances can be calculated from the masses and semi-major axes of the giant planets, and values of forced eccentricities at these resonances can be calculated also using eccentricities of the giant planets in addition to their masses and semi-major axes. Thus, from the masses, semi-major axes, and eccentricities of the giant planets, we can calculate ranges of semi-major axes of test particles where significant increase in their eccentricities can be expected due to secular resonances. We use results of such calculation to select initial semi-major axes of test particles, and also to analyze results of our orbital integration.

**Results:**

We found that most of test particles initially placed in orbits interior to the giant planets eventually hit the central star, similar to the results of the previous works [5, 7]. Figure 1 shows the evolution of semi-major axis, eccentricity, and perihelion distance of a test particles, which eventually hit the central star. Evolution of the semi-major axes of the three giant planets are also shown. We can see that effects of secular resonance increase the test particle's eccentricity while keeping the change in its semi-major axis rather small, resulting in rapid increase in its perihelion distance. Similar orbital evolution was observed for most of test particles initially placed in orbits interior to the giant planets; they experience rapid increase (decrease) in eccentricity (perihelion distance) and eventually collided with the central star. In this example shown in Fig.1, the test particle first experienced a period with $q < 0.1$AU at $t \simeq 1.1 \times 10^5$ years, but $q$ became large again after this period. Then, it experienced periods where its perihelion distance became smaller than 0.1AU several times, before it finally hit the central star.

Figure 2 shows an example of a test particle initially placed in orbits exterior to the giant planets. The perihelion distance of this one also became smaller than 0.1AU a few times at around $t \simeq 4 \times 10^5$ years. However, in this case, the particle did not collide with the central star before the end of the simulation. These results show that orbital behavior of small bodies under the influence of giant planet scattering is rather complicated, thus we need to be cautious in adopting criterion for collision with the central star.

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**References:**
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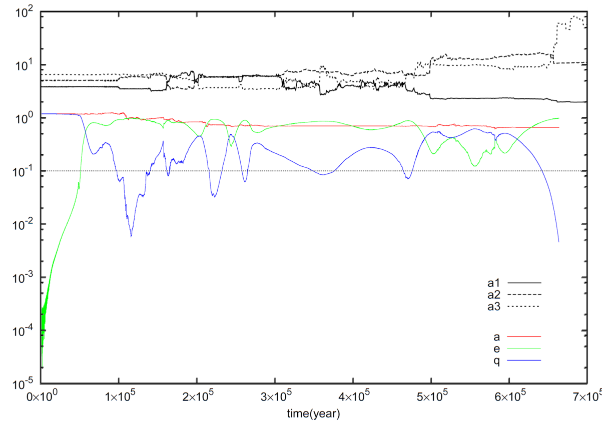


Figure 1: Evolution of orbital elements of a test particle. Semi-major axis ($a$), eccentricity ($e$), and perihelion distance ($q$) are shown with red, green, and blue lines, respectively. Note that $a$ and $q$ are shown in units of AU. Semi-major axes of the three giant planets are also shown with black solid, dashed, and dotted lines. The horizontal line at 0.1AU represents the minimum perihelion distance below which particles were regarded as colliding with the central star in some of previous works. The initial semi-major axes of the giant planets were $a_1 = 3.85$AU, $a_2 = 5$AU, and $a_3 = 6.5$AU, and the initial semi-major axis of the test particle was $a = 1.2$AU.

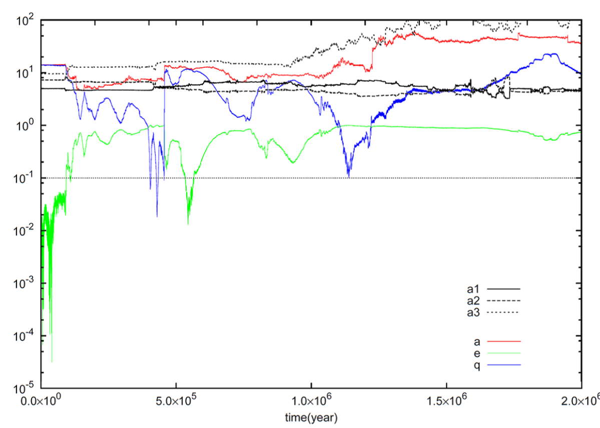


Figure 2: Same as Figure 1, but a test particles was initially placed in orbits exterior to the giant planets. The initial semi-major axes of the giant planets were $a_1 = 5$AU, $a_2 = 7.25$AU, and $a_3 = 9.5$AU, and the initial semi-major axis of the test particle was $a = 14$AU.