Icarus 243 (2014) 287–295

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Giga-year evolution of Jupiter Trojans and the asymmetry problem

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ARTICLE INFO

Article history:
Received 17 June 2014
Revised 19 August 2014
Accepted 1 September 2014
Available online 10 September 2014

Keywords:
Asteroids, dynamics
Jupiter
Trojan asteroids

ABSTRACT

We present a series of numerical integrations of observed and fictitious Jupiter Trojan asteroids, under the gravitational effects of the four outer planets, for time-spans comparable with the age of the Solar System. From these results we calculate the escape rate from each Lagrange point, and construct dynamical maps of "permanence" time in different regions of the phase space.

Fictitious asteroids in L_4 and L_5 show no significant difference, showing almost identical dynamical maps and escape rates. For real Trojans, however, we found that approximately 23% of the members of the leading swarm escaped after 4.5 Gyrs, while this number increased to 28.3% for L_5. This implies that the asymmetry between the two populations increases with time, indicating that it may have been smaller at the time of formation/capture of these asteroids. Nevertheless, the difference in chaotic diffusion cannot, in itself, account for the current observed asymmetry (~40%), and must be primarily primordial and characteristic of the capture mechanism of the Trojans.

Finally, we calculate new proper elements for all the numbered Trojans using the semi-analytical approach of Beaugé and Roig (Beaugé, C., Roig, F.V. [2001]. Icarus, 153, 391–415), and compare the results with the numerical estimations by Brož and Rosehnal (Brož, M., Rosehnal, J. [2011]. Mon. Not. R. Astron. Soc. 414, 565–574). For asteroids that were already numbered in 2011, both methods yield very similar results, while significant differences were found for those bodies that became numbered after 2011.

1. Introduction

Although more than a century has passed since the discovery of the first Trojan asteroid in Jupiter's orbit (Wolf, 1906), the origin and orbital evolution of the Jupiter Trojans is still a matter of debate. As of March 2012, a total of 5179 members have been cataloged, including numbered and multi-oppositional asteroids. Of these, 3394 are located around L_4, while only 1785 inhabit the tadpole region around L_5.

In recent years a number of Trojans have also been detected around other planets (e.g., Innanen, 1991; Tabachnik and Evans, 1999; Connors et al., 2011). Although those associated to the terrestrial planets are believed to be dynamically unstable in the long run, and therefore temporary populations, the asteroids associated to the outer planets appear more long lived. In particular, there is evidence that Neptune houses a Trojan population that rivals and may even surpass that around Jupiter (Chiang and Lithwick, 2005).

Many different mechanisms have been proposed to explain the origin of these bodies, particularly the Jupiter Trojans. Traditionally, these mechanisms have either disregarded planetary migration or assumed that any variation in the orbital architecture of Jupiter and Saturn was fairly smooth and adiabatic. According to this scenario, rouge asteroids in heliocentric orbits were trapped into the Lagrange points either through the effects of gas drag with the primordial nebula (Kary and Lissauer, 1995) or through the increase in size of the tadpole regions accompanying the mass growth of Jupiter itself (Marzari and Scholl, 1998). Collisions among these asteroids could also have caused sufficient changes in their orbital elements to cause permanent trapping around the equilateral Lagrange points (Shoemaker et al., 1989).

Gomes (1998) and Michtchenko et al. (2001) analyzed the stability of the Trojan region assuming that Jupiter and Saturn were locked in mean-motion resonances (MMR). They found that the tadpole region would then become unstable, ejecting any primordial Trojan there in place. Although the aim of these papers was to place limits on planetary migration, Morbidelli et al. (2005) inverted this interpretation and pointed out that the same instability could also allow for the capture of new asteroids into the region. This new scenario, dubbed *chaotic capture*, appeared as a natural consequence of the chaotic evolution of the giant planets under the Nice model. Contrary to more traditional theories, it

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http://dx.doi.org/10.1016/j.icarus.2014.09.002
0019-1035/

seemed to be able to reproduce the inclination distribution, a dynamical characteristic until then elusive.

As the Nice model evolved, so did its interpretation of the origin of Trojans. Nesvorný et al. (2013) presented new numerical simulations within the Jumping-Jupiter version of the Nice model (Morbidelli et al., 2009; Nesvorný, 2011; Nesvorný and Morbidelli, 2012). This new *jump-capture* mechanism proposes that part of the remnant planetesimal disk was trapped in the Lagrange points following almost instantaneous changes in the semimajor axis of Jupiter caused by close encounters with ice giants.

Perhaps the most prominent and curious dynamical characteristic of the Jupiter Trojans is the observed asymmetry between the populations in L_4 and L_5. Not only does the leading swarm have almost 40% more asteroids than the trailing region (Grav et al., 2011; Nesvorný et al., 2013), but there are also significant differences in the asteroid families. While L_4 hosts several numerous family candidates (Eurypides being the most notorious, see Beaugé and Roig, 2001; Brož and Rosehnal, 2011), the region around L_5 only contains small (albeit compact) agglomerations.

The origin of this asymmetry is still a mystery. Dynamical studies of the Trojan region show the same resonance structure and stability limits in both Lagrange points, even when considering the perturbations of additional planets (e.g. Érdi, 1996; Marzari et al., 2002; Robutel and Gabern, 2006). Most of the proposed formation mechanisms also predict similar populations in both equilateral Lagrange points, including the first versions of the Nice model (e.g. Morbidelli et al., 2005). So, it appears that even under the most complex scenarios, both L_4 and L_5 are dynamically equivalent. However, recently Hou et al. (2014) showed that a temporary asymmetry my be obtained with the same initial conditions in both tadpole regions. this asymmetry, however, is short-lived and cannot at present account for the observed disparity.

Perhaps even more drastic measures are necessary to create an asymmetry. In the mechanism proposed by Nesvorný et al. (2013), close encounters with an ice giant could have partially depleted one of the Lagrange points while leaving the other virtually unaffected. Once again, as it occurs several times in exoplanetary systems, planetary scattering appears as an excitation mechanism much more effective than slow-acting long-range gravitational perturbations. Since scattering is stochastic and extremely sensitive to initial conditions, the final ratio of Trojans in L_4 and L_5 (i.e. $N(L_4)/N(L_5)$) is not deterministic. However, some of the runs presented in Nesvorný et al. (2013) do seem to be able to obtain values similar to those observed in the real asteroids.

The aims of this paper are very simple. Since it is known that even today the Trojan population is undergoing slow chaotic diffusion (Tsiganis et al., 2005; Érdi et al., 2013), what dynamical characteristics can be considered primordial? In particular, can the current $N(L_4)/N(L_5)$ ratio be considered invariant in time, or was the original asymmetry different?

This paper is organized as follows. In Section 2 we review and analyze the main physical and dynamical characteristics of the Trojan swarm and present the results of a long term integration of observed Trojans. In Section 3, we extend our Gyr-simulations to fictitious massless particles in L_4 and L_5, and compare those results with the evolution of the real asteroids. Finally, discussions and conclusions close the paper in Section 4.

2. The observed population

2.1. Orbital and dynamical features

As of March 2013, there were 2972 numbered Jupiter Trojans, thus with fairly reliable orbits. Of these, 1975 (over 66%) display tadpole orbits around L_4, while 997 are associated to L_5. The population of Jupiter Trojans is believed to be complete up to absolute magnitude $H = 12$ (Szabó et al., 2007); however for the purposes of the present study we will consider the complete (numbered) population regardless of the absolute magnitude.

Fig. 1 shows the distribution of both swarms in the (e, a) and (i, a) planes, where a is the semimajor axis (in AU), e the eccentricity and i the inclination with respect to the Laplace plane of the outer Solar System. The upper half of the plots (positive values of e and i) corresponds to L_4, while the lower half corresponds to L_5. The orbital elements are osculating, but each asteroid was integrated until it crossed the representative plane defined by the conditions $M - M_J = 0$, $\varpi - \varpi_J = \pm 60^\circ$ and $\Omega - \Omega_J = 0$. Here M is the mean anomaly, ϖ the longitude of pericenter and Ω the longitude of the ascending node. Variables with subscript "*J*" correspond to Jupiter. The orbits were evolved using the hybrid integrator EVORB (Fernández et al., 2002) including the gravitational perturbations of all outer planets. The masses of the inner planets were added to the Sun, and we adopted a time-step of 0.2 years.

One of the most interesting dynamical characteristics of the Trojan asteroids is that not all of them lie in orbits that are stable over time-spans comparable with the age of the Solar System. Although the chaotic nature of some of these asteroids has been known for many years (e.g. Milani, 1993), at first it was not clear whether this chaoticity was local (i.e. "stable-chaos") or whether it could lead to ultimate escapes from the Lagrange points. Levison et al. (1997) were the first to present Gyr-long numerical simulations of known and fictitious Trojans, showing that indeed approximately 12% of the asteroids were unstable due to the gravitational perturbations of the other giant planets in times of the order of the age of the Solar System. Furthermore, they showed that the orbits of the escaped asteroids resemble those of the Jupiter Family Comets.

Tsiganis et al. (2005) revisited this problem, calculating dynamical maps of Lyapunov characteristic exponents for grids of elements (D, e) for a set of discrete values of the inclination i. Here D is the semi-amplitude of libration of the asteroid. Although their total integration time was only equal to 4 Myr, it was sufficient to correlate their maps with the distribution of real Trojans, and identify which asteroids could lie in unstable orbits. Those candidates were integrated a second time for 4.5 Gyr, confirming the unstable nature of their motion. The results of Tsiganis et al. (2005) show that $\sim$17% of the real Trojans escape from the Lagrange regions in this time interval and are effectively unstable. The "effective" stability region shrinks with increasing orbital inclination.

It is also possible to observe some special features of the orbital elements of the Trojan population. In Fig. 1, the inclinations of L_5 Trojans seems to be more disperse than in L_4. There is a well-defined set of low inclination Trojans in L_4 that is not observed in such a number in L_5. In fact, while the mean values of osculating semimajor axis and eccentricity are almost the same for L_4 and L_5, i.e. $\langle a_{L_4} \rangle = 5.2062$ AU, $\langle a_{L_5} \rangle = 5.2068$ AU, $\langle e_{L_4} \rangle = 0.072$, $\langle e_{L_5} \rangle = 0.074$, the mean value of the inclinations in L_5 is greater than in $L_4 : \langle i_{L_5} \rangle = 14^\circ.2$, $\langle i_{L_4} \rangle = 10^\circ.4$. Both results are in agreement with Slyusarev (2013).

However, the difference in inclination distribution is size-dependent. There are a number of papers that analyzed the dependence of the cumulative size distribution (CSD) and albedos on the Trojan sizes. Jewitt et al. (2000) found that there must be a break in the CSD at diameters $d \sim 60 - 80$ km. Yoshida and Nakamura (2008) analyzed the CSD of L_4 and L_5 and found that on a range of 5 km $< d <$ 93 km, the slope of the CSD is nearly constant, breaking at $d \sim 90$ km. Fraser et al. (2014) obtained a CSD power-law for Trojans that breaks at absolute magnitude $H = 8.4$, that corresponds to a diameter $d = 130$ km (for albedo 0.045). Fernández et al. (2003) derived visual albedos for 32 Trojans with diameters $d > 50$ km and found a mean value of 0.056 and 0.041 depending on the beaming parameter. Later, Fernández et al. (2009) presented thermal observations of 44 small Trojans with diameters $5 < d < 24$ km