Effect of Gravitational Scattering by a Large Captured Body on the Stability of Jupiter's Trojan Asteroids

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Introduction: The Trojan asteroids orbit the Sun about the L4 and L5 Lagrangian points of Jupiter. These objects have a wide range of eccentricities and inclinations, and are thought to be captured planetesimals. Since the origin of the Trojan asteroids is expected to provide clues to the dynamical evolution of the planets and small bodies in the Solar System, various models have been proposed, e.g., capture due to gas drag from the solar nebula, capture during Jupiter's mass growth, or capture during smooth migration of Jupiter. However, such models failed to reproduce some important characteristics of the present Trojan asteroids, such as the total mass of the Trojans, the distribution of orbital elements, or the distribution of the libration amplitudes. On the other hand, recent models for the formation of the Solar System suggest that the giant planets likely experienced significant radial migration and orbital instability after their formation [1, 2]. Studies of capture of Trojan asteroids based on such models of giant planet migration (i.e., the "Nice model" and the "Jumping Jupiter model") show that icy planetesimals (or KOBs) originally in the outer Solar System can be captured into Jupiter's Trojan regions, and the present total mass as well as the observed orbital characteristics of the Trojan asteroids can be explained in such models [3, 4].

However, in such studies of capture of the Trojan asteroids, planetesimals were treated as test particles, thus gravitational interactions between planetesimals are not taken into account. Also, effects of mutual gravity among asteroids are also neglected in the studies of the stability of the Trojan asteroids after their capture into the Lagrangian points [e.g., 5]. Although effects of gravitational interactions between sufficiently small asteroids may reasonably be neglected, there may have been significantly large objects in the original swam of Trojan asteroids immediately after their capture. In the above-mentioned recent models of capture, Trojan asteroids likely originated from the outer region of the Solar System, including the Kuiper belt. Among the current KBOs, there are many objects that are much larger than the largest of the present Trojans, some of them being as large as 1,000km across in diameter. If such a large body is captured into the Trojan regions even temporarily, it may have a significant influence on the stability of other Trojan bodies, and some of them would be scattered out of the Trojan regions.

In the present study, we assume that a large body was captured into Jupiter's Trojan region, and examine its dynamical influence on other Trojan asteroids using orbital integration.

Method: We assume that a putative large body was captured in the Trojan region around the L4 Lagrangian point of Jupiter, and examine orbital evolution of other asteroids in the L4 Trojan region by orbital integration. Because of the dynamical symmetry, we focus on the case of asteroids about the L4 Lagrangian points. We assume that other asteroids in the Trojan swarm are much smaller than the above-mentioned captured large body, thus they are treated as test particles, neglecting their gravitational influence on other bodies. On the other hand, previous studies show that perturbation from the giant planets other than Jupiter tends to destabilize the orbits of Trojan asteroids, and we have confirmed results of the previous study [5] by performing orbital integration including perturbation from the other three giant planets but without a large captured body in the Trojan swarm. However, in the rest of our calculations, we do not include effects of the other three giant planets, in order to focus on the effect of a putative large captured body. Thus, we perform orbital integration for the four-body problem for the Sun, Jupiter, a large body, and an asteroid.

Because of the gravitational influence of the large body, orbits of the Trojan asteroids would become unstable and be scattered out of the Trojan region. Using orbital integration, we examine the lifetime of Trojans before they become unstable and are removed from the Trojan region about the L4 Lagrangian point. In this case, the lifetime was found to depend on the initial phases of the Trojan asteroid and the large body. Thus, we examined 30 cases with different initial phases, and calculated the mean value of the lifetime. Orbital integrations are terminated when one of the following three conditions is met: (i) the asteroid escapes from the co-orbital region; (ii) the asteroid collides with the large body or Jupiter; or (iii) integration time exceeds five billion years. The dynamical lifetime is obtained when the asteroid satisfies the above conditions (i) or (ii).

The current Trojan asteroids have values of the libration amplitude D ($\equiv \delta\lambda_{max} - \delta\lambda_{min}$; $\delta\lambda$ is the difference in the mean longitudes of Jupiter and a Trojans) about the L4 point approximately ranging from 0^{o} to 80^{o} [5]. Thus, we study cases with various values of the initial libration amplitudes for Trojans asteroids and the large body, and examine the dependence of the dynamical lifetime of the asteroids on these values. We also examine cases of various masses of the large body (10^{23}-10^{26}g) to see how the stability of asteroids depends on the mass of the large body. Also, we examine two cases for the initial orbital elements (eccentricity e_L and inclination i_L) of the large body: In Case 1, the large body is initially on a circular orbit, i.e., e_L=0, i_L=0, and in Case 2, it has non-zero eccentricity and inclination, approximately corresponding to the observed maximum values for the present Trojan asteroids. Asteroids are assumed to be on non-inclined circular orbits initially.

Results: Figure 1 shows examples of orbital evolution of two Trojan asteroids that were initially placed in the L4 region of Jupiter and move under the gravitational effects of the Sun, Jupiter, and the large body. We confirmed that these Trojans are stable for five billion years in the absence of the large body. The pink curve shows the orbit of the Trojan that escaped from the co-orbital region after a close encounter with the large body, while the blue curve denotes that of the Trojan that escaped after experiencing a close encounter with Jupiter. Even in the latter case, the gradual increase in the libration amplitude that eventually lead to the escape of the body from the Trojan region was caused by gravitational interaction with the large body. Thus, gravitational interaction with the large body is essential for the occurrence of the orbital instability.

Figure2 shows instability time in the case where the large body is fixed at Jupiter's L4 point (i.e., D=0º for the large body). In Case1, orbits of all the asteroids in the Trojan region became unstable within 10^7 years when the mass of the large body is equal to or larger than 10^{23}g. We found that instability time becomes shorter with increasing mass of the large body. As for the dependence on the libration amplitude of the asteroids, the instability time becomes slightly shorter when the asteroid's amplitude is close to that of the large body, but overall the dependence on D was found to be rather weak. We confirmed similar tendency in other case with different values of the libration amplicude of the large body. Therefore, it seems that the instability time depends on the libration amplitudes only weakly.

On the other hand, the duration before the onset of instability significantly increases in Case2 ($e_L \neq 0$, $i_L \neq 0$). This is because the frequency of close encounters with the large body becomes significantly lower in the case of inclined orbits. From the results of our present calculations, we can derive constraints on the mass of bodies existed in the Trojan swarm in the past.

References:

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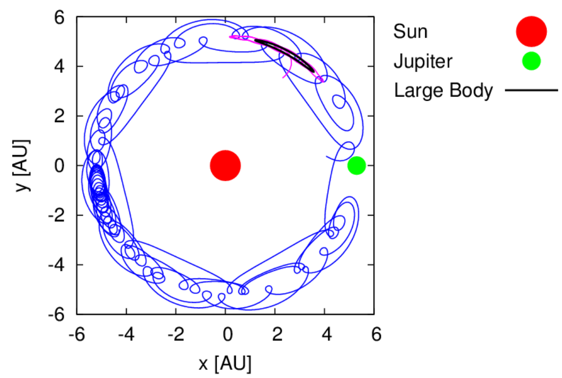

Figure 1: Examples of orbital evolution of asteroids under the gravitational incluence of the Sun, Jupiter, and a large body in the L4 region. The pink and blue lines denote the asteroid orbits. Mass of the large body is 10^{26}g, its initial libration amplitude D is 30º, and the asteroids initially have D = 40º.

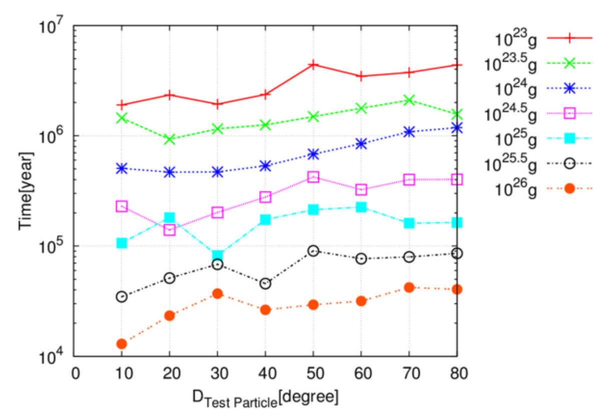

Figure 2: Duration before the onset of instability for the orbit of Trojan asteroids due to gravitational influence of the large body as a function of the libration amplitude of the asteroid. Several cases with different values of the mass of the large body are shown. The large body's D is fixed to be zero.