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Search strategies for Trojan asteroids in the inner Solar System

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ABSTRACT

Trojan asteroids are minor planets that share the orbit of a planet about the Sun and librate around the L4 or L5 Lagrangian points of stability. They are important because they carry information on early Solar System formation, when collisions between bodies were more frequent. Discovery and study of terrestrial planet Trojans will help constrain models for the distribution of bodies and interactions in the inner Solar System.

We present models that constrain optimal search areas, and strategies for survey telescopes to maximize the probability of detecting inner planet Trojans. We also consider implications for detection with respect to the Gaia satellite, and limitations of Gaia's observing geometry.

1. Introduction

Trojan asteroids are minor planets that share the orbit of a planet about the Sun, and librate around the Lagrangian points of stability that lie 60° ahead of (L4), or behind (L5), the planet in its orbit. Trojans represent the solution to Lagrange's famous triangular problem and appear to be stable on long time-scales (100 Myr to 4.5 Gyr) (Pilat-Lohinger et al., 1999; Scholl et al., 2005) in the N-body case of the Solar System. This raises the question whether the Trojans formed with the planets from the Solar nebula or were captured in the Lagrangian regions by gravitational effects. Study of the Trojans therefore provides insight into the early evolution of the Solar System.

About 5000 Jupiter Trojans are currently known to exist. Some searches have been conducted for Earth Trojans (ET) (Dunbar and Helin, 1983; Whiteley and Tholen, 1998; Connors et al., 2000). A search covering approximately 0.35 deg^2 by Whiteley and Tholen (1998) resulted in a crude upper population limit of fewer than three objects per square degree, down to R=22.8. A subsequent search by Connors et al. (2000) covering about nine square degrees, down to R=22, failed to discover any ETs. Recent examination of data from the WISE satellite has resulted in the discovery of the first known ET (Connors et al., 2011). Among the other terrestrial planets, four Trojans have been discovered in the orbit of Mars. Current models (Mikkola and Innanen, 1990; Tabachnik and Evans, 2000a) suggest that this represents less than a tenth of the Mars Trojan population.

This paper describes probability distributions synthesized from existing models. This allows us to constrain optimal search areas and examine strategies to maximize the probability of detecting Trojans. We also examine the possibility of detection of Trojans by the Gaia satellite.

2. Models

2.1. Earth Trojans

A synthesis of a stable orbit inclination model (Morais and Morbidelli, 2002) and heliocentric longitude model (Tabachnik and Evans, 2000b) was used to identify probability regions for existence of bodies (Fig. 1). With limits established for the regions of interest the sky area in the heliocentric frame can be easily determined using the standard solid angle integral $\int\int_S (\mathbf{r}\cdot\mathbf{n})/r^3\,dS$ (where $\mathbf{r}$ is the radius vector, $\mathbf{n}$ is the unit normal vector, and $r=|\mathbf{r}|$). Calculation of the geocentric solid angle, necessary for Earth-based observations, requires a transformation from the heliocentric reference. A numerical integration is performed with which we can calculate the sky area presented by any region from any position. This enables determination of the sky area for an Earth-based observer, or a space-based instrument such as the Gaia satellite which will be positioned at Earth's L2 Lagrangian point.

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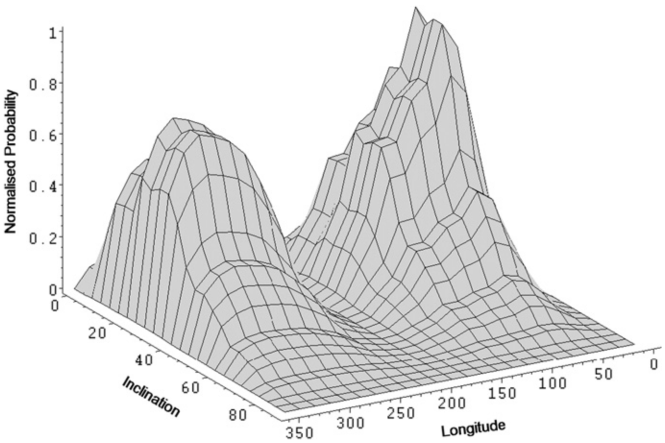

Fig. 1. Normalised probability contour for Earth Trojan bodies by inclination and Heliocentric longitude (degrees). The figure shows peak detection probabilities for longitudes consistent with the classical Lagrangian points but that bodies, while co-orbital with Earth, are unlikely to be co-planar.

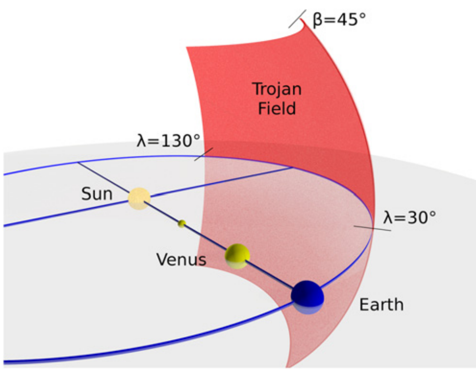

Fig. 2. Perspective illustration of Earth Trojan (L4) field. The field is bounded by Heliocentric longitude limits $30^\circ \le \lambda \le 130^\circ$ and inclination limit $\beta \le 45^\circ$. A complementary field exists in the trailing Lagrangian L5 region.

The ET fields (Fig. 2) are bounded by the upper inclination limit (FWHM) of $\sim 45^\circ$ (Morais and Morbidelli, 2002) and heliocentric longitude limits (FWHM) of $30^\circ \lesssim \lambda \lesssim 130^\circ$ (L4 region) and $240^\circ \lesssim \lambda \lesssim 340^\circ$ (L5 region) (Tabachnik and Evans, 2000b). The heliocentric solid angle of each of these regions is 2.468 sr (8100 deg^2). The geocentric solid angle[1] of the L4 ET field is 1.066 sr (3500 deg^2). The time required to completely survey this area, several hours even for widefield survey telescopes (see Table 1), is greater than the amount of time the field is visible per day.

Selecting inclination limits of $10^\circ \lesssim \beta \lesssim 45^\circ$ (Fig. 3), based on the FWHM of the binned inclination distribution in Morais and Morbidelli (2002), reduces the sky area of the field to about 1300 deg^2 and includes $\sim 74\%$ of those simulated bodies. A widefield telescope can survey this field in a single session of about 1.5 hours (Table 2). A second set of observations is normally necessary for moving object detection. These paired sessions should be repeated at intervals of no more than three months since the field spans 100° longitude. Such a programme will take one year to complete. This strategy requires a significant amount of telescope time on these nights. This is not considered an optimal strategy as one aim is to have minimal impact on other activities.

[1] The Python code used to calculate these areas is available from the first author on request.

Table 1
Comparison of survey telescopes showing the required time to survey the entire field.

Telescope	Limiting mag.	Exposure (s)	FOV (deg^2)	Entire field		Instrument capabilities
				FOVs	Time (h)	
Catalina	$V \sim 20$	30	8.0	437	3.6	Drake et al. (2003)
Pan-STARRS	$R \sim 24$	30	7.0	499	4.2	Jedicke et al. (2007)
LSST[a]	$r \sim 24.7$	30	9.6	364	3.0	Jones et al. (2009)
Gaia[b]	$V \sim 20$		0.69	63		Mignard et al. (2007)

[a] The Large Synoptic Survey Telescope (LSST) is still in the development phase (www.lsst.org).
[b] Gaia will operate in a continuous scanning mode where the CCD array will be read out at a rate corresponding to the angular rotation rate of the satellite (6 h period). The FOV value represents the number of rotations by Gaia. Gaia's specific precession parameters are not considered so values should be considered as representative.

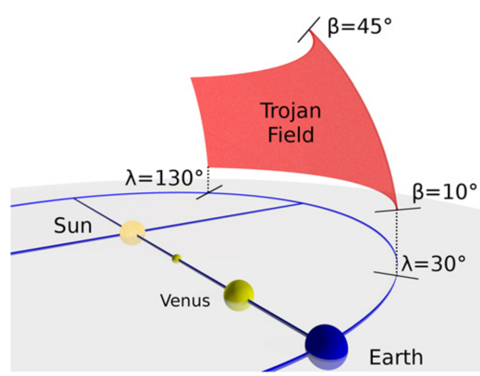

Fig. 3. The Earth Trojan (L4) target field ranges from Heliocentric longitude $30^\circ \le \lambda \le 130^\circ$ and latitude $10^\circ \le \beta \le 45^\circ$. A complementary field exists in the trailing Lagrangian L5 region. This illustration represents the search field in which a body will be observable some time during its orbit.

Table 2
Comparison of survey telescopes showing the required time for different survey strategies.

Telescope	Entire field		Restricted field		Ecliptic region		10° swath	
	FOVs	Time (h)	FOVs	Time (h)	FOVs	Time (min)	FOVs	Time (min)
Catalina	437	3.6	163	1.4	112	56	18	9
Pan-STARRS	499	4.2	186	1.6	128	64	20	10
LSST	364	3.0	136	1.2	94	47	15	8

A strategy which further reduces the per-session time is to survey a region bounded by the longitude limits and lower inclination limits to detect ETs as they cross the ecliptic. This reduces the sky area of the region to 900 deg^2 and results in a corresponding decrease in telescope time per-session (Table 2). The duration of this programme is six months as any Trojans detected in that six-month period would be crossing either to the North or to the South. However, the observations must be repeated at more frequent intervals since, in this region, the ET will have a higher apparent motion than at the highest or lowest points in its orbit, as indicated in Morais and Morbidelli (2002). As a consequence it will cross this region relatively quickly.