Mon. Not. R. Astron. Soc. **367,** L20–L23 (2006) doi:10.1111/j.1745-3933.2006.00131.x

The capture of Centaurs as Trojans

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Accepted 2005 November 30. Received 2005 November 29; in original form 2005 October 31

ABSTRACT

Large-scale simulations of Centaurs have yielded vast numbers of data, the analysis of which allows interesting but uncommon scenarios to be studied. One such rare phenomenon is the temporary capture of Centaurs as Trojans of the giant planets. Such captures are generally short (10–100 kyr), but occur with sufficient frequency (∼40 objects larger than 1 km in diameter every Myr) that they may well contribute to the present-day populations. Uranus and Neptune seem to have great difficulty capturing Centaurs into the 1 : 1 resonance, while Jupiter captures some, and Saturn the most (∼80 per cent). We conjecture that such temporary capture from the Centaur population may be the dominant delivery route into the Saturnian Trojans. Photometric studies of the Jovian Trojans may reveal outliers with Centaur-like as opposed to asteroidal characteristics, and these would be prime candidates for captured Centaurs.

Key words: comets: general – minor planets, asteroids – planets and satellites: general – Solar system: general.

1 INTRODUCTION

Lagrange was the first to observe that there is an exact solution of the three-body problem in which the bodies lie at the vertices of an equilateral triangle. This has a direct application to the Solar system. The Trojan asteroids librate about the so-called L_4 and L_5 Lagrangian points, and lie roughly 60° ahead and behind the mean longitude of the planet (e.g. Danby 1988).

Jupiter provides the best-known and longest-studied case. The population of the Jovian Trojans is substantial. For example, the number of objects with radii in excess of 1 km may exceed $\sim 10^5$ in total (Jewitt, Trujillo & Luu 2000). By contrast, very few Trojans of the other planets are known. Only three Mars Trojans [namely (5261) Eureka, 1998 VF_{31} and 1999 UJ_7] have been securely identified (see e.g. Tabachnik & Evans 1999; Rivkin et al. 2003). Recent wide-field surveys of the outer Solar system (Chiang et al. 2003; Sheppard & Trujillo 2005) have also discovered two Neptunian Trojans (namely 2001 QR_{322} and 2004 UP_{10}). There have been surveys for Trojans of Saturn, Uranus and the Earth, but they have not yielded any positive detections (e.g. Whiteley & Tholen 1998; Sheppard & Trujillo 2005). None the less, numerical simulations by a number of authors (e.g. Holman & Wisdom 1993; Evans & Tabachnik 2000) suggest that Trojans could exist in long-lived and stable orbits in the vicinity of these planets.

A number of possible formation scenarios for the Jovian Trojan asteroids have been proposed. One suggestion is that the Trojans are planetesimals formed near, and captured by, the growing Jupiter possibly with the aid of a dissipative mechanism like gas drag or collisions (e.g. Marzari & Scholl 1998; Fleming & Hamilton 2000). Another possibility is that the Trojans were captured into co-orbital motion with Jupiter in the early Solar system, during the time of migration of the giant planets (Morbidelli et al. 2005). The origin of the Trojan asteroids of Mars and Neptune may, however, be different from the Jovian case. Chiang et al. (2003) suggest that debris from planetesimal collisions occurring after Neptune reached its current location may have accreted naturally in the 1 : 1 resonance to provide its Trojan clouds.

In this Letter, we consider the possibility that some of the Trojans may originate from the capture of Centaurs. This idea seems to have been first suggested by Rabe (1972), but hard evidence from numerical simulations has so far been lacking. The mechanism of capture is often invoked to explain the irregular outer satellites of Jupiter, Uranus and Neptune (e.g. Sheppard & Jewitt 2003; Sheppard, Jewitt & Kleyna 2005). Here, we supply examples from our suite of numerical integrations to confirm that it can also provide Trojans.

2 SIMULATIONS

In order to understand the behaviour of the comet-like Centaurs, 32 of them were chosen as the subject for large-scale numerical integrations. The orbits of each of the chosen objects – as given by The Minor Planet Center in 2002 June – were then incrementally modified to give 729 ‘clones’, which formed a 9 × 9 × 9 grid in the space of semimajor axis *a*, eccentricity *e* and inclination *i*. This gave a total of 23 328 test particles, which were then followed for 3 Myr under the gravitational influence of the Sun, Jupiter, Saturn, Uranus

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and Neptune, using the MERCURY integrator (Chambers 1999). The gravitational effects of the terrestrial planets were neglected. A more detailed exposition of the simulations is given in Horner, Evans & Bailey (2004a,b).

One of the areas of interest that prompted the integrations was the question of the temporary capture of objects by the giant outer planets, to both Trojan-like and satellite-like orbits. The orbits of the clones were recorded only at 100-yr intervals. Although short-lived satellite-like behaviour, such as that displayed by comets P/Helin–Roman–Crockett (Tancredi, Lindgren & Rickman 1990) and P/Gehrels 3 (Rickman & Malmort 1981), is missed, longer term captures are detectable within our numerical data set. Consequently, the data were searched for objects whose semimajor axis stayed within one Hill radius of that of Jupiter, Saturn, Uranus and Neptune – temporarily captured as either a moon or a Trojan. These provisional candidates were then examined in the co-rotating frame of the orbit of the planet to see whether they had Trojan-like or satellite-like behaviour. To ensure that an object was indeed captured, a minimum number of 800 orbital periods was required. For example, in the case of Jupiter, the object had to show Trojan-like or satellite-like behaviour for at least 9.5 kyr (∼800 orbital periods of Jupiter).

3 RESULTS AND DISCUSSION

From a total sample of 23 328 objects, 67 were captured as Trojans for a time-span of 800 or more orbital periods. This is approximately 0.3 per cent of the sample. The numbers are broken down according to each giant planet in Table 1. It is interesting that – even though there are no known Saturnian Trojans – Saturn is more efficient at capturing Centaurs temporarily into Trojan-like orbits than Jupiter. Table 1 also gives the mean duration $\langle T_{\mathrm{cap}} \rangle$ of the capture events. Of course, Newton's equations of motion are time-reversible, so some form of dissipation is required for permanent capture. All the captures in our data set are temporary with average durations of the order of kiloyears. It must be remembered that no capture events shorter than 800 orbital periods were examined and that such short captures could be the most common type of event.

Holman & Wisdom (1993) carried out surveys of the stability of test particles placed in the vicinity of the Lagrangian points of Jupiter and Saturn. They noted that the stable regions are much more ragged for Saturn than for Jupiter. In the case of Saturn, the stability zone is disrupted by islands of instability, possibly caused by the near 5 : 2 resonance between Jupiter and Saturn (Innanen & Mikkola 1989). Therefore it is understandable that the long-lived population of Jovian Trojans is larger than that of Saturn. Our calculations raise the possibility that the reverse may pertain to temporary captures. Such temporary Saturnian Trojans may well exist in substantial numbers. It may be that for Saturn the main delivery mechanism of Trojans is temporary capture from the Centaur region, rather than primordial capture of planetesimals.

Table 1. The numbers of objects captured as Trojans or satellites of the giant planets during 3-Myr integrations of 23 328 Centaur-like objects. $\langle T_{\mathrm{cap}} \rangle$ gives the mean duration of these capture events.

Object type	Number	$\langle T_{\mathrm{cap}} \rangle$ (in kyr)
Jupiter Trojans	10	81
Saturn Trojans	54	37
Uranus Trojans	3	139
Neptune Trojans	0	–
Jovian Satellites	1	–
Saturnian Satellites	0	–
Uranian Satellites	0	–
Neptunian Satellites	0	–

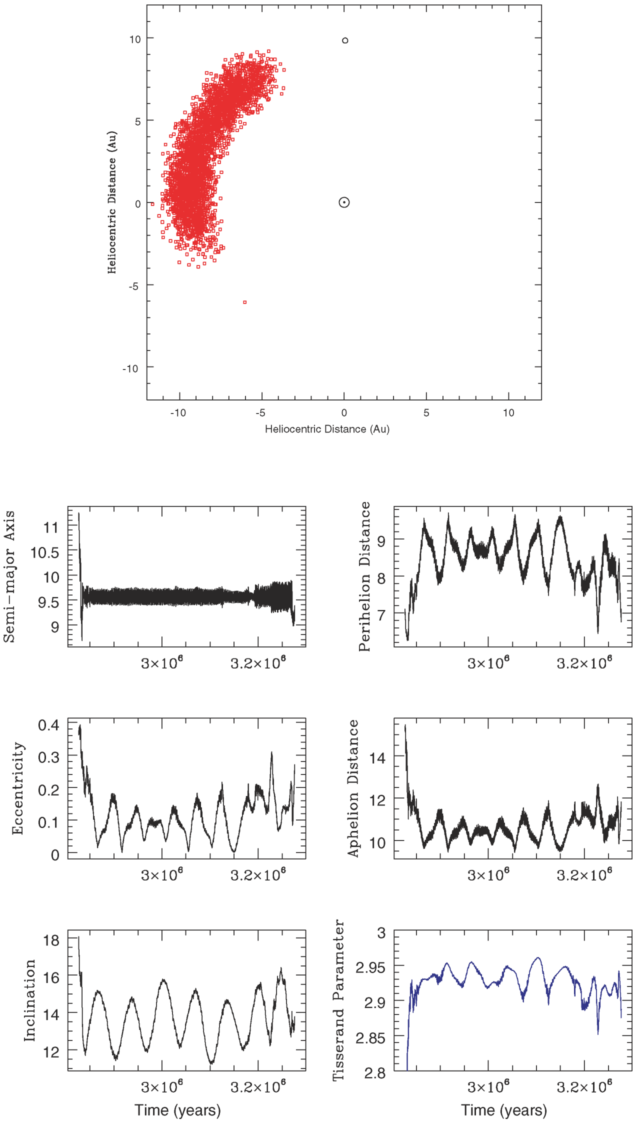

Figure 1. Capture of a clone of (10199) Chariklo as a Saturnian Trojan. The upper panel shows the orbit plotted in a frame co-rotating with Saturn. The positions of the Sun and Saturn are marked. The lower panel shows the evolution of the semimajor axis, perihelion and aphelion distance (all in au), inclination (in degrees) and eccentricity and the Tisserand parameter with respect to Saturn T_S. (The initial semimajor axis, eccentricity and inclination of the clone are $a = 15.724$ au, $e = 0.154$ and $i = 23\overset{\circ}{.}46$.)

Let us give two examples out of the 67 events listed in Table 1. Fig. 1 shows the temporary capture of a clone of (10199) Chariklo into the 1 : 1 resonance with Saturn. The upper panel shows the projection of the orbit on to the invariable plane in a frame co-rotating with Saturn. It is clear that the clone follows a tadpole orbit (e.g. Murray & Dermott 2000), librating about the leading or L_4 Lagrangian point. The temporary Trojan phase lasts for ∼400 kyr, during which the eccentricity e and inclination i librations are modest compared with its prior and subsequent evolution.

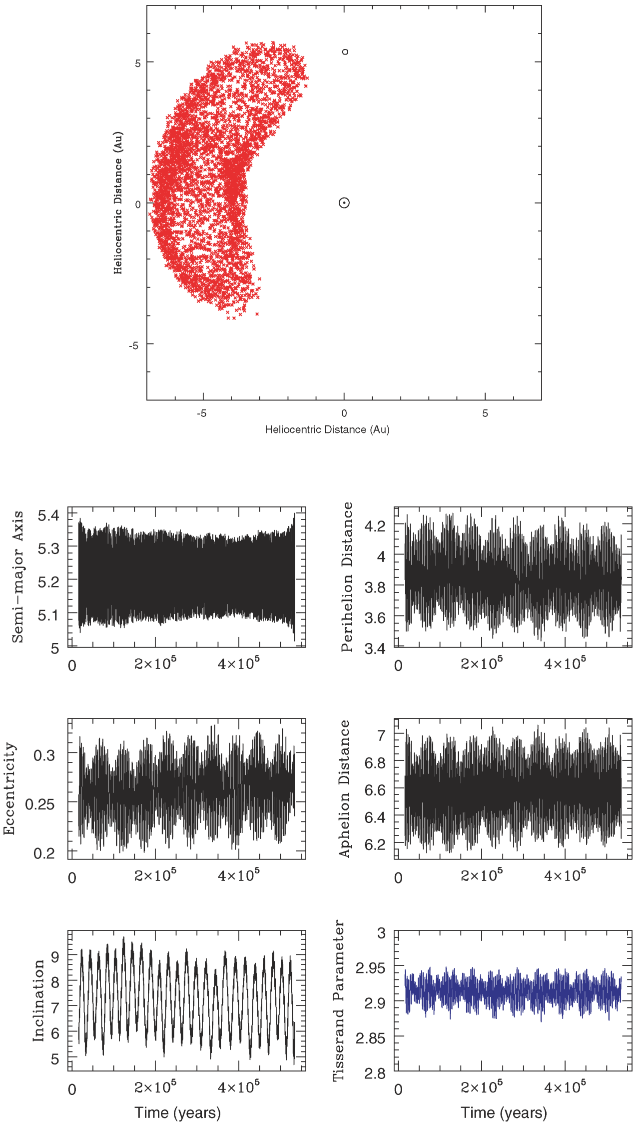

Figure 2. Capture of a clone of 1996 AR_{20} as a Jovian Trojan. The upper panel shows the orbit plotted in a frame co-rotating with Jupiter. The lower panel shows the evolution of the semimajor axis, perihelion and aphelion distance (all in au), inclination (in degrees) and eccentricity and the Tisserand parameter with respect to Jupiter T_{J}. (The initial semimajor axis, eccentricity and inclination of the clone are $a = 15.177$ au, $e = 0.617$ and $i = 6\overset{\circ}{.}17$.)

Fig. 2 shows the temporary capture of a clone of 1996 AR_{20} into the 1 : 1 resonance with Jupiter. The upper panel again shows that the clone is librating about the L_4 Lagrangian point. The clone displays moderate variations in semimajor axis a, eccentricity e and inclination i whilst in the resonance. It resides in the resonance for ~ 0.5 Myr before ejection from the Solar system. This is the longest example of Trojan capture in our data set.

In addition to the Trojan-like objects, we also searched for temporary satellite-like captures of Centaurs. As shown in Table 1, this is a much rarer occurrence. We found only one convincing example – a clone of (32532) Thereus (or 2001 PT_{13}) displayed behaviour which hints at a temporary moon capture by Jupiter. Although it has often been conjectured that the outer irregular satellites of the giant planets may have been captured, this seems to be a scarcer phenomenon than Trojan capture in our data set.

Table 2. The number of objects captured into the leading (L_4) and trailing (L_5) Trojan clouds, along with those objects captured on to horseshoe orbits. Objects that displayed two periods of Trojan behaviour in different regions gave a score of 0.5 in each region occupied.

Planet	L_4 capture	L_5 capture	Horseshoe
Jupiter Trojans	2	5	3
Saturn Trojans	25	26	3
Uranus Trojans	2.5	0	0.5
Neptune Trojans	0	0	0

In previous work (Horner et al. 2004a), the current population of the Centaurs with nuclei larger than ∼1 km in diameter was estimated at ∼44 300. Using the results of our simulations, we reckon that the capture rate of Centaurs as temporary Trojans is ∼40 objects every Myr (for lengthy captures). The average duration of such a capture is a few tens of thousands of years. Given the length of time that the clones can spend in these stable orbits, it is quite possible that there are objects lurking in the Trojan clouds of the outer planets that are temporary Centaur captures. In fact, simulations of the Jovian Trojans show that at least two objects currently classified as Trojans are experiencing only a brief visit to the region, rather than a prolonged stay (Karlsson 2004, and simulations by the authors).

The permanent Trojans of Jupiter are known to be more populous in the leading (L_4) cloud than in the trailing (L_5) cloud. Analysing the captured objects in our data set, no such trend is present. Table 2 shows the breakdown of the capture locations for our sample. It seems that the captured population has a different profile from the permanent one, with nearly equal likelihood of capture in the L_4 or L_5 region. Finally, Table 2 also records the fact that few of the captures are into horseshoe orbits. One possible reason is that such orbits are significantly less stable than their tadpole brethren. Hence captures in such orbits may be far less likely to survive the 800 revolutions required for detection in this survey.

4 CONCLUSIONS

This Letter has demonstrated a new possibility for the origin of some of the Trojans of the giant planets. They may be Centaurs, temporarily captured into the 1 : 1 resonances. We have used data from 3-Myr simulations of representatives of the Centaur population to provide specific examples of this delivery mechanism. In particular, Saturn seems to be most efficient at making such temporary captures from the Centaur region. Saturn captures the bulk of the ∼40 Centaurs every Myr that pass through a lengthy temporary Trojan phase (a capture for 800 or more orbital periods of the parent object). Since we expect ∼40 such lengthy captures, it is quite likely that the number of shorter captures is significantly higher, and hence that there may well be such temporary visitors residing in these regions at the present time. The objects captured within these simulations display a roughly equal likelihood of capture into the leading and trailing Trojan clouds, a quantitative difference from the observed long-lived population of Jovian Trojans.

Possible evidence of such interlopers within the Trojan clouds might be garnered from observations of colours or from photometric activity. For example, it would be interesting to see whether any Jovian Trojans display cometary out-gassing, since recently captured Centaurs may still contain volatiles, whilst any Trojans captured since the birth of the Solar system are unlikely to display such activity. Similarly, if any Jovian Trojans are found be of significantly different colour from other objects in the cloud, this may hint at a different delivery mechanism, and may help the identification of such temporary visitors. At Saturn, since it is unlikely that many Trojans would survive at the L_4 and L_5 points on time-scales approaching the age of the Solar system, it is likely that any Trojans discovered in the future represent recent, temporary captures, rather than a native population.

Morbidelli et al. (2005) suggested that the Jovian Trojan population may have been captured into co-orbital motion with Jupiter during the latter part of its proposed migration. The fact that temporary captures can be seen in our data set with such frequency seems to add weight to this mechanism for the formation of the Trojan clouds, by illustrating that temporary captures are not uncommon even at the current day. Given the fact of Jupiter's migration, it is quite feasible that objects originally captured on temporary orbits could be converted to ones that could reside in the Trojan region for the age of the Solar system.

ACKNOWLEDGMENTS

The authors thank Mark Bailey and David Asher for helpful comments.

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