A look at the capture mechanisms of the "Temporarily Captured Asteroids" of the Earth

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Temporarily captured asteroids of the Earth are a newly discovered family of asteroids, which become naturally captured in the vicinity of the Earth for a limited time period. Thus, during the temporary capture these asteroids are in energetically favorable conditions, which makes them appealing targets for space missions to asteroids. Despite their potential interest, their capture mechanisms are not yet fully understood, and basic questions remain unanswered regarding the taxonomy of this population. The present work looks at gaining a better understanding of the key features that are relevant to the duration and nature of these asteroids, by analyzing patterns and extracting conclusions from a synthetic population of temporarily captured asteroids.

Key Words: Asteroids, temporarily captured asteroids, capture dynamics, asteroid retrieval.

Acronyms

TCA	:	Temporarily captured asteroids
TCO	:	Temporarily captured orbiters
TCF	:	Temporarily captured fly-bys

1. Introduction

The origin of planetary satellites in the Solar System has been a long standing question, giving rise over time to many hypotheses, conjectures and theories, as well as a wealth of bibliographic references on the topic. The capture of Sun-orbiting bodies in the neighborhood of a planet is widely accepted as a plausible origin for many planetary satellites and has been studied in depth.[1–7)] Heppenheimer and Porco[6)] defined the *capture* as the process whereby a body undergoes transition from heliocentric orbit to a planetocentric orbit. Therefore, the three-body problem is the natural framework where the capture mechanisms need to be studied. However, it is agreed that under a purely gravitational three-body problem, captures can only be temporary.[7,8)] Several examples of temporarily captured objects can be found in the Solar System, and in particular, the temporary capture of comets in the Jovian system has been well-studied.[9–11)] However, no such objects had been observed in the Earth-Moon system until recently.

Asteroid 2006 RH_{120} was discovered while it became temporarily captured around the Earth in 2006, yielding the discovery of a new class of the natural population of asteroids, known as *temporarily captured* asteroids of the Earth. Granvik et al.[12)] define temporarily captured asteroids as those which have a negative planetocentric energy while orbiting within a planetocentric distance of 3 Hill radii (~ 0.03 AU in case of the Earth) during an extended but finite period of time. The outer planets are known to have many such temporary visitors, also referred to as *mini-moons*. Asteroids like 2006 RH_{120} get naturally captured within the gravitational potential of the Earth, but due to the strongly perturbed environment the capture has a limited duration until the asteroids escapes the Earth-Moon system. Asteroid 2006 RH_{120} is so far the only known member of this population, though statistical studies by Granvik et al.[12)] support the evidence that such objects are actually common companions of the Earth, and thus it is expected that an increasing number of them will be found as survey technology improves.[13)]

During their temporary capture phase these asteroids are technically orbiting the Earth rather than the Sun, since their Earth-binding energy is negative. Therefore, they are in energetically favourable conditions so Earth-bound spacecraft can reach them affordably.[14)] Consequently, these asteroids have become interesting targets for future asteroid missions and eventual spaceborn resource utilization.[13,15)] Given their enormous potential interest, Urrutxua et al.[16,17)] suggested the idea of artificially extending the duration of these temporary captures, as well as the possibility of inducing temporary capture phases to asteroids that would otherwise not get temporarily captured at all. These ideas were proven plausible, but the systematic design of asteroid deflection strategies to achieve these goals was found to be difficult, mainly due to the limited understanding of how these mechanisms operate and how they affect the properties of the resulting temporary capture, such as the lifetime. These mechanisms are understood only to a certain degree, and the invariant manifolds of the orbits around the collinear Lagrange points are known to play a significant role.[10,11)] However, the case of the Earth is much more complex due to interaction with the Moon, which may profoundly affect the processes involved in the capture, and give rise to diverse realizations of the mechanisms that drive these temporary captures. Hence, it is not yet well understood if the processes that govern the capture of mini-moons around Jupiter is extensible to the full population of temporarily captured asteroids of the Earth, or meaningful differences may exist between members of this population.

This paper intends to address this point, by studying the capture phase of a synthetic population of temporarily captured asteroids of the Earth. In particular, energy-related indicators, interaction with the Earth-Moon system, and the geometric layout throughout the temporary capture will be studied and related to the characteristics of the resulting capture, in order to infer signature patterns that correspond to key features of the temporary capture. In brief, the intent of the paper is to answer the fundamental question of *why* and *how* these asteroids get temporarily captured, understand the principles and mechanisms that ensure these captures, and ultimately learn how to artificially induce temporary capture phases that could be exploited for asteroid retrieval and Earth-delivery purposes.

2. Population of Temporarily Captured Asteroids

Rigorous calculations show that there is a significant flux of temporarily captured asteroids (TCA) within the Earth-Moon system; in particular, it is expected that a 10 meter-sized asteroid gets temporarily captured every 50 years, and at any given time there are at least two meter-sized and a dozen half-meter-sized objects.[12)] The temporary capture occurs when an object complies simulatenously with the conditions that: 1) its planetocentric energy is negative; and 2) its planetocentric distance is less than 3 Hill radii. This condition would typically last for a limited period of time only; specifically, the mean lifetime of the Earth's TCA (i.e. the duration of the temporary capture phase) is predicted to be 9.5 months. Granvik et al.[12)] extracted these conclusions from analyzing a synthesic population of asteroids formed by fictitious TCA, which they kindly shared with us for the present work. Therefore, the results presented in this paper are based on the very same sample of TCA, which is intended to be representative of the true population of these objects.

Temporary captures around the Earth are best studied in a Sun-Earth synodic frame, i.e. an Earth-centered rotating frame where the X-axis is pointing along the Sun-Earth direction (i.e. the Sun is located at $x = -1$ AU), the Z-axis is perpendicular to the ecliptic plane (of Epoch) and pointing North, and the Y-axis completes a right-handed frame. With respect to this frame, temporary captures can be classified as prograde or retrograde, depending on whether the synodic, ecliptic projection of their Earth-centered trajectories revolve counterclockwise or clockwise, respectively. Following Ref. 12, the number of revolutions are counted by recording the ecliptic, longitudinal angle traversed in the synodic frame during the capture. Thus, temporarily captured objects can be classified as temporarily captured orbiters (TCO) when they complete at least one full revolution around the Earth (in synodic frame coordinates) while being captured, or temporarily captured fly-bys (TCF) if they fail to complete a full revolution. On average, TCA of the Earth complete almost 3 revolutions about the Earth during their capture.[12)]

Granvik et al.[12)] provided us with a set 18,096 TCO for the purpose of this study. We were able to reproduce a temporary capture for 18,081 of them (99.2%). However, while 14,752 of these fictitious asteroids (81.59%) were successfully reproduced as TCO, the nature of the remaining 3,329 asteroids (14.41%) changed to TCF when numerically propagating their orbits. Temporary captures are extremely sensitive to the dynamical environment (e.g. ephemerides model) and numerical integration of the orbit, and it is therefore not surprising that reproducing the same temporary captures with a different propagation tool may yield slightly different results in some cases; in particular, many TCA close to the boundary of one completed revolution may easily fall below this limit. Thus, for the remainder of the paper we shall base our results on the set of 14,752 TCO that could be successfully reproduced.

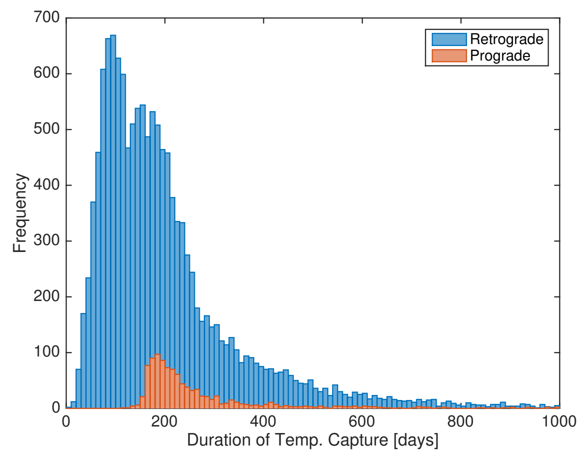


Fig. 1. Duration of capture for retrograde and prograde TCO. The longest capture lasted about 25,300 days but the histogram has been cut off at 1000 days.

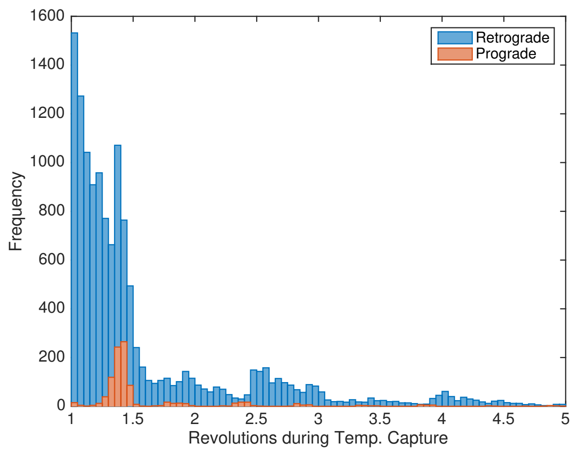


Fig. 2. Number of revolutions for retrograde and prograde TCO during their capture. The maximum number of revolutions recorded was 1,265 but the histogram has been cut off at 5.

Granvik et al.[12)] studied the pre- and post-capture distribution of TCA in Heliocentric coordinates, but less emphasis was placed in studying their distribution in Geocentric coordinates. Whereas the former in necessary to characterize the population of TCA, the latter is certainly more insightful when it comes to understanding the mechanisms that enable the capture in the Earth-Moon system.

3. Taxonomy of Temporarily Captured Orbiters

Further statistical analysis of these temporary captures reveals interesting observations, which allow to classify the TCO into more alike sub-groups or types. For instance, TCO may or may not cross the Hill sphere during their temporary capture, i.e. the condition of negative planetocentric energy may occur for a wide range of planetocentric distances, including or ex-

Table 1. Statistical information of the synthetic TCO population broken down by type.

Type of TCO	Total	Prograde		Retrograde	
	Count	Count	Fraction	Count	Fraction
TCO (100%)	14,752	1,066	7.23%	13,686	92.77%
Type I (99.044%)	14,611	1,066	7.30%	13,545	92.70%
Type IA (90.98%)	13,293	1,024	7.70%	12,269	92.30%
Type IB (5.75%)	840	32	3.81%	808	96.19%
Type IC (3.27%)	478	10	2.09%	468	97.91%
Type II (0.956%)	141	0	0.00%	141	100.00%
Type IIA (39.72%)	56	0	0.00%	56	100.00%
Type IIB (60.28%)	85	0	0.00%	85	100.00%

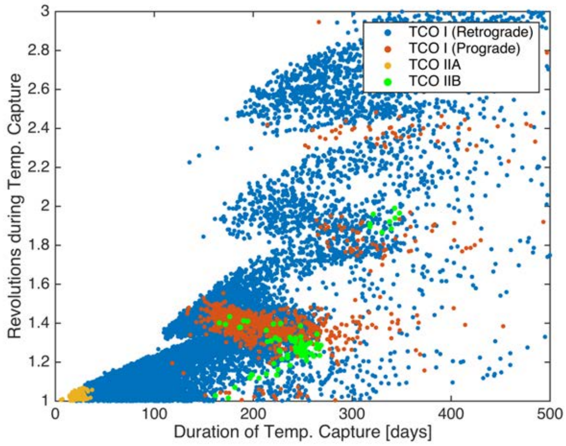


Fig. 3. Number of revolutions as a function of the capture duration for different TCO sub-classes. The axes have been cut off to 500 days and 3 revolutions.

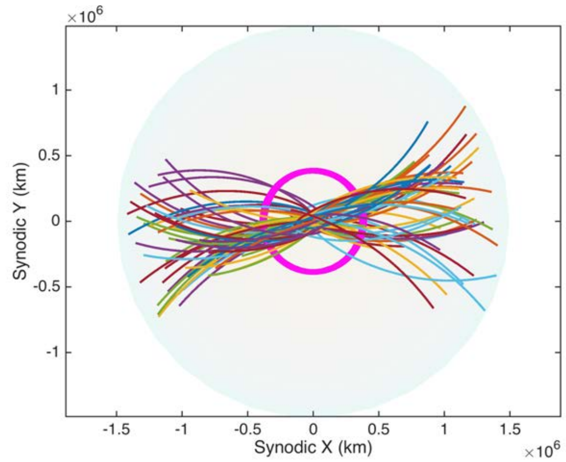


Fig. 4. Trajectories of the 56 asteroids of type IIA. The Earth's Hill sphere and the Moon's trajectory are also displayed.

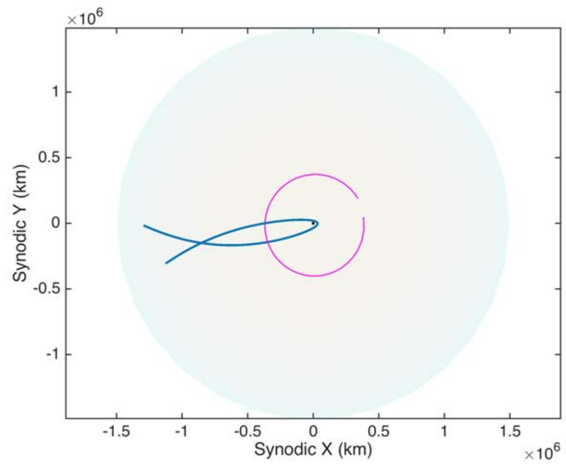


Fig. 5. Example of a type IIA trajectory. The capture lasts for 27.6 days. The Earth's Hill sphere and the Moon's trajectory are also displayed.

cluding the region circumscribed by the 1 Hill radius sphere; thus the Hill sphere serves as an intuitive reference distance to measure the penetration of the TCO into the Earth-Moon system and sub-classify them accordingly. In this regard, the overwhelming majority of the analysed TCO (99.044%) did cross the Hill sphere during their temporary capture phase; we classify these asteroids as TCO of type I. However, a non-negligible amount of 141 TCO (0.956%) did not pass through the Hill sphere during the temporary capture phase; these asteroids will be referred to as TCO of type II. From the latter group, 56 of them (39.72%) were TCO that lived strictly inside the Hill sphere, i.e. though the asteroid clearly had to cross the Hill sphere, the asteroid only experienced a negative planetocentric energy while inside the Hill sphere; these will be hereafter referred to asTCO of type IIA. The remaining 85 TCO (60.28%) never crossed the Hill sphere at all, i.e. they were temporarily captured while strictly beyond the Hill sphere; these will be classified as TCO of type IIB.

The TCO of type I can also be broken down into subclasses. Interestingly, most of them (90.98%) cross the Hill sphere twice, i.e. the temporary capture begins when the asteroid is outside the Hill sphere, then the asteroid makes an excursion inside the Hill sphere, and finally leaves the Hill sphere before the temporary capture is over; this type of TCO will be classified as type IA. Alternatively, the TCO of type IB (5.75%) are those which start their temporary capture outside the Hill sphere and end the capture phase inside; i.e. the planetocentric energy becomes positive before they exit the Hill sphere. Conversely, TCO of type IC (3.27%) enter the Hill sphere with positive planetocentric energy, the energy becomes negative (i.e. they become temporarily captured) once inside the Hill sphere, and leave the Hill sphere before the energy turns positive again and the capture is over.

Table 1 summarizes these statistics, along with the distribution of prograde and retrograde orbits per each type of TCO. Surprisingly (or perhaps not) there is a staggering preference towards retrograde motions about the ecliptic pole. This results

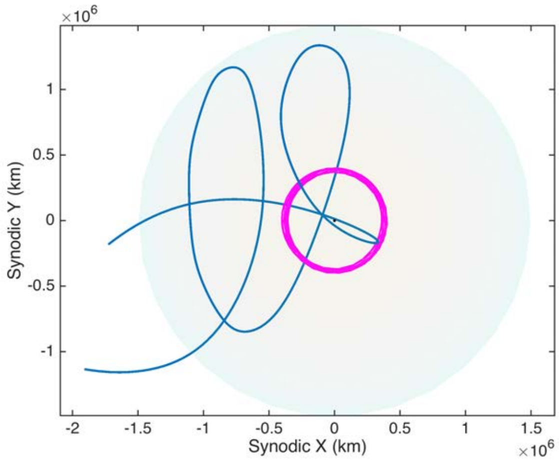


Fig. 6. Example of a TCF trajectory. The capture lasts for 334.75 days and completes 0.93 revolutions. The Earth's Hill sphere and the Moon's trajectory are also displayed.

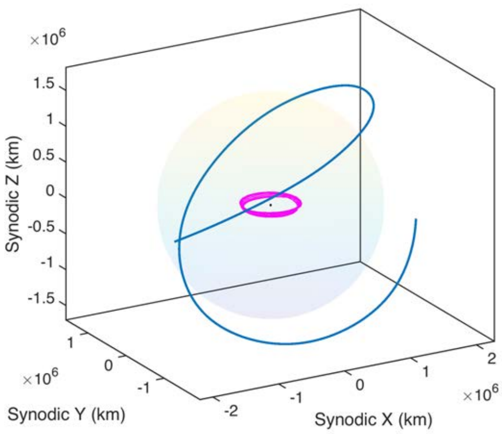


Fig. 7. Example of a type IIB trajectory. The capture lasts for 227.67 days and completes 1.4 revolutions. The Earth's Hill sphere and the Moon's trajectory are also displayed.

clearly exceed the 2:1 ratio between retrograde and prograde TCA implied in Ref. 12, which we have been unable to explain so far.

Figure 3 shows the correlation between the duration of the temporary captures and the number of completed revolutions, for each sub-type of TCO. It can be noted that type IIA captures are of short duration and revolve only about once before escaping; this suggests they might be closely related to TCF. Figure 4 shows how these trajectories are confined within the Hill sphere, and Fig. 5 shows the trajectory of one TCO of this type.

Figure 5 actually looks much like what one would intuitively expect from a TCF. In fact, it is only coincidental that the trajectory completes a full revolution around the Earth in the synodic XY plane, whereas a front view would reveal that the trajectory's projection in the synodic XZ plane does not even complete a full revolution. Consequently, the classification of this asteroid as a TCO is questionable in the first place.

The discussion gets more interesting when type IIA objects are compared to TCF trajectories. Though many TCF trajectories would resemble that of Fig. 5, the TCF of Fig. 6 is a

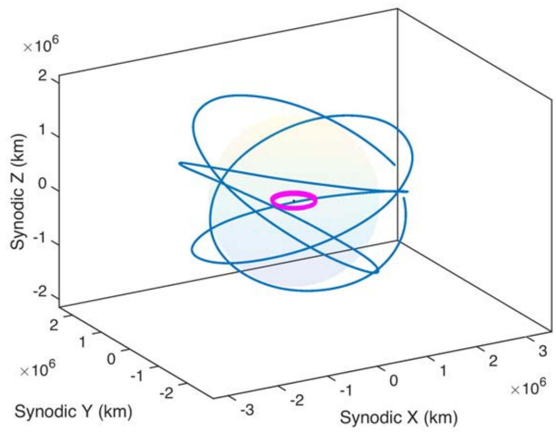


Fig. 8. Example of a type IIB trajectory. The capture lasts for 747.5 days and completes 3.97 revolutions. The Earth's Hill sphere and the Moon's trajectory are also displayed.

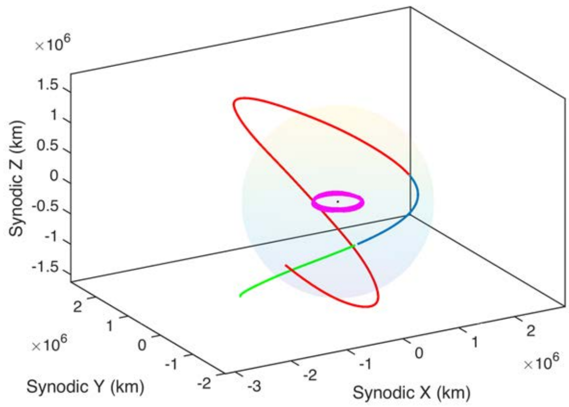


Fig. 9. Example of a type IA trajectory. The capture lasts for 293 days and completes 1.93 revolutions. The colors identify the trajectory segments before entering (green), inside (blue) and after leaving (red) the Hill sphere. The Earth's Hill sphere and the Moon's trajectory are also displayed.

great counter-example, which swirls about the Earth for over 300 days, combining retrograde and prograde motions, such that the aggregated count of revolutions lies below the unity. Clearly, it just feels wrong that the asteroid of Fig. 6 is classified as a TCF whereas Fig. 5 is labeled as a TCO. This suggests that the proposed procedure for counting revolutions may not be appropriate for the purpose, and a more suitable magnitude may be required, which links the duration of the capture and the number of revolutions with a higher correlation than that shown in Fig. 3. This also explains why in Fig. 3 there is such a large variability in the duration of the capture for a given number of revolutions.

The TCO of type IIB seem to complete between 1 and 2 revolutions and last between 6 and 12 months, as illustrated in Figure 7, where it can be observed that the trajectory does not intercept the Hill sphere during the capture phase. Longer lasting captures are also possible though, as shown in Fig. 8.

The TCO of Type I are the most common and cover a wide casuistic. Figure 9 illustrates an example the trajectory followed during a temporary capture, pointing out the segments that oc-

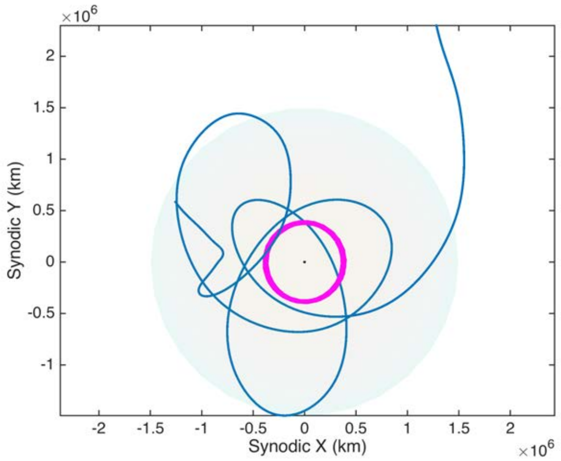


Fig. 10. Example of a type IA trajectory. The capture lasts for 549.3 days and completes 2.74 revolutions. The Earth's Hill sphere and the Moon's trajectory are also displayed.

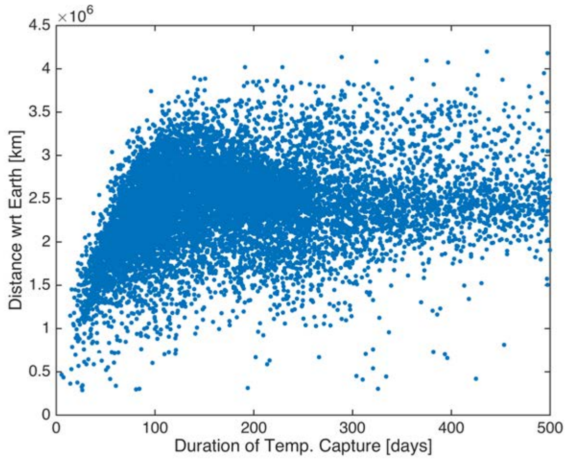
cur before entering the Hill sphere, inside the Hill sphere and after exiting the Hill sphere. Figure 10 shows another example of a long-lived temporary capture which, in particular, crosses the Hill sphere more than twice. This fact suggests that the Hill sphere may not necessarily be in every case the most appropriate reference for effectively sub-classifying TCO.

4. A look at the Capture Mechanisms

It is known that comets and asteroids can be temporarily captured by planets from time to time, as several examples have been observed of comets being captured by Jupiter. This problem has been studied in the past and the most fundamental mechanisms are reasonably well understood, though a profound understanding of the problem is still unaccomplished. As Heppenheimer pointed out[4] a (temporary) capture implies the transfer of an object from a motion around the Sun, to a motion around the planet; in an unperturbed (or slightly perturbed) dynamical system, such a transfer involves passing through a separatrix in phase space. In the restricted three-body problem, such separatrix is given by the curves of zero velocity in the region of a collinear libration point, and thus the capture and escape trajectories are both governed by manifold dynamics. Quoting Horedt:[5] *"the capture and escape paths belong to the dark infinity of possible orbits in the restricted three-body problem"*.

In the case of Jupiter's TCA a very complex transport mechanism has been identified whereby resonant transitions bring asteroids or comets close to the L_1 or L_2 points of the Sun-Jupiter system, and once in the vicinity of these Lagrange points, the invariant manifolds of libration orbits are able to attract these bodies and pull them into the region around the planet following a stable manifold; there, they remain temporarily captured until the asteroids escape following an unstable manifold.[10,11] In the particular case of asteroid 2006 RH_{120}, Anderson et al.[18] claimed that it may have entered the vicinity of the Earth following the stable manifold of a northern halo orbit around L_1, and towards the end of the temporary capture escaped through the unstable manifold of a southern halo orbit around L_2.

These (or similar) mechanisms are believed to be common-



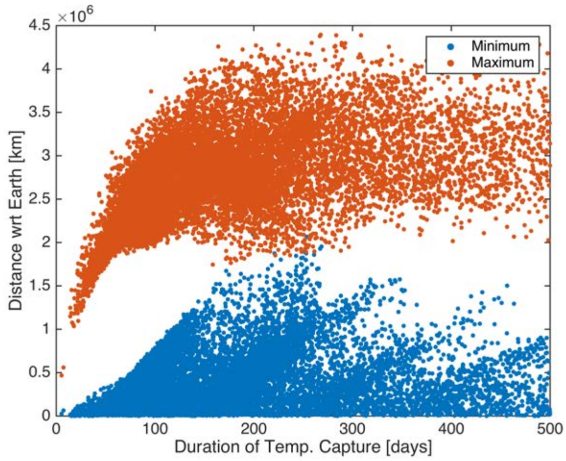


Fig. 11. Above: Geocentric distance of the retrograde TCO at the beginning of the temporary capture expressed as a function of the capture duration. Below: minimum and maximum values throughout the capture.

place for all temporary captures. However, the methods on which they rely are founded on the circular, restricted three-body approach, which is a mere simplification of a more complex reality. In fact, a further degree of approximation would require considering the elliptic, restricted three-body problem, where the Jacobi *constant* is no longer preserved, thus incorporating additional difficulty to the analysis. Even then, this model falls apart when the Earth and Moon are considered as separate bodies (instead of considering their mutual barycenter), which is observed to have a huge impact in the processes that originate temporarily captured satellites of the Earth.[12] The inclusion of the Moon complicates the study enormously and is currently an ongoing topic of research.

An interesting approach to gain some understanding on the properties of these temporary captures might be that of looking for patterns in the population of TCA, or a strong correlation between features of different captures, which would reveals some underlying common physical properties. It must be noted, however, that this paper is solely an early step towards this goal.

An obvious first observation might be to identify tighter bounds to the geocentric distance at which the captures begin. This is illustrated in Fig. 11, which shows that the bulk of the population starts the capture at similar distances from the Earth, typically between 1 and 2 Hill radii. The minimum distance during the capture, however, can get close to the Earth, which

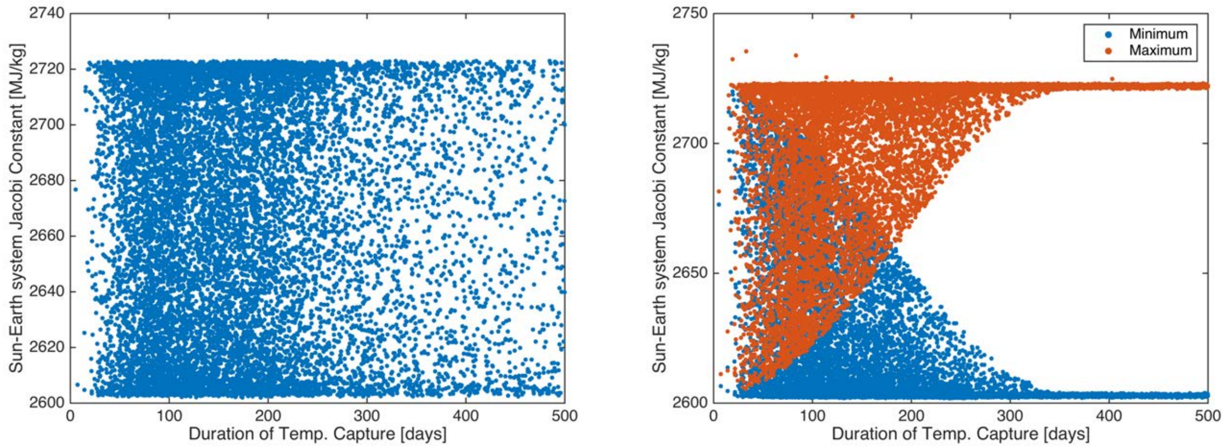


Fig. 12. Jacobi Constant (dimensional) of the retrograde TCO at the beginning of the temporary capture (left), and minimum & maximum values (right), expressed as a function of the capture duration.

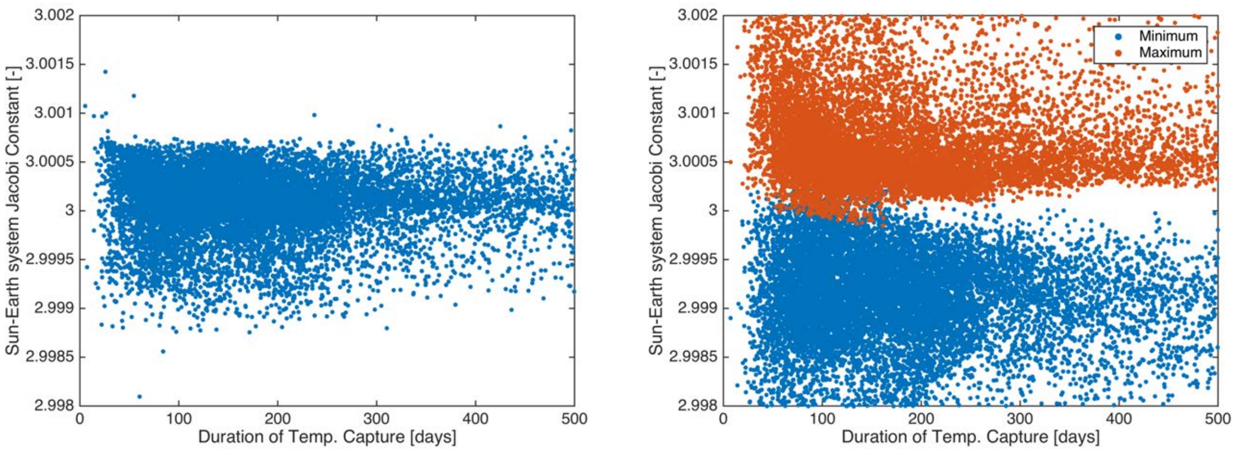


Fig. 13. Jacobi Constant (non-dimensional) of the retrograde TCO at the beginning of the temporary capture (left), and minimum & maximum values (right), expressed as a function of the capture duration.

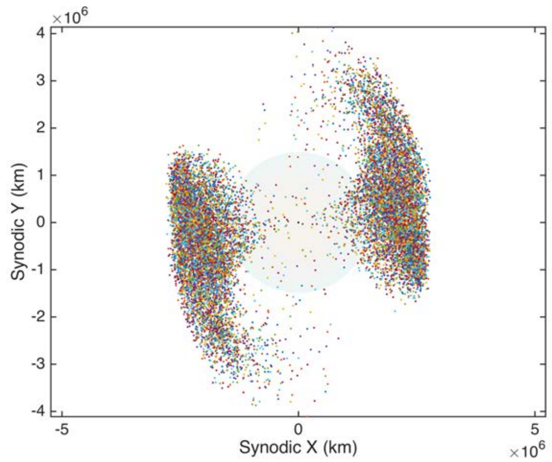


Fig. 14. Initial position of the temporary capture for each TCO in the population. The Earth's Hill sphere is also displayed for visual reference.

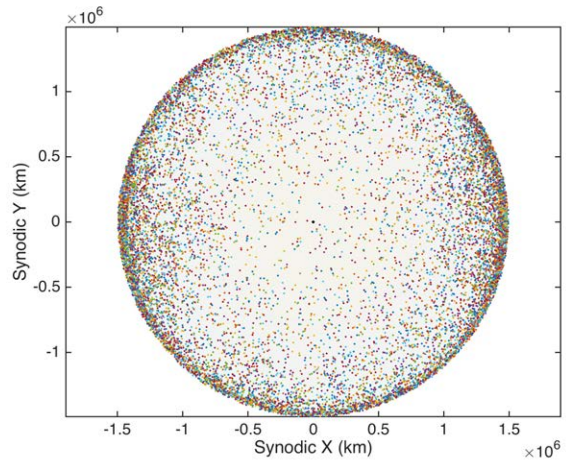


Fig. 15. Position of the entry point in the Hill sphere for every TCO of type IA and IB in the population. The Earth's Hill sphere is also displayed for visual reference.

might actually be a desirable property for asteroid resource utilization missions.

Another obvious feature to look at is the Jacobi constant. Figure 12 displays, for the synthetic populaton of retrograde TCO, the value of the Jacobi constant at the beginning of the capture, revealing a great variability. Also, the minimum and maximum values are shown. The gap between them is mainly associated to the ellipticity of the Earth's orbit around the Sun. Thus, a perhaps more meaningful variable would be the non-dimensional

Jacobi constant, which is normalized with the instantaneous semi-major axis and orbital angular velocity of the Earth, thus yielding the results of Fig. 13, where the variability due to the ellipticity of the Earth orbit has been removed. And interesting next step would be to confirm whether the remaining variability (i.e. the gap between the maximum and minimum values) is due to the presence of the Moon, or has a different source.

Figure 14 shows the position of every member of the TCO population at the beginning of their temporary capture phase. Two main conglomerations can be identified in the vicinity of both Lagrange points, L_1 and L_2, which is in agreement with the expectation that all TCO should reach the vicinity of the Earth following one or another manifold around these libration points. This reveals a strong symmetry in the distribution of incoming TCO trajectories. It is also interesting to note that this symmetry feature can be so clearly inferred so far away from the Hill sphere. In this regard, what is perhaps more unexpected is the fact that by the time these trajectories enter the Hill sphere, these entry points seem evenly distributed on the Hill sphere, leaving no clear indication of the aforementioned symmetry. This suggests that the Hill sphere may not be an adequate reference surface to look for indicators or signatures that allow us to understand and characterize the nature and properties of the TCO.

Acknowledgments

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References

1) Bailey, J. M.: Jupiter: its captured satellites, *Science* **173** (1971), pp. 812–183.
2) Bailey, J. M.: Origin of the outer satellites of Jupiter, *J. Geophys. Res.* **76** (1971), pp. 7827–7832.
3) Bailey, J. M.: Studies on outer satellites. Satelite capture in the three-body elliptical problem, *The Astronomical Journal* **77** (1971), pp. 177–182.
4) Heppenheimer, T. A.: On the Presumed Capture Origin of Jupiter's Outer Satellites, *Icarus* **24** (1975), pp. 172–180.
5) Horedt, G. P.: Capture of planetary satellites, *The Astronomical Journal* **81** No. 8 (1976), pp. 675–678.
6) Heppenheimer, T. A. and Porco, C.: New Contributions to the Problem of Capture, *Icarus* **30** (1977), pp. 385–401.
7) Huang, T.-Y. and Innanen, K. A.: The Gravitational Espace/Capture of Planetary Satellites, *The Astronomical Journal* **88** No. 10 (1983), pp. 1537–1548.
8) Tanikawa, K.: Impossibility of the capture of retrograde satellites in the restricted three-body problem, *Celestial Mechanics and Dynamical Astronomy* **29** Issue 4 (1983), pp. 367–402.
9) Carusi, A. and Valsecchi, G. B.: Temporary Satellite Captures of Comets by Jupiter, *Astronomy and Astrophysics* **94** (1981), pp. 226–228.
10) Koon, W. S., Lo, M. W., Marsden, J. E., and Ross, S. D.: Resonance and Capture of Jupiter Comets, *Celestial Mechanics and Dynamical Astronomy*, **81** No. 1 (2001), pp. 27-38. DOI: 10.1007/978-94-017-1327-6_3.
11) Howell, K. C., Lo, M. W., and Marchand, B. G.: Temporary Satellite Capture of Short-Period Jupiter Family Comets from the Perspective of Dynamical Systems, *Journal of Astronautical Sciences*, **49** No. 4 (2001).
12) Granvik, M., Vaubaillon, J., and Jedicke, R.: The population of natural Earth satellites, *Icarus* **218** No. 1 (2012), pp. 262–277. ISSN: 0019-1035. DOI: 10.1016/j.icarus.2011.12.003.
13) Granvik, M., Jedicke, R., Bolin, B., Chyba, M., Patterson, G. and Picot, G.: Earth's Temporarily-Captured Natural Satellites – The First Step towards Utilization of Asteroid Resources, *Asteroids – Prospective Energy and Material Resources*, Springer Berlin Heidelberg (2013), Chapter 6, pp. 151–167. DOI: 10.1007/978-3-642-39244-3_6. ISBN: 978-3-642-39243-6.
14) Brelsford, S., Chyba, M., Haberkom, T. and Patterson, G.: Rendezvous missions to temporarily captured near Earth asteroids, *Planetary and Space Science*, **23** (2016), pp. 4–15. DOI: 10.1016/j.pss.2015.12.013.
15) Jedicke, R., Bolin, B., Bottke, W. F., Chyba, M., Fedorets, G., Granvik, M. and Patterson, G.: Small asteroids temporarily captured in the Earth-Moon system, *Proceedings of the International Astronomical Union*, **10** Issue S318 (Asteroids: New Observations, New Models) (2015), pp. 86–90.
16) Urrutxua, H., Scheeres, D. J., Bombardelli, C., Gonzalo, J. L. and Peláez, J.: Temporarily Captured Asteroids as a Pathway to Affordable Asteroid Retrieval Missions, *Journal of Guidance, Control and Dynamics*, **38** No. 11 (2015), pp. 2132–2145. DOI: 10.2514/1.G000885.
17) Urrutxua, H., Scheeres, D. J., Bombardelli, C., Gonzalo, J. L. and Peláez, J.: What Does it Take to Capture an Asteroid? A Case Study on Capturing Asteroid 2006 RH_{120}, *Advances in the Astronautical Sciences*, **152** (2014), pp. 1117–1136.
18) Anderson, B. and Lo, M. W.: Dynamics of Asteroid 2006 RH_{120}: Pre-Capture and Escape Phases, *Advances in the Astronautical Sciences* (2016), Paper 16-484.