Icarus 247 (2015) 112–125

Contents lists available at ScienceDirect

Icarus

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

The intrinsic Neptune Trojan orbit distribution: Implications for the primordial disk and planet migration

Alex H. Parker

University of California at Berkeley, Department of Astronomy, 501 Campbell Hall # 3411, Berkeley, CA, 94720-3411, United States

ARTICLE INFO

Article history:
Received 13 July 2014
Revised 22 September 2014
Accepted 23 September 2014
Available online 2 October 2014

Keywords:
Trans-neptunian objects
Trojan asteroids
Planets, migration
Neptune
Origin, Solar System

ABSTRACT

The present-day orbit distribution of the Neptune Trojans is a powerful probe of the dynamical environment of the outer Solar System during the late stages of planet migration. In this work, I conservatively debias the inclination, eccentricity, and libration amplitude distributions of the Neptune Trojans by reducing *a priori* unknown discovery and follow-up survey properties to nuisance parameters and using a likelihood-free Bayesian rejection sampler for parameter estimation. Using this *survey-agnostic* approach, I confirm that the Neptune Trojans are a dynamically excited population: at >95% confidence, the Neptune Trojans' inclination width must be $\sigma_i > 11^\circ$. For comparison and motivation purposes, I also model the Jupiter Trojan orbit distributions in the same basis and produce new estimates of their parameters (Jupiter Trojan $\sigma_i = 14.4^\circ \pm 0.5^\circ$, $\sigma_{L11} = 11.8^\circ \pm 0.5^\circ$, and $\sigma_e = 0.061 \pm 0.002$). The debiased inclination, libration amplitude, and eccentricity distributions of the Neptune Trojans are nominally very similar to those of the Jupiter Trojans. I use these new constraints to inform a suite of simulations of Neptune Trojan capture by an eccentric, rapidly-migrating Neptune from an initially dynamically-hot disk. These simulations demonstrate that if migration and eccentricity-damping timescales were short ($\tau_a \lesssim 10$ Myr, $\tau_e \lesssim 1$ Myr), the disk that Neptune migrated into *must* have been pre-heated (prior to Neptune's appearance) to a width comparable to the Neptune Trojans' extant width to produce a captured population with an inclination distribution width consistent with that of the observed population.

1. Introduction

A small sample of Neptune Trojans has been accumulated by a variety of surveys; however, inferences drawn from this sample about the intrinsic distributions of Neptune Trojan orbital properties have been limited and generally qualitative. The challenge inherent in extracting meaningful information from this sample is accurately determining the properties of the surveys that discovered them, and the properties of all surveys that, while sensitive to Neptune Trojans, did not discover any. In this work, I treat these unknown survey properties as nuisance parameters, and marginalize over them to extract as much useful information about the intrinsic orbital distributions of the Neptune Trojans as possible.

Of particular dynamical interest are the inclination, eccentricity, and libration amplitude distributions. These distributions encode information about the formation mechanism (in situ formation, chaotic capture, or other processes) and post-formation evolution. Several Neptune Trojans have remarkably high inclinations ($\sim$25° to 30°), even though surveys have by-and-large targeted fields near the Ecliptic where objects on inclined orbits spend relatively little time. Previous works have noted that this qualitatively indicates the existence of a large, poorly-sampled high-inclination Neptune Trojan population (Sheppard and Trujillo, 2006, 2010a).

In this work, I simultaneously consider the inclination, eccentricity, and libration amplitude distributions, generate synthetic populations of Neptune Trojans defined by these distributions, then pass these synthetic populations through "coverage functions:" simplified observational filters that are treated as independent functions of heliocentric ecliptic latitude β, and heliocentric longitudinal separation from the Trojan libration centers λ' (libration centers located roughly ±60° from Neptune), and inclination. The properties of these observational coverage functions are then marginalized over, effectively marginalizing the unknown properties of the surveys which discovered the Trojans. Like the Jupiter Trojans and other trans-Neptunian populations, the inclination distribution is modeled as a Brown's distribution ($p(i) \propto \sin(i)\exp(-i^2/2\sigma^2)$). The libration amplitude L_{11} and eccentricity e distributions are both modeled as Rayleigh distributions, motivated by the distributions of the Jupiter Trojans. The inclination, libration amplitude, and eccentricity distributions are all truncated at upper limits derived from stability constraints, requiring appropriate corrections to their proposal volume and

E-mail address: alexharrisonparker@gmail.com

http://dx.doi.org/10.1016/j.icarus.2014.09.043
0019-1035/

probability density functions. All statistical analysis is performed in the conceptually simple yet analytically powerful "Approximate Bayesian Computation" framework, described in Section 3.

2. Sample

The Minor Planet Center (MPC) lists nine Neptune Trojans (six L4, three L5), but one of the L5 Trojans is unstable and likely a recently captured Centaur (Gladman et al., 2012; Horner and Lykawka, 2012). This object is therefore not considered to be reflective of the intrinsic inclination distribution of the (putatively primordial) Neptune Trojans. With the addition of the newly discovered L5 Trojan 2011 HM_{102} (Parker et al., 2013), the 8 known long-term stable Trojans have ecliptic inclinations ranging from 1.3° to 29.4°, and heliocentric ecliptic latitudes at discovery ranging in amplitude from 0.6° to 11.7°. Fig. 1 illustrates these properties, and it is clear that Trojans have generally been discovered at latitudes significantly lower than their inclinations, even though an object spends roughly 50% of their time at latitudes greater than 70% of their inclination. Only the object 2006 RJ_{103} was higher than its median latitude at the time of discovery. This indicates that it is likely that most surveys that discovered Neptune Trojans targeted the ecliptic, and were therefore strongly biased toward detecting low inclination objects, and yet discovered a surplus of high-inclination objects. The larger number of known L4 Neptune Trojans compared to L5 is likely an artifact of the L5 cloud being more poorly surveyed due to its current proximity to the Galactic plane.

These Neptune Trojans were discovered by a variety of surveys, performed at a variety of facilities and under varying conditions, and normally would not represent a sample from which estimating an intrinsic, debiased orbit distribution would be statistically advisable. However, using appropriate statistical care, we can make a conservative estimate of the range of plausible properties of the Neptune Trojan orbital distribution by marginalizing over the plausible volume of the unknown characteristics of all discovery surveys. This *survey-agnostic* approach can conceivably be applied to other populations, and since it is performed in a Bayesian framework, the outcomes can be meaningfully combined with

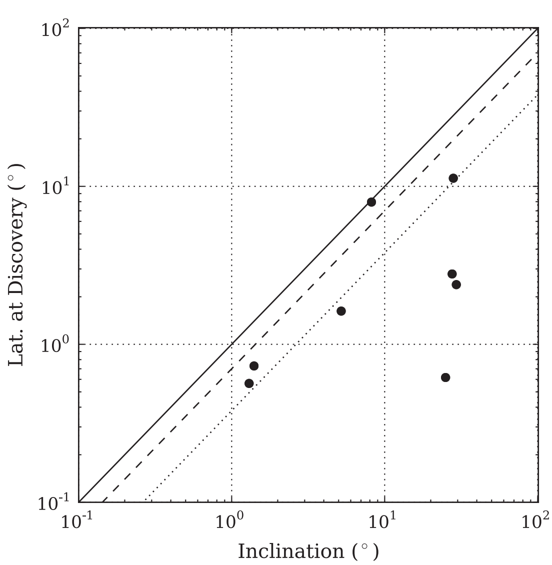

Fig. 1. Heliocentric ecliptic latitude at discovery vs. inclination for known long-lived Neptune Trojans. Solid line indicates maximum possible latitude achievable for a given inclination, dashed line indicates an object's median latitude for a given inclination, and dotted line indicates an object's lower-quartile latitude for a given inclination. All but one object falls below the median, and half the sample falls in the lowest quartile.

Table 1
Adopted Neptune Trojan properties.

Name	i^{a} (°)	$L_{11}{}^{b}$ (°)	$\vert\beta\vert^{d}$ (°)	λ'^{c} (°)
2001 QR_{322}	1.3	$25.5^{+0.4}_{-0.8}$	0.57	10.46
2004 UP_{10}	1.4	$10.8^{+1.0}_{-0.3}$	0.73	10.24
2005 TN_{53}	25.0	$8.7^{+0.3}_{-0.5}$	0.62	8.51
2005 TO_{74}	5.2	$9.2^{+0.2}_{-0.5}$	1.62	9.12
2006 RJ_{103}	8.2	$6.3^{+0.1}_{-0.3}$	7.99	0.58
2007 VL_{305}	28.1	$14.2^{+0.03}_{-0.10}$	11.25	9.44
2008 LC_{18}	27.6	$16.4^{+1.3}_{-1.1}$	2.80	0.84
2011 HM_{102}	29.4	$9.8^{+0.4}_{-0.4}$	2.60	7.72

[a] J2000 ecliptic inclination.
[b] Half-peak RMS libration amplitude and 1σ uncertainty.
[c] Absolute value of J2000 heliocentric ecliptic longitude separation of object and nominal Trojan center; see Eq. (7).
[d] J2000 Heliocentric ecliptic latitude.

results from large, monolithic, well-characterized surveys such as DES (e.g., Gulbis et al., 2010), CFEPS (e.g., Petit et al., 2011) and the ongoing *Outer Solar System Origins Survey*.[1] Because of their small sample size and currently poorly-characterized orbit distributions, I consider the Neptune Trojans a useful demonstration population.

The libration amplitudes listed in Table 1 were generated with the same technique as Parker et al. (2013). Each object's motion was integrated with *mercury6* (Chambers, 1999) in the presence of the giant planets for 1 Myr. 100 clones of each object were integrated, with initial state vectors centered on the JPL Horizons solution, perturbed to populate the Cartesian uncertainty manifold generated by fitting all ground-based observations of each object with the *fit_radec* and *abg_to_xyz* routines developed in association with Bernstein and Kushalani (2000). Libration amplitudes for each clone were measured by assuming that libration is sinusoidal and deriving the sinusoidal half-amplitude from the RMS of the n samples of the resonant angle over the entire 1 Myr integration: (see Table 2)

$$L_{\rm fit} = \left(\frac{2}{n}\sum_{i=1}^{n}(\phi_i - \langle\phi\rangle)^2\right)^{\frac{1}{2}}, \tag{1}$$

which produces the more appropriate half-amplitude for scaling a sinusoidal model than the usual peak-to-peak definition of $L = \frac{1}{2}[\max(\phi_i) - \min(\phi_i)]$. The RMS produces a value that better reflects the mean libration behavior, while defining the amplitude from peak to peak is sensitive to large, single-cycle excursions of the resonant argument. As such, the RMS-defined amplitude is always smaller than the peak-to-peak definition.

3. Approximate Bayesian computation

For all parameter estimation in this work I utilize a likelihood-free rejection sampler – specifically, the "Approximate Bayesian Computation" rejection (ABCr) scheme first presented in Pritchard et al. (1999). Approximate Bayesian Computation (ABC) is conceptually simple but statistically powerful, and has the primary advantage of not requiring the computation of any true likelihood value. I briefly outline this approach below, and refine its description later as merited by the specifics of each application. The literature on ABC is well-developed, with much more sophisticated methods available than those employed here; for a recent review see Marin et al. (2011).

[1] CFHT Large Program proposal: http://cfht.hawaii.edu/en/science/LP_13_16/OSSOS.pdf.