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Jupiter's Metastable Companions

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Abstract

Jovian co-orbitals share Jupiter's orbit and exhibit 1:1 mean-motion resonance with the planet. This includes >10,000 so-called Trojan asteroids surrounding the leading (L4) and trailing (L5) Lagrange points, viewed as stable groups dating back to planet formation. A small number of extremely transient horseshoe and quasi-satellite co-orbitals have been identified, which only briefly (<1,000 yr) exhibit co-orbital motions. Via an extensive numerical study, we identify for the first time some Trojans that are certainly only "metastable"; instead of being primordial, they are recent captures from heliocentric orbits into moderately long-lived (10 kyr–100 Myr) metastable states that will escape back to the scattering regime. We have also identified (1) the first two Jovian horseshoe co-orbitals that exist for many resonant libration periods and (2) eight Jovian quasi-satellites with metastable lifetimes of 4–130 kyr. Our perspective on the Trojan population is thus now more complex as Jupiter joins the other giant planets in having known metastable co-orbitals that are in steady-state equilibrium with the planet-crossing Centaur and asteroid populations; the 27 identified here are in agreement with theoretical estimates.

Unified Astronomy Thesaurus concepts: Jupiter trojans (874); Celestial mechanics (211); N-body simulations (1083)

1. Introduction

The five famous Lagrange points of the circular restricted three-body problem are locations relative to the moving planet where objects have tiny relative accelerations. In particular, the "triangular" L4 and L5 Lagrange points are located 60° ahead of and behind the planet along its orbit, and small bodies can oscillate for long durations back and forth around these points. The L4/L5 stability was initially a theoretical discovery, which was followed by the first Trojan detections in 1906 (Nicholson 1961; Shoemaker et al. 1988) but now include more than 10,000 cataloged members; these >10,000 Trojans are viewed as stable populations that date back to planet formation.

Twenty-five years ago, Levison et al. (1997) computed the stability of the first 270 Jupiter Trojans on their nominal orbits, showing that some Trojans may leave in the next 0.3–4 billion yr; that study assumed all Trojans were primordial and that any recent departures were due to a combination of collisions and dynamical erosion, allowing some primordial Trojans to leak away at the current epoch. Here we will demonstrate the additional importance of recent temporary (metastable) captures into and out of co-orbital states on the shorter timescales of tens of kyr to Myr.

Most planets are now known to host temporary co-orbital companions (reviewed in Greenstreet et al. 2020 and Alexandersen et al. 2021), defined as objects undergoing oscillation (libration) of their 1:1 resonant argument for timescales much shorter than the age of the solar system before escaping the resonance; for direct orbits, the resonant argument is simply the angle between the mean longitudes of the objects and planet. In addition to Trojans, co-orbital motion can be of the horseshoe type (when the small body passes through the direction 180° away from the planet and motion encloses both the L4 and L5 points). Like Trojan motion, horseshoe orbits were predicted analytically but are in most cases very unstable (Rabe 1961). No long-term stable horseshoe sharing a planet's solar orbit has ever been observed. Lastly, in the frame corotating with Jupiter, so-called "quasi-satellites" have orbits that maintain large-distance motion encircling the planet (Wiegert et al. 2000).

Restricting our attention to the giant planets, Uranus and Saturn do not have L4 and L5 points stable for 4 Gyr (Nesvorny & Dones 2002). Nevertheless, a metastable Uranian L4 Trojan (Alexandersen et al. 2013) and a metastable Saturnian horseshoe orbit (Alexandersen et al. 2021) are known; "metastable" objects are here defined by undergoing many resonant argument librations before exiting the co-orbital state. Neptune's L4 and L5 points have long-term stability, but both stable and metastable Neptune Trojans are known (Horner & Lykawka 2012; Lin et al. 2021). Curiously, Jupiter has been the sole giant planet to have no known metastable co-orbitals, despite the expectation that the planet should host such a population (Greenstreet et al. 2020).

Planet-crossing small bodies can (rarely) find their way into co-orbital states, and numerical simulations can estimate both the steady-state fraction relative to the current planet-crossing population and the expected distribution of temporary-capture timescales (see Discussion). Because Jupiter is constantly being approached by objects originating in the outer solar system (Centaurs, which become Jupiter-family comets), and given the estimated number of Jupiter-encountering Centaurs, Greenstreet et al. (2020) calculated that the metastable capture fraction was high enough that metastable Jovian co-orbitals should exist and trapping would generate all of Trojan, horseshoe, and quasi-satellite motions. Examples of all of these types will be illustrated in our results below (see Figure 1).

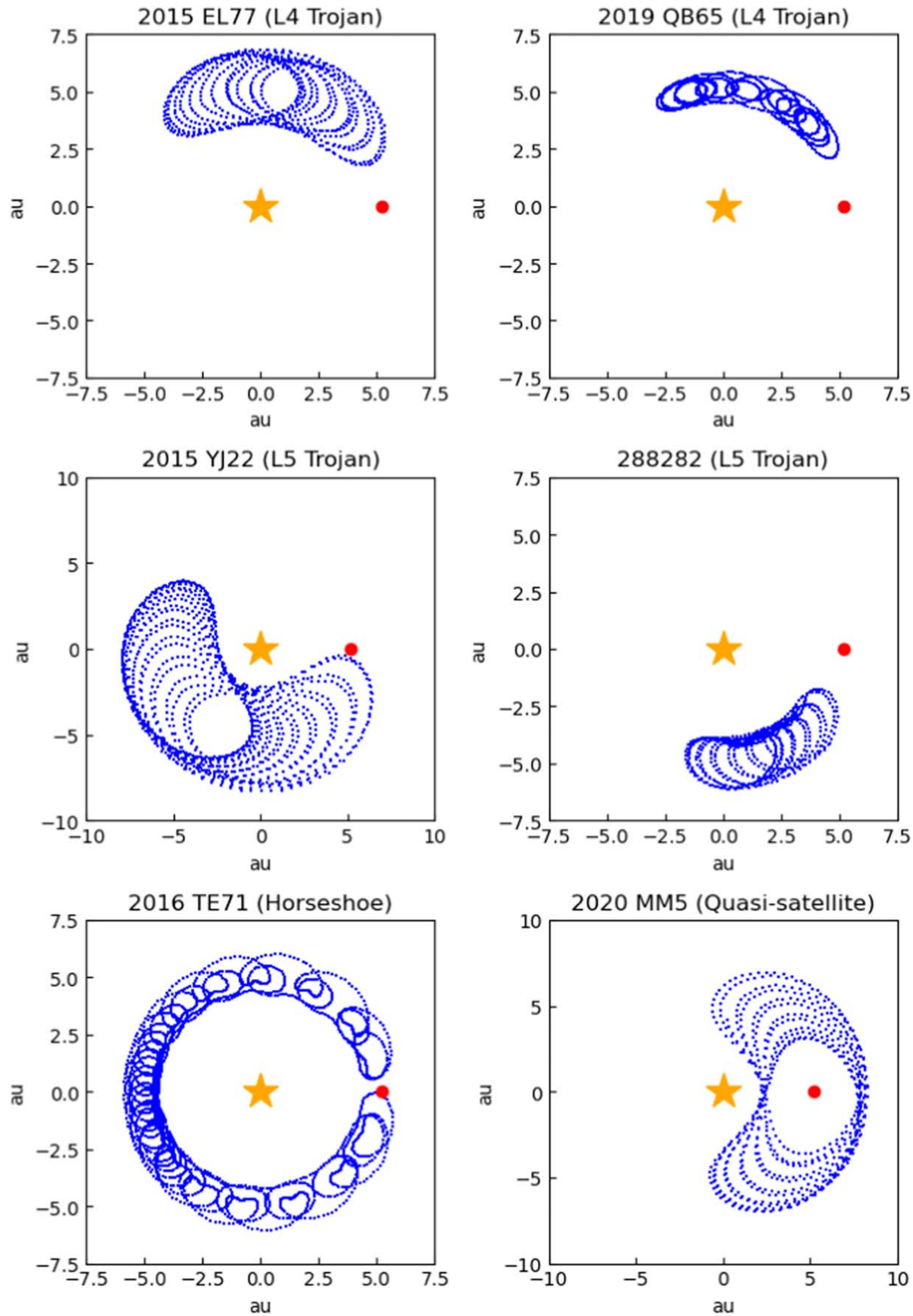

Figure 1. Forward-integrated motion of six example metastable Jovian co-orbitals identified in our analysis. Each object's motion is shown in the heliocentric reference frame corotating with Jupiter (red dot) for a single resonant libration period, which are roughly as follows: 2015 EL77 (L4): 165 yr; 2019 QB65 (L4): 175 yr; 2015 YJ22 (L5): 250 yr; 288282 (L5): 145 yr; 2016 TE71 (HS): 480 yr; and 2020 MM5 (QS): 145 yr. Note the different axis scales for each object.

There has been a great deal of work studying the complex problem of co-orbital companions (Christou 2000; Beauge & Roig 2001; Karlsson 2004; Wajer & Krolikowska 2012; Morais & Namouni 2013a, 2013b; Wiegert et al. 2017; Morais & Namouni 2019; Di Ruzza et al. 2023); these studies have either been done in the context of a simplified problem (one planet, sometimes on a circular orbit) or for timescales that are only slightly longer than the resonant libration period (of hundreds of years) or did not explore the range of behaviors and timescales possible due to the orbital uncertainties. Our work pushes the sample size and the level of the model detail much further by using full *N*-body simulations, exploring timescales covering thousands of resonant libration periods, and utilizing large numbers of "clones" drawn from the orbital uncertainty region for determining the robustness of the resonant states; we also study the entire population of known objects with semimajor axes near that of Jupiter (nearly 12,000 objects). As a result, we have identified not only the first such metastable (2–13 kyr) Jovian horseshoe orbits but also the first known set of Jovian Trojans that are metastable on intermediate timescales of 0.01–30 Myr and must be recently captured into L4 or L5 motion, increasing the complexity of how we should view the Jupiter Trojan population.

2. Methods

2.1. Production of Sample Set and Dynamical Integrations

To produce the sample set for this study, we queried the JPL Horizons Small Body Database Browser[4] for objects fitting the following constraints: 4.5 au $\leqslant a \leqslant$ 5.9 au (semimajor axis a within twice Jupiter's Hill sphere radius); the semimajor axis uncertainty, *a-sigma*, is defined; and the observational arclength, *data-arc span*, is defined and is >30 days. Because we focus our study on searching for temporary co-orbital behavior among the Jupiter Trojans, which exclude objects that show evidence of cometary activity (i.e., objects classified as Jupiter-family comets), we then manually removed all cometary provisional designations. In 2022 August, this resulted in a sample set containing 11,581 known objects in the near-Jupiter region with arc lengths of at least 30 days to ensure the orbital uncertainty was small enough to confidently be used to determine each object's orbital stability in the 1:1 co-orbital resonance with Jupiter.

We then used the Small Body Dynamics Tool (SBDynT)[5] to query the JPL Horizons Small Body Database Browser to obtain the orbit and covariance matrix of each small body in our sample set, including for the best-fit orbit and 999 clones of each object within the orbital uncertainty region. This produced a set of 1000 "clones" (best-fit orbit and 999 clones) for each of our 11,581 objects, totaling ≃11.6 million state vectors. For more details on how our sample set is produced, see Appendix A.1 below.

To date, we have numerically integrated the 1000 clones for *all* of the 11,581 objects for 0.5 Myr into the future using the SWIFT-RMVS4 package (Levison & Duncan 1994). We included the planets Venus–Neptune, adding Mercury's mass to that of the Sun. In the planetary input files, we expanded Jupiter's radius by 1000x and turned on the "lclose" exit condition in SWIFT to remove particles from the integrations when they come too close to Jupiter. In this study of the current 1:1 co-orbital resonant behavior of objects with $a \simeq a_J$, any particle that comes within 1000x Jupiter's radius (≃0.48 au, or about 2 Hill spheres) of the planet is unlikely to remain stable in the resonance, and we terminate its integration. We use a base time step of 3.7 days and an output interval of 1000 yr. Particles are removed from the integrations when they get within 0.4 au or beyond 19.0 au from the Sun or too close to Jupiter as described above; the inner heliocentric distance of 0.4 au allows us to study the 1:1 Jovian co-orbital behavior of highly eccentric ($e \sim 0.9$) objects with $a \simeq a_J$, and the outer distance limit, while larger than is needed for objects with $a \simeq a_J$, is consistent with the outer limits used in Greenstreet et al. (2020). We are currently continuing to integrate all ≃11.6 million state vectors for longer time periods with the goal of eventually reaching 4 Gyr.

3. Results

We used the numerical integrations of the observationally derived orbits and 999 clones within the orbital uncertainty region (≃11.6 million state vectors) to search for semimajor axis oscillation around Jupiter's value of 5.20 au as well as resonant argument libration for periods of time long enough (>1 kyr) to distinguish transient co-orbital capture or non-resonant behavior from primordial Trojan stability (Alexandersen et al. 2013, 2021; Greenstreet et al. 2020). This calculation required approximately 20 CPU years on a Beowulf cluster at the University of British Columbia. Details of the methods used for co-orbital detection, resonant island classification, and determination of resonant sticking timescales can be found in Appendix A.2 and A.3.

We securely identify the transient co-orbitals and nonresonant objects in the sample of 11,581 objects in the "near-Jupiter population" (i.e., semimajor axes $a = 4.5$–5.9 au, within ≃2 Jovian Hill sphere radii of Jupiter's a_J). We classify objects as belonging to one of the following dynamical classes based on their fraction of resonant clones and resonant timescales: "Trojans," "transients," "nonresonant," or "insecure" (see Figure 2 caption, Appendix A.2 and A.3, and Table 3 for details). Figure 2 shows the semimajor axis versus eccentricity distribution of the sample of near-Jupiter objects along with our classifications. The "Trojans" (objects for which ⩾95% of the 1000 clones remain in the 1:1 Jovian resonance for 0.5 Myr) are deemed long-term stable and have not been integrated beyond this timescale; in the future, we will extend these integrations to 4 Gyr to study the stability of these objects on solar system timescales. All other objects ("transient," "nonresonant," and "insecure") have been integrated for timescales long enough that all 1000 clones have left the resonance; these integration timescales range from a few hundred years for the nonresonant objects to up to ~2 Gyr for the transient co-orbitals. We note that some "transient" or "insecure" objects can become trapped in the 1:1 resonance multiple times during the integrations. We base our classifications on the start of the integrations (i.e., the current time) and do not discuss (rare) multiple resonant traps in this paper.

Among the near-Jupiter sample, we have identified 27 objects (Table 1), which we are confident are *not* primordial objects. Instead, they are almost certainly recently captured as Jupiter co-orbitals that remain metastable for timescales of 10^3–10^8 yr. While each of these 27 objects share a commonality with the primordial Trojans by their presence in the 1:1

[4] https://ssd.jpl.nasa.gov/tools/sbdb_query.html
[5] https://github.com/small-body-dynamics/SBDynT

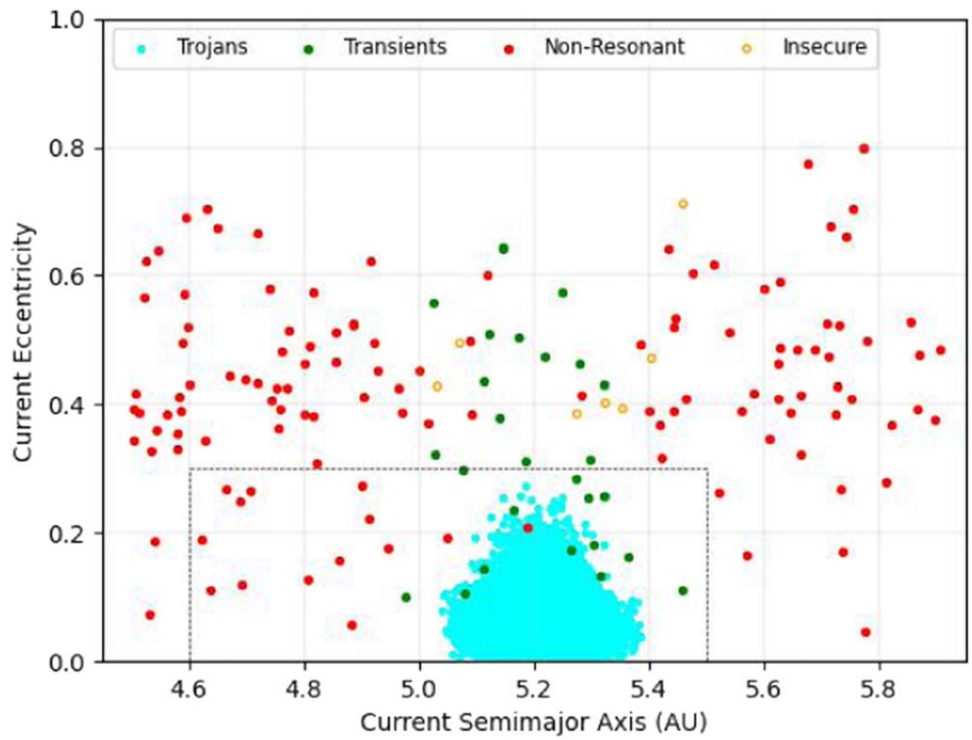

Figure 2. Osculating semimajor axis vs. eccentricity for the 11,581 objects with $a \simeq a_J = 5.20$ au that we classify with numerical integrations. The 11,423 "Trojans" (cyan) are objects for which ⩾95% of their 1000 clones remain in 1:1 Jovian resonance for 0.5 Myr. The 27 "transients" (green) have ⩾95% of their clones remain resonant for ⩾1 kyr but then leave the resonance (see Table 1). The 124 "nonresonant" (red) objects have ⩾95% of their 1000 clones ejected from the resonance in <1 kyr (see Table 5). The seven "insecure" (orange) objects have 5%–95% of their 1000 clones remain in the resonance for ⩾1 kyr before escaping (i.e., these objects would likely move to either "nonresonant" or "transient co-orbitals" upon further improvement of their orbital uncertainties; see Table 4). The dashed rectangle shows the a, e region that JPL Horizons and the Minor Planet Center (personal communication, Peter Vereš) currently define as the "Jovian Trojan" parameter space; the 14 nonresonant objects in this box (listed in Table 5) are not Trojans, however, given that ⩾95% of their 1000 numerically integrated clones are ejected from the resonance in as little as tens or hundreds of years. The 27 metastable transients (green) have a larger range of semimajor axes, eccentricities, and inclinations (see Figure 4 for the semimajor axis vs. inclination and eccentricity vs. inclination projections) than the stable Trojans (cyan); objects can become temporarily bound to the resonance along its borders that stretch beyond the stable L4/L5 regions (cyan).

Table 1
Classifications of Metastable Jovian Co-orbitals

Classification	Members				
L4 Trojan	163240	2010 AQ134	2010 VT278	2014 EJ166	**2015 EL77**
	2015 HF178[a]	2015 HX159	2017 PC52	**2019 QB65**	2020 RL50
	2020 RO89	2020 SN84	…	…	…
L5 Trojan	**288282**	613709	**2015 YJ22**[a]	2018 BE7	…
Horseshoe	2015 OL106	**2016 TE71**	…	…	…
Quasi-satellite	241944[b]	363135[b]	526889[b]	2003 WG133	2004 AE9[b]
	2017 SN215	2018 UH25	**2020 MM5**[b]	…	…
Retrograde	**514107**	…	…	…	…

Notes. Objects in bold are shown in Figures 1 and/or 3. Table 2 provides the resonance escape timescales for these 27 objects.
[a] Over the next 600 yr, Di Ruzza et al. (2023) classified 2015 HF178 as a Trojan (as we do) and 2015 YJ22 as a horseshoe (which we classify as a L5 Trojan), but we follow their orbital evolutions much longer and show that these objects leave the resonance and are not primordial.
[b] Wajer & Krolikowska (2012) and/or Di Ruzza et al. (2023) classified 241944, 363135, 526889, 2004 AE9, and 2020 MM5 as current quasi-satellites; Wajer & Krolikowska (2012) integrated the nominal orbits of 241944 and 526889 for ∼10 kyr and identified their transient nature in the resonance and classified 353135 and 2004 AE9 as long-lasting quasi-satellites remaining stable for >10 kyr. By studying longer timescales, we find the median resonant lifetimes for the 1000 clones of each of these five objects to be 20–130 kyr.

Jovian mean-motion resonance, they are unique in their much shorter resonant stability timescales that can only mean that they are recent captures into the co-orbital population and are thus required to be placed in a category of Jovian co-orbitals separate from the primordial Trojans.

First, we identify 12 L4 and 4 L5 Trojans (four of which are shown in Figures 1 and 3) that are surely unstable on timescales much shorter than ever previously discussed (only ∼Gyr timescales are discussed in Levison et al. 1997). The median timescales over which these metastable Trojans escape the resonance range from 1 kyr–23 Myr (Table 2); however, their observational uncertainties result in instability timescales that vary by an order of magnitude or more, as evidenced by the range in escape times of each object's 1000 clones (see Figure 3). This rapid departure means these 16 L4/L5 metastable Trojans cannot be members of the primordial

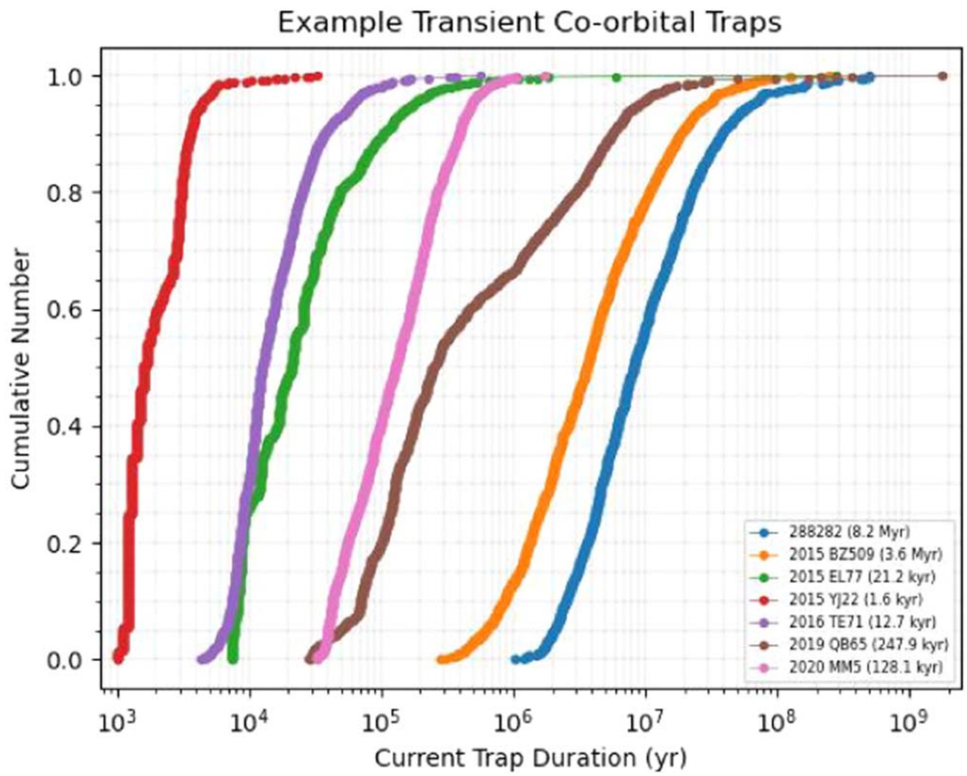

Figure 3. Cumulative distribution for the resonance escape times for the 1000 clones of seven selected transient Jovian co-orbitals. The number in parentheses after each designation is the median resonant timescale for each object's current trap in the 1:1 resonance. For the full list of resonant sticking timescales for each of our 27 identified metastable Jovian co-orbitals, see Table 2.

population that is departing today but must be recent metastable captures.

To date, no transient horseshoe co-orbitals of Jupiter have been identified to librate in the resonance on timescales of more than a couple hundred years (long enough for the object to experience several libration periods), despite the expectation that they should exist among the metastable Jovian co-orbital population (Greenstreet et al. 2020). We have here identified the first two known metastable horseshoes of Jupiter: 2015 OL106 and 2016 TE71. The latter provides the first known example of a real object that remains in horseshoe motion with Jupiter for dozens of libration periods and resembles historical predictions of Jovian horseshoe behavior (Rabe 1961). 2016 TE71 is shown in Figures 1 and 3.

Altogether, our metastable identifications include 12 L4 Trojans, 4 L5 Trojans, 2 horseshoes, 8 quasi-satellites, and the retrograde Jovian co-orbital (514107) Ka'epaoka'āwela 2015 BZ509. We note that a handful of these objects have been previously classified (Karlsson 2004; Wajer & Krolikowska 2012; Di Ruzza et al. 2023) based on their dynamical behavior over the next few hundred to couple thousand years (see captions for Tables 1, 4, and 5); differences between previous shorter-timescale classifications and the longer metastable timescale classifications presented here are discussed below. Figure 1 shows the forward-integrated motion for a single libration period for six metastable object examples.

A unique aspect of our work is to determine the timescales over which these objects (and the clones representing their orbital uncertainty) will eventually escape the resonance. To determine their metastable timescales, we extended each object's integrations until all 1000 clones were removed (most often for getting too close to Jupiter). The cumulative distributions for the resonance escape times for the 1000 clones of each of the six objects shown in Figure 1 are given in Figure 3. This figure also presents our measurement of the instability timescale for the retrograde co-orbital (514107) with a median value of 3.6 Myr; Wiegert et al. (2017) estimated that the object remained in the near-Jupiter region for a lower limit of at least 1 Myr, while Namouni & Morais (2020) estimated a median lifetime of 6.5 Myr for the object to escape the solar system or collide with the Sun. The examples shown in Figure 3 depict the range in metastable resonant sticking timescales (10^3–10^8 yr or longer) we have identified so far. Table 2 contains the full list of resonant sticking timescales for each of our 27 identified metastable Jovian co-orbitals. For more details on the determination of the resonance escape timescales, see Appendix A.3.

4. Discussion

After the identification of asteroid (514107) as a retrograde Jovian co-orbital (Wiegert et al. 2017), these are the first securely identified metastable Jovian co-orbitals for which the resonant sticking timescales have been established. While other groups (Beauge & Roig 2001; Karlsson 2004; Wajer & Krolikowska 2012; Di Ruzza et al. 2023) have identified resonant behaviors of some of these objects, those analyses do not extend beyond the next ∼1–10 kyr nor do they utilize large numbers of clones drawn from the orbital uncertainty region for determining the certainty of a resonant classification. We confirm the current nonresonant and quasi-satellite classifications for a handful of objects (see Tables 1 and 5). However, our analysis is largely unique in identifying the transient nature of these objects by determining the timescales over which they

Table 2
Resonant Island Configuration and Resonance Escape Timescales for Our 27 Identified Metastable (10^3–10^8 yr) Jovian Co-orbitals

Designation	JPL Class	Island	Min. Trap (kyr)	Median Trap (kyr)	Max. Trap (Myr)
(163240) 2002 EM157	Trojan	L4	1928	22,915	>200[a]
(241944) 2002 CU147	Asteroid	QS	11.5	79	4.5
(288282) 2004 AH4	Trojan	L5	1031	8192	>500[a]
(363135) 2001 QQ199	Asteroid	QS	8.4	59	3.7
(514107) 2015 BZ509	Asteroid	R	281	3606	247
(526889) 2007 GH6	Asteroid	QS	9.8	44	1.6
(613709) 2007 RK185	Asteroid	L5	1.2	1.2	0.006
2003 WG166	Asteroid	QS	6.3	45	3.3
2004 AE9	Asteroid	QS	14.5	19	0.8
2010 AQ134	Asteroid	L4	12.5	102	3.7
2010 VT128	Asteroid	L4	48.9	136	1.9
2014 EJ166	Trojan	L4	1.2	7	1.8
2015 EL77	Trojan	L4	7.4	21	285
2015 HF178	Asteroid	L4	5.5	9	1.1
2015 HX159	Trojan	L4	1080	8704	>200[a]
2015 OL106	Trojan	HS	1.7	2	0.5
2015 YJ22	Asteroid	L5	1.0	2	0.03
2016 TE71	Trojan	HS	4.4	13	0.6
2017 PC52	Trojan	L4	1.8	2	0.2
2017 SN215	Asteroid	QS	1.9	4	0.5
2018 BE7	Trojan	L5	5.9	25	2.2
2018 UH25	Asteroid	QS	3.6	27	2.2
2019 QB65	Trojan	L4	28.5	248	1818
2020 MM5	Asteroid	QS	33.0	128	1.8
2020 RL50	Trojan	L4	104.8	995	634
2020 RO89	Trojan	L4	25.9	116	134.2
2020 SN84	Trojan	L4	1.0	5	0.6

Note. Objects we classify as "transient" have ⩾95% of their 1000 clones librate in the 1:1 Jovian resonance for at least 1 kyr and are then ejected from the resonance (green points in Figures 2 and 4). Current resonant island configurations are classified as L4 Trojan, L5 Trojan, horseshoe (HS), quasi-satellite (QS), or retrograde (R) motion. Min., median, and max. trap durations refer to the amount of time the 1000 clones for each of these objects remain trapped in the 1:1 Jovian resonance before being ejected. Objects in bold are shown in Figures 1 and/or 3.
[a] (163240) 2002 EM157, (288282) 2004 AH4, and 2015 HX159 have 46, 4, and 41 clones, respectively, still resonant at the end of 200, 500, and 200 Myr integrations, respectively.

(and the clones representing their orbital uncertainty) will eventually escape the resonance.

We find a number of resonant classifications that differ from previous studies (Beauge & Roig 2001; Karlsson 2004; Wajer & Krolikowska 2012; Di Ruzza et al. 2023); these objects are noted in Tables 1, 4, and 5. Note that Di Ruzza et al. (2023) include many objects in their analysis having arc lengths of ⩽5 days, which we omit given our requirement that objects have arc lengths >30 days to ensure their orbital uncertainty regions are determined by the observations rather than dominated by orbit fitting assumptions. We additionally require resonant objects to librate in the 1:1 for at least 1 kyr in order to experience several libration periods before possible departure from the resonance (in the case of the transient captures). This is responsible for the classification differences for the objects that we classify as nonresonant that other studies find are resonant during the <1 kyr timescales they use (e.g., Di Ruzza et al. 2023 provide classifications based on 600 yr integrations). In addition, we integrate each object's 1000 clones until all the clones have been removed from the integrations, which allows us to securely classify each co-orbital as transient in nature and determine the timescales over which they are stable in the resonance. This differs from the majority of the previous studies, which can only determine if an object is currently resonant but not how long it will remain resonant or the fact that observational uncertainties can result in instability timescales that vary by an order of magnitude or more (see Figure 3).

We expect the number of transient co-orbitals and primordial Trojans among the 11,581 object sample to shift as we continue to integrate the 1000 clones for time periods longer than 0.5 Myr. Very long-lived resonant objects unstable in $\lesssim$1 Gyr (i.e., long-lived temporary captures) will become evident in longer integrations, shifting some objects from "Trojan" to "transient co-orbital" classification. This will then meld into the few long-known Jupiter Trojans unstable on Gyr timescales, which was suggested (Levison et al. 1997) to be due to a combination of long-term dynamical erosion and collisions.

Our perspective is thus now more complex. The Jupiter co-orbital population consists of a mix of objects with different resonant timescales that we very loosely divide into the following categories: extremely transient ($\lesssim$1 kyr), metastable (10 kyr–100 Myr), primordial Trojan erosion (∼Gyr), and stable Trojans (longer than 5 Gyr solar system timescales). Cases of extremely transient objects, which only last one (or a few) resonant libration periods, have been studied (for example, Beauge & Roig 2001; Karlsson 2004; Wajer & Krolikowska 2012; Di Ruzza et al. 2023). Here we have shown for the first time that Jupiter joins the other giant planets by having recently trapped co-orbitals that last for an enormous range of metastable timescales (10 kyr–100 Myr) consistent with the transient co-orbital populations of all the giant planets. At the very longest timescales, only Jupiter and Neptune harbor both stable Trojan swarms and Trojans whose current stability timescales are of order Gyr. These latter objects can be a combination of the longest-lived traps of Centaurs and the slowly eroding edges of the original primordial population. The metastable objects we identify in this paper, however, must be recently captured into the co-orbital state out of the planet-crossing Centaur population, with a possible (probably small) contribution from escaping main-belt asteroids (Greenstreet et al. 2020).

A preliminary examination of the (sparse) color data from the Sloan Digital Sky Survey (Sergeyev & Carry 2021) for the faint metastable co-orbitals identified here shows that, relative to most known Trojans (Szabo et al. 2007) and the Lucy flyby targets, the objects 2016 TE71 (metastable horseshoe), (288282) 2004 AH4 (metastable L5 Trojan), and (163240) 2002 EM157 (metastable L4 Trojan) have evidence for redder photometric $g-r$ and/or $g-i$ optical colors than typical Trojans. This would be expected if they are recently trapped Centaurs.

The metastable co-orbitals identified here thus represent the discovery of the first (curiously missing) Jovian members of the expected transient co-orbital population accompanying each giant planet (Alexandersen et al. 2013; Greenstreet et al. 2020; Alexandersen et al. 2021). Numerical simulations of the

Centaur and escaped asteroid populations, both of which can become temporarily trapped into 1:1 Jovian resonance, allowed Greenstreet et al. (2020) to compute the steady-state fractions present in the Jovian co-orbital population at any given time. Given the number of absolute magnitude $H < 18$ (sizes of order 1 km) near-Earth objects and Centaurs (Lawler et al. 2018), Greenstreet et al. (2020) estimated that there should be $\sim$1–100 metastable Jovian co-orbitals that remain resonant on timescales of $\lesssim$10 Myr. Here we identify 27 metastable Jovian co-orbitals, all of which have $H < 18$, that remain stable for timescales of 10^3–10^8 yr, in agreement with the theoretical estimate.

More metastable Jovian co-orbitals will certainly be telescopically detected; given the rarity of capture into co-orbital resonance, these additional co-orbitals are likely to be small, which is partly the reason more have not been identified to date by current surveys. The upcoming Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), with its large aperture and magnitude depth, should increase the number of Jupiter Trojan detections by $\sim$25x (LSST Science Collaborations 2009). These fainter detections will also provide more objects currently in metastable traps with Jupiter; their identification as metastable, however, will require more than simple osculating element cuts in semimajor axis and eccentricity near Jupiter's values, as our extensive numerical study has demonstrated (see Figures 2 and 4).

The Lucy spacecraft mission will visit five Trojans during 2027–2033 (Levison et al. 2021). We have carefully integrated these Trojans for 50 Myr to study their stability in the 1:1 Jovian resonance. We find that all 1000 clones for each of these five mission targets remain stable in the resonance over this timescale and thus are almost certainly primordial objects.

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Appendix
Details on Dynamical Integrations

A.1. Sample Set Production

After querying the JPL Horizons Small Body Database Browser[6] to obtain the 11,581 near-Jupiter objects in our sample set and then using the SBDynT[7] to obtain the best-fit orbit and 999 clones within the orbital uncertainty region of each object, the SBDynT then queries Horizons for the value of *GM* associated with each orbit and converts the best-fit and clone Keplerian orbits to heliocentric Cartesian positions and velocities. This produced a set of 1000 "clones" (best-fit orbit and 999 clones) for each of our 11,581 objects, totaling $\simeq$11.6 million state vectors. Each object's set of 1000 clones were for a non-user-determined epoch associated with the Horizons-generated covariance matrix for a given object. In order to generate a set of planetary positions and velocities to be used for numerically integrating each object's clone set, we then used the SBDynT to obtain the heliocentric position and velocity of Venus–Neptune at the corresponding epoch from JPL Horizons via its web API request.

A.2. Co-orbital Detection and Resonant Island Classification

In order to distinguish transient co-orbital capture (or even entirely nonresonant behavior) from primordial Trojan stability, we used a 1 kyr running window to search for semimajor axis oscillation around Jupiter's $a_J = 5.20$ au, as well as resonant argument libration. Similar to the requirements used in Greenstreet et al. (2020) and Alexandersen et al. (2013, 2021), a particle's average semimajor axis must remain within 0.2 au of a_J, and no individual semimajor axis value may differ by more than 0.65 au from a_J within the 1 kyr window, if the object is to be considered resonant during that 1 kyr time period. Objects for which <5% of the 1000 clones are resonant for at least a single 1 kyr time period are classified as "nonresonant." These include the 14 MPC/JPL-classified "Trojans" we find for which $\geqslant$95% of the 1000 clones leave the near-Jupiter region in as little as tens or hundreds of years, which are clearly *not* long-term stable resonant L4/L5 primordial Trojans. We also identify another 110 asteroids and Centaurs that are currently not in co-orbital resonance with Jupiter (see Tables 3 and 5 and Figures 2 and 4).

Objects for which $\geqslant$95% of the 1000 clones are resonant for the duration of the 0.5 Myr integration are classified as long-term stable "Trojans." We identify 7482 L4 Trojans and 3941 L5 Trojans (11,423 Trojans in total) among our 11,581 object sample set. Objects that have $\geqslant$95% of their 1000 clones resonate for at least 1 kyr but then leave the resonance are classified as "transient co-orbitals." To date, we have identified 27 metastable Jovian co-orbitals (see Table 2 and Figures 2 and 4). We further classify the metastable co-orbitals by their resonant argument ($\phi_{11} = \lambda - \lambda_J$, where λ is the object's mean longitude and λ_J is that of Jupiter) behavior as L4 or L5 Trojans (ϕ_{11} remains in the leading or trailing hemisphere, respectively, during a 1 kyr running period), horseshoes (ϕ_{11} crosses the direction 180° away from Jupiter at any time during a window interval), or quasi-satellites (all other objects since these must cross between the leading and trailing hemispheres at $\phi_{11} = 0°$ instead of 180°; Alexandersen et al. 2013; Greenstreet et al. 2020; Alexandersen et al. 2021). Among our 27 identified metastable co-orbitals, we find 12 L4 Trojans, 4 L5 Trojans, 2 horseshoes, 8 quasi-satellites, and the retrograde co-orbital (514107) Ka'epaoka'āwela 2015 BZ509 (see Table 3).

A minor shortcoming of using a running window for diagnosing co-orbital behavior is that the end of each resonant object's current trap may not be well identified due to the end of the window not falling entirely within the trap. Additionally, the resonant island classification algorithm described above can produce erroneous classifications, in particular for co-orbitals

[6] https://ssd.jpl.nasa.gov/tools/sbdb_query.html
[7] https://github.com/small-body-dynamics/SBDynT

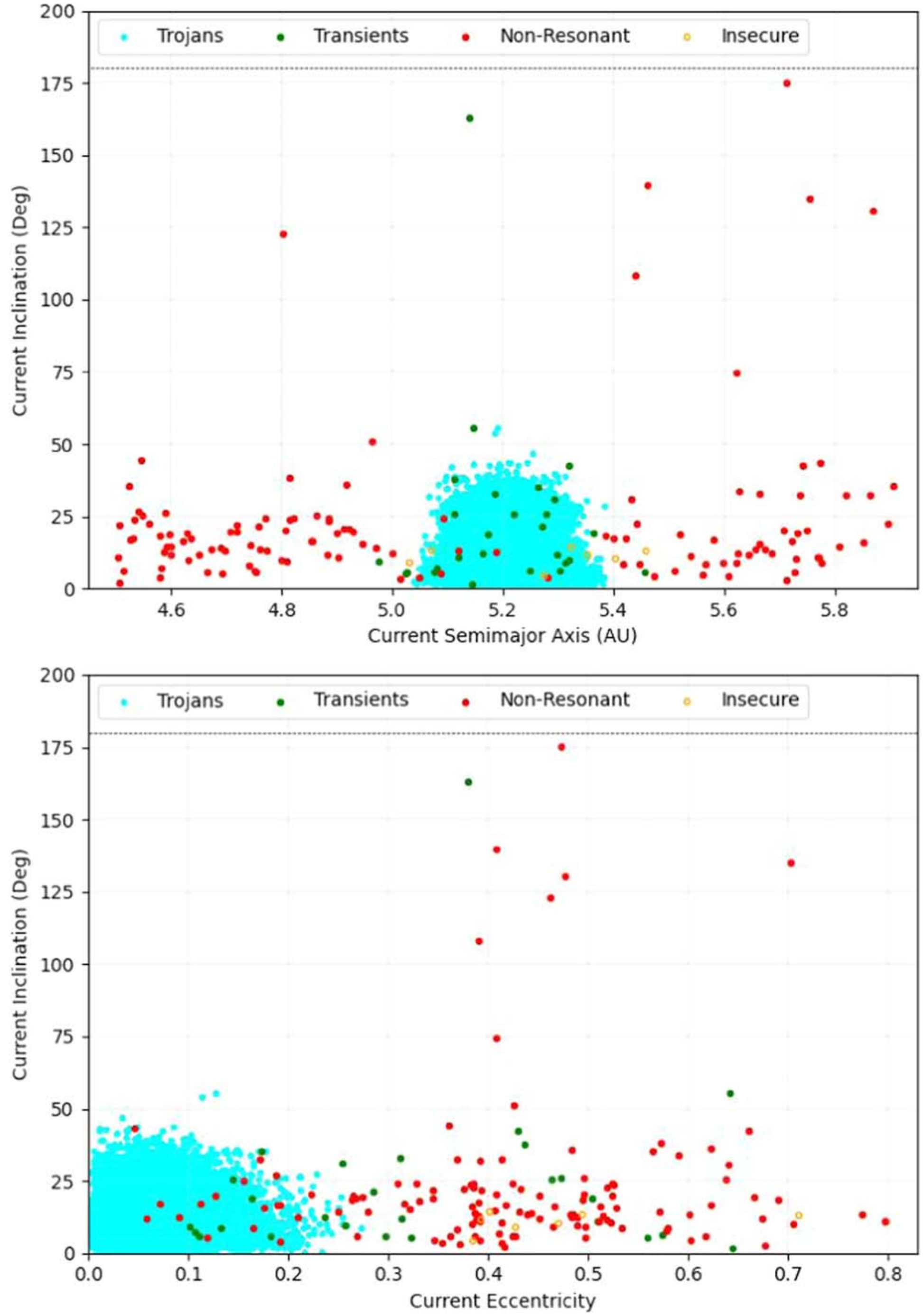

Figure 4. Heliocentric semimajor axis vs. osculating J2000 inclination (top) and eccentricity vs. inclination (bottom) for the 11,581 objects with $a \simeq a_J$ and their 1:1 Jovian resonant classifications (similar to Figure 2).

with large-amplitude librations that encompass Lagrange points not typically associated with their resonant state (e.g., large-amplitude Trojans whose librations cross either the leading or trailing hemisphere at $\phi_{11} = 180°$ or 0°) or those that (rarely) transition to libration around another resonant island (e.g., a Trojan transitioning to a horseshoe). However, our algorithms are adjusted to account for these minor shortcomings (Alexandersen et al. 2013; Greenstreet et al. 2020; Alexandersen et al. 2021), and these errors affect <10% of cases upon manual inspection of dozens of objects and their clones, including careful examination of the resonant behavior of the 27 metastable Jovian co-orbitals we have identified among our 11,581 object sample set.

Lastly, objects for which 5%–95% of their 1000 clones remain resonant for at least a single 1 kyr running window period are classified as "insecure." Upon further improvement of their orbital uncertainties, these objects would likely move from an "insecure" classification to either "nonresonant" or "transient co-orbitals." We identify seven "insecurely" resonant objects among our sample set of 11,581 near-Jupiter objects; each of these seven objects are classified by the MPC/JPL as asteroids (see Tables 3 and 4 and Figures 2 and 4).

Table 3
Number of Objects in Our 11,581 Near-Jupiter Object Sample Given Each Resonant Classification

Resonant Configuration	Number of Objects
Transients	**27**
L4 Trojans	12
L5 Trojans	4
Horseshoes	2
Quasi-satellites	8
Retrograde	1
Nonresonant	**124**
Trojans	14
Asteroids/Centaurs	110
Insecure	**7**
Asteroids/Centaurs	7
Trojans	**11,423**
L4 Trojans	7482
L5 Trojans	3941
Total	**11,581**

Table 4
Objects We Classify as "Insecure," i.e., 5%–95% of Their 1000 Clones Remain Resonant for ⩾1 kyr and Then Leave the Resonance

Designation	JPL Class	Transient Clones	Max. Trap Duration (Myr)
(32511) 2001 NX17[a]	Asteroid	534	1.1
2009 BM124	Asteroid	115	0.002
2012 BL173	Asteroid	804	0.24
2013 GE26	Asteroid	633	0.29
2013 VB17	Asteroid	910	0.42
2014 DB64	Asteroid	77	0.28
2016 VS10	Asteroid	76	0.32

Note. These objects would likely move to either "nonresonant" or "transient co-orbitals" upon further improvement of their orbital uncertainties (orange points in Figures 2 and 4). The number of transient clones that remain trapped in the 1:1 Jovian resonance for ⩾1 kyr and then leave the resonance is provided along with the maximum resonant trap duration.
[a] Karlsson (2004) classified the nominal orbit of (32511) 2001 NX17 as nonresonant.

A.3. Determination of Resonant Sticking Timescales

Any object in our 11,581 object sample set found to have at least one clone that does not remain resonant for the duration of the 0.5 Myr integrations has had their integrations extended (or are being extended) to the point where all 1000 clones have been removed from the integrations by entering one of the exit criteria described above. The 27 metastable co-orbitals, 124 nonresonant objects, and 7 "insecure" objects all fall into this category; none of the 11,423 L4/L5 Trojans in our sample set had a single clone leave the 1:1 Jovian resonance in the 0.5 Myr integrations. While the nonresonant objects had <5% of their 1000 clones librate in the resonance for ⩾1 kyr, some nonresonant objects did have some number of clones that remained resonant for at least that length of time. The number of transient clones for each nonresonant object and the maximum trap durations of those transient clones are listed in Table 5, along with the same information for the "insecure" objects listed in Table 4.

Table 5
Objects We Classify as "Nonresonant," i.e., <5% of Their 1000 Clones Librate in the Jovian 1:1 Resonance for at Least 1 kyr (Red Points in Figures 2 and 4)

Designation	JPL Class	Transient Clones	Max. Trap Duration (kyr)
(944) A920 UB	Centaur	0	⋯
(6144) 1994 EQ3[a]	Asteroid	0	⋯
(118624) 2000 HR24[a]	**Trojan**	**0**	⋯
(145485) 2005 UN398	OMB	0	⋯
(275618) 2000 AU242	Asteroid	0	⋯
(301964) 2000 EJ37[a]	Asteroid	0	⋯
(318875) 2005 TS100[b]	Centaur	0	⋯
(365756) 2010 WZ71	Centaur	4	29
(371522) 2006 UG185[a]	**Trojan**	**0**	⋯
(380282) 2002 AO148	Centaur	0	⋯
(434762) 2006 HA153	OMB	0	⋯
(461363) 2000 GQ148	Centaur	0	⋯
(487496) 2014 SE288[c]	Asteroid	0	⋯
(490171) 2008 UD253	Asteroid	0	⋯
(494219) 2016 LN8	Centaur	0	⋯
(497619) 2006 QL39[c]	Asteroid	0	⋯
(497786) 2006 SA387[c]	**Trojan**	**0**	⋯
(498901) 2009 AU1	OMB	0	⋯
(504160) 2006 SV301	Asteroid	0	⋯
(515718) 2014 UQ194	**Trojan**	**0**	⋯
(517594) 2014 WX199	**Trojan**	**0**	⋯
(528972) 2009 HM15	**Trojan**	**0**	⋯
(529456) 2010 AN39	OMB	0	⋯
(576525) 2012 TQ67	**Trojan**	**0**	⋯
(584530) 2017 GY10	Asteroid	0	⋯
(613349) 2006 BF208	Centaur	8	123
(614590) 2009 XY21	Asteroid	0	⋯
2000 CN152	**Trojan**	**0**	⋯
2002 CF329	Asteroid	0	⋯
2002 GE195[c]	**Trojan**	**0**	⋯
2005 NP82	Centaur	0	⋯
2005 TX214	OMB	0	⋯
2007 EV40[c]	Asteroid	0	⋯
2007 VW266	Asteroid	0	⋯
2009 SV412[c]	Asteroid	0	⋯
2010 BR88	Asteroid	0	⋯
2010 BT86	**Trojan**	**6**	**1**
2010 CR140	Centaur	0	⋯
2010 ER22	Asteroid	0	⋯
2010 GP49	Asteroid	0	⋯

Table 5
(Continued)

Designation	JPL Class	Transient Clones	Max. Trap Duration (kyr)
2010 JJ52	Asteroid	0	…
2010 KF52	Asteroid	0	…
2010 KG43	Centaur	0	…
2010 LV121	Asteroid	0	…
2010 RH69	OMB	0	…
2011 AF94	Asteroid	0	…
2011 AT15	OMB	0	…
2011 WM183	Asteroid	0	…
2012 DM127	OMB	0	…
2012 CM36	Centaur	0	…
2012 UJ38	OMB	0	…
2012 XO144	Asteroid	0	…
2013 AP182	Asteroid	0	…
2013 BU1	Centaur	0	…
2013 HA	OMB	0	…
2013 KY14	Asteroid	0	…
2013 LA2	Centaur	0	…
2013 OL15	Centaur	5	6
2013 VX9	OMB	1	2
2014 JK14	**Trojan**	**0**	…
2014 JL128	Asteroid	2	1
2014 KV3	Centaur	10	10
2014 MA71	Centaur	0	…
2014 PA7	Centaur	0	…
2014 SZ398	Asteroid	0	…
2014 WY359	Asteroid	0	…
2015 AJ260	Asteroid	0	…
2015 BX306	Centaur	0	…
2015 CD60	OMB	0	…
2015 HO176	Centaur	0	…
2015 KM119	OMB	1	1
2015 KW15	Asteroid	0	…
2015 MY90	Centaur	0	…
2015 OS110	OMB	0	…
2015 PC58	Asteroid	0	…
2015 PG119	Centaur	0	…
2015 VA53	Asteroid	0	…
2016 AH350	Centaur	0	…
2016 CE150[c]	Asteroid	0	…
2016 NG39	Asteroid	0	…
2016 PH135	Asteroid	0	…
2016 PW84	Centaur	0	…
2016 UV4	Asteroid	3	4
2016 YB13	Asteroid	0	…
2017 DE104	OMB	0	…
2017 CD39	Asteroid	0	…
2017 FP50	Centaur	0	…
2017 OY68	Asteroid	0	…
2017 TX13	Asteroid	0	…
2017 QO100[c]	Centaur	0	…
2017 WJ30[c]	Asteroid	0	…
2017 XJ65	Asteroid	0	…
2018 AN25	Centaur	0	…
2018 RG39	Centaur	0	…
2018 RH54	OMB	0	…
2018 VL10	OMB	0	…
2018 VX121	OMB	0	…
2018 XV35	Centaur	0	…
2019 KW30	Asteroid	0	…
2019 LM26	Asteroid	0	…
2019 PR2	Amor	0	…
2019 QS3	Amor	0	…
2019 QR6	Amor	0	…
2019 RF13	Centaur	0	…
2019 SD164	**Trojan**	**33**	**3**
2019 SO48	Centaur	0	…
2020 BL76	Centaur	2	2
2020 BZ43	**Trojan**	**0**	…
2020 HQ62	Asteroid	0	…
2020 PY28	Asteroid	0	…
2020 YH25	**Trojan**	**0**	…
2021 CD29	Asteroid	0	…
2021 CX19	Asteroid	0	…
2021 GT72	Centaur	32	15
2021 JN58	Centaur	5	8
2021 MJ1	OMB	0	…
2021 PM66[c]	OMB	0	…
2021 RZ47	Centaur	0	…
2021 VA28	Centaur	0	…
2021 UR	OMB	5	26
2021 WT6	Centaur	0	…
2022 BB25	Centaur	4	4
2022 BF15	Asteroid	0	…
2022 CA31	Centaur	0	…
Total	**124**		
Total Trojan	14		
Total asteroid	48		
Total Centaur	38		
Total OMB	21		
Total Amor	3		

Notes. If an object had any clones that librate in the resonance for ⩾1 kyr, the number of transient clones and their maximum resonant trap duration are provided. The 14 objects classified by the MPC/JPL as Trojans are shown in bold.
[a] Same classification as Karlsson (2004), Wajer & Krolikowska (2012), Di Ruzza et al. (2023), and/or Beauge & Roig (2001).
[b] Wajer & Krolikowska (2012) classified (318875) 2005 TS100 as nonresonant, while Di Ruzza et al. (2023) classified it as a horseshoe.
[c] Wajer & Krolikowska (2012) and/or Di Ruzza et al. (2023) classify (487496) 2014 SE288, (497619) 2006 QL39, (497786) 2006 SA387, 2002 GE195, 2016 CE150, 2017 WJ30, and 2021 PM66 as horseshoes, and Di Ruzza et al. (2023) classify 2007 EV40 as a quasi-satellite, 2009 SV412 as "compound," and 2017 QO100 as "transient," all based on their short-term orbital behavior over the next ≲1000 yr. We require objects to remain stable in the 1:1 Jovian resonance for ⩾1 kyr in order to experience several libration periods before possible departure from the resonance (in the case of the transient captures); this is responsible for the classification differences for the objects that we classify as nonresonant that other studies find are resonant during the ⩽1 kyr timescales they use.

These longer integrations have been run for tens to hundreds of Myr, or in one case, ∼2 Gyr. The extension of these numerical integrations until the final clone has exited allows us, for the first time, to determine their resonant trapping timescales (see Tables 2, 4, and 5 and Figure 3). A resonant "trap" includes the duration of consecutive 1 kyr running windows for which a state vector satisfies our resonant criteria described above. Some "transient" or "insecure" objects can become trapped multiple times during the integrations. We base our classifications on the start of the integrations (i.e., the current time) and do not discuss (rare) multiple resonant traps in this paper.

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