TEMPORARY CAPTURE OF ASTEROIDS BY A PLANET: DEPENDENCE OF PROGRADE/RETROGRADE CAPTURE ON ASTEROIDS' SEMIMAJOR AXES.
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Introduction: Irregular satellites around giant planets are small satellites with elliptical and inclined orbits (e.g., [1,2]). They have relatively large (planetocentric) semimajor axes. Because of their orbits, they are usually thought to be captured passing asteroids rather than formed *in situ*. In some cases, when the velocity of an asteroid relative to the planet is relatively low, it is temporarily trapped in the planetary Hill sphere. The trapped body must eventually exit the Hill sphere. But, if some energy loss (e.g., tidal dissipation, drag force from a circumplanetary disk when it existed, or collisions with other solid bodies in the disk) affects the asteroid's orbit, it can be permanently captured afterward. Many studies on the origins of irregular satellites have been published (e.g., [3-9]). However, they mainly used numerical orbital integrations in the restricted three-body problem or more complex framework. In this study, we approximate a circular three-body problem (Sun-planet-asteroid) into a combination of two independent two-body problems (Sun-asteroid and planet-satellite), identifying the asteroid with the satellite, and derive the relation between the pre-capture heliocentric orbit and the planetocentric orbit at the moment of capture. We derive analytical formulae with simple assumptions and show that the formulae reproduce the results of orbital integrations very well. The analytical formulae reveal the intrinsic dynamics that regulates the relation between the heliocentric and planetocentric orbital elements. In particular, we show a clear dependence of prograde vs. retrograde capture of Jupiter's irregular satellites on the heliocentric semimajor axes of the original asteroids.

Derivation of Analytical Formulae for Temporary Capture: We use four conditions for temporary capture. We split a circular three-body problem (Sun-planet-asteroid) into two independent two-body problems (Sun-asteroid and planet-asteroid), identifying the asteroid with the satellite. We use the relative velocity between the asteroid and the planet in heliocentric orbits as a satellite velocity orbiting around the planet (condition 1) at the L_1 or L_2 Lagrangian point of the planet, which is a Hill radius away from the planet on the x-axis (condition 2). Entering the zero-velocity surface that surrounds the planet via the L_1 or L_2 points provides the easiest access to planetocentric orbits in the restricted three-body problem. Additionally, we set two other conditions to make the derivation simpler: we assume that the body's position at the moment of transition from heliocentric motion to planetocentric motion, (i.e., the L_1 or L_2 point) is the aphelion or perihelion of the heliocentric orbit (condition 3). Condition 3, which implies that the relative radial velocity is zero, leads to the condition that the body has its apocenter or pericenter on the planetocentric orbit at L_1 or L_2 (condition 4). An apocenter at L_1 or L_2 corresponds to a planetocentric orbit within a Hill radius from the planet. A temporary capture does not always start with such a tightly bound orbit, so we relax the condition to having either an apocenter or pericenter at L_1 or L_2. The four conditions give one to one relation between the heliocentric orbit and the planetocentric orbit after the capture. The details of the derivation and the validity of the assumptions confirmed by numerical integrations are given in Higuchi and Ida 2016 [10].

Results: Figure 1 shows the relation between the heliocentric semimajor axes, inclinations, and the planetocentric eccentricities for temporary capture by Jupiter via the L_1 (top) and L_2 (bottom). The parameter κ is defined by $1\text{-}e_s$ at planetocentric apocenter and $1+e_s$ at planetocentric pericenter, where e_s is the planetocentric eccentricity. Applying $\kappa=2$ as the upper limit of the temporary capture, the ranges of heliocentric semimajor axes a and inclination i that allow the temporary capture by Jupiter are $3.6 < a < 10.2$ AU and $i < 9.6$ deg, respectively. Figure 2 shows the relation between the heliocentric semimajor axes and the planetocentric inclination for L_1 and L_2 captures for several heliocentric inclinations. For the middle a range near the semimajor axis of Jupiter (i.e., $4.2 < a < 6.2$ AU), the distribution is dominated by retrograde orbits, whereas the a range on both sides of it (i.e., $a < 4.2$ AU and $a > 6.2$) is dominated by prograde orbits. The results suggest that, in Jupiter's case, the retrograde irregular satellites likely originated as Trojan asteroids and the majority of the prograde irregular satellites are from far inner regions such as main-belt asteroids. This is consistent with the recent observations of irregular satellites and Trojan asteroids of Jupiter ([11-13]).

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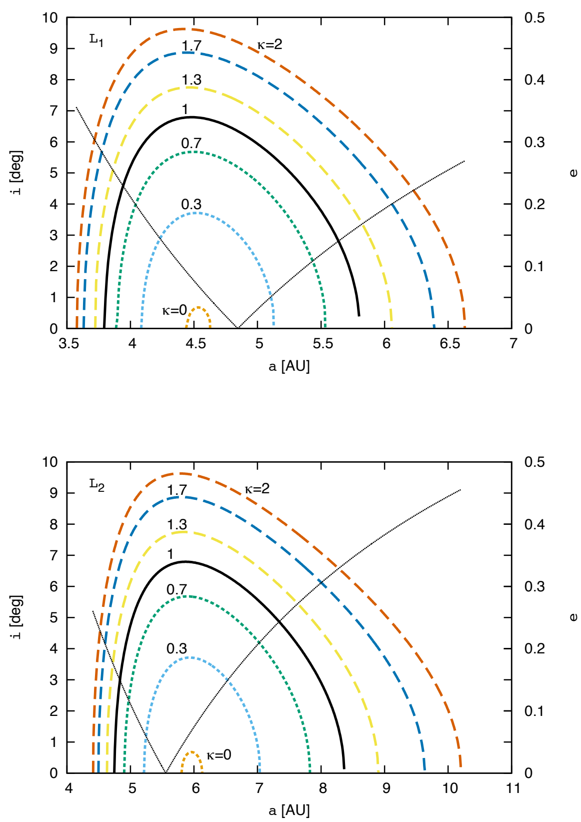

Figure 1: Solutions to the analytical formulae on the a-i plane for various κ. The upper and lower panels are for L_1 and L_2 capture, respectively. The numbers labeled on the curves represent the values of κ. The eccentricity e given for each a by condition 3 is also plotted against the secondary (right) y-axis (thin dashed curve).

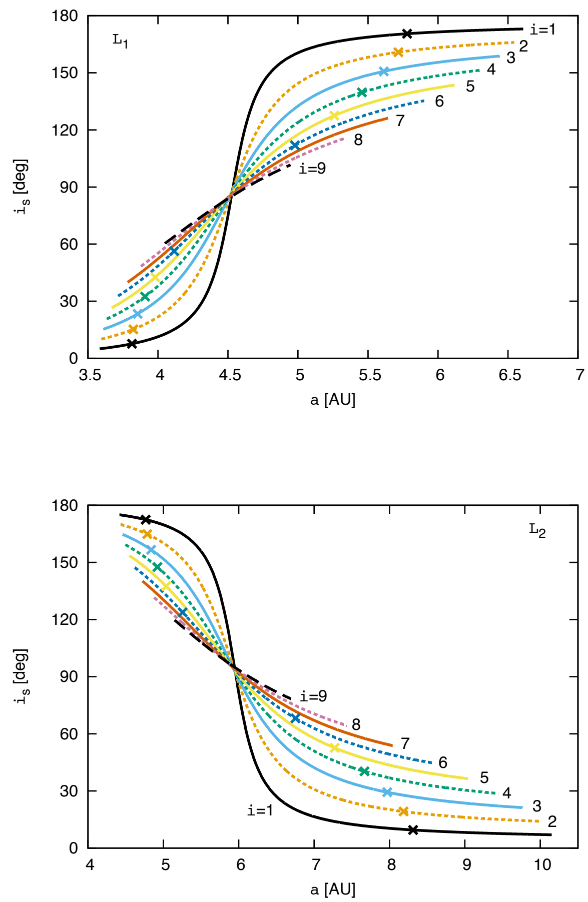

Figure 2: Planetocentric inclination i_s as a function of heliocentric semimajor axis a for various heliocentric inclinations i, given by the analytical formulae. The upper and lower panels are for L_1 and L_2 capture, respectively. The numbers labeled on the curves represent the values of i. Two crosses in each curve show the points of $\kappa = 1$ capture. The solutions between the two crosses on each curve correspond to $\kappa < 1$ capture.