Earth's Trojan Asteroid

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It was realized in 1772 that small bodies can stably share the orbit of a planet if they remain near 'triangular points' 60° ahead of or behind it in its orbit[1]. Such so-called "Trojan asteroids" have been found co-orbiting with Jupiter[2], Mars[3], and Neptune[4]. They have not hitherto been found associated with Earth[5], where the viewing geometry poses difficulties, although other kinds of co-orbital asteroids (horseshoe orbiters[6] and quasi-satellites[7]) asteroids have been observed[8]. Here we report the search of the archive of an infrared satellite for possible Earth Trojans, producing the candidate 2010 TK_7. We subsequently made recovery observations, establishing that it is a Trojan companion of Earth, librating around the L_4 (leading) Lagrange triangular point. Its orbit is stable over at least ~10^4 years.

The existence of Trojan asteroids of other planets raises the question of whether such companions could exist for our planet. Despite studies showing that such bodies could be relatively stable[5], and possibly wander relatively far from the Lagrange points[9], they would dwell mostly in the daylight sky as seen from Earth, making detection difficult. Indeed they hitherto have never been observed. The launch of the Wide-field Infrared Survey Explorer (WISE) in 2009[10] provided improved viewing circumstances that enabled new detections of over 500 near-Earth objects[16]. WISE searched large areas of sky always 90º from the Sun, with high efficiency for asteroidal bodies, and good astrometric accuracy. Examining WISE discoveries in the expectation that Earth co-orbitals, possibly including a Trojan, could be found, resulted in two

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promising candidates, 2010 SO_{16} and 2010 TK_7. Both are larger than most co-orbital objects, being several hundred meters in diameter, and the former is horseshoe orbiter[17]. The latter we identified as likely being an Earth Trojan, based on a 6-day observational arc near the time of discovery. Its observational recovery at the Canada-France-Hawaii telescope[18] in April 2011, after spending months in an unfavorable position as seen from Earth, so greatly improved the knowledge of the orbit that we can state with certainty that 2010 TK_7 is the first known Earth Trojan.

The characteristic "tadpole" motion of this Trojan asteroid is shown in Fig. 1 in the frame corotating with Earth. The one-year averaged curve shows the center of motion librating about the L_4 Lagrange point 60° ahead of Earth. The period of this motion is presently 390 years. Superposed on this is an annual motion or epicycle[19,20,2] (not shown for clarity). This mode of display emphasizes the longitudinal motion despite the enhanced radial scale: the asteroid's mean position drifts along the red line, from the "head" of the tadpole near the Earth, to the far "tail" where it is nearly on the opposite side of the Sun from the Earth. The asteroid's relatively large eccentricity of e=0.191 results in an annual radial motion between roughly 0.81 and 1.19 AU (an AU is the Earth-Sun distance). The inclination of 2010 TK_7 is about i=20.9°, so that there is significant motion perpendicular to Earth's orbital plane. The asteroid's e and i produce a large epicycle which is responsible for the object being able to be viewed at the solar elongation of 90° at which WISE observed, with it now at the near-Earth end of the tadpole. Changes in relative longitude θ-θ_E and semimajor axis a of the object's orbit are shown for the period 420 B.C. to 4300 A.D (Fig. 1 middle panel). In the present epoch, the longitude remains in the sector of L_4, trapped between Earth and L_3. Interaction with Earth at the near-Earth end of the tadpole results in rapid decrease in a, making the object increase its angular speed (Kepler's third law), and outpace Earth. This is currently taking place. Slow resonant interaction on the other parts of the tadpole increases a, making the object slow gradually so that it again approaches Earth. In the current cycle, this takes place in the years 2050 to 2350 A.D., approximately. Repetition of this cycle leads to a sawtooth pattern in the semimajor axis a (lower panel of Fig 1).

The present motion of 2010 TK_7 is well-established, but there are inherent limits on our ability to compute orbits into the past or future. Chaos limits our ability to predict the asteroid's position with high accuracy over time scales greater than about 250 years. However, we can still discuss the basic nature of its orbit with confidence by computing the motion of many 'dynamical clones' whose orbital parameters vary[7] within the limits set by observations. Approximately 1800 years in the past, and over 5000 years in the future, the 100 clone orbits we computed diverged sufficiently that we must say that even the asteroid's precise behaviour cannot be predicted with certainty outside that ~7000 year span. The range of behaviour shown by the clones, and thus possible for the real object, includes transition to horseshoe modes and "jumping" between Lagrange points. Short-term unstable libration about the L_3 Lagrange point opposite the Sun can occur due to the asteroid's large inclination i. Such orbits were theorized as early as 1920[20], but no real object had yet been suspected to enter them.

Jumping from one Lagrange point to the other is a behaviour previously attributed to Jupiter Trojan 1868 Thersites[26], and was found in about half the clone orbits. Here, the large e leads to longitudinal excursions when near L_3. In Fig.2 these are shown to have allowed (about 500 A.D.) a rapid transition of 2010 TK_7 from L_5 to the present L_4 libration. The libration now remains only in the sector of L_4 and is relatively stable, in a classic[19] Trojan pattern, though of large amplitude.

Chaotic effects play a large role in the behaviour of this asteroid. Its sensitivity to small influences when in the vicinity of the L_3 point allows the range of outcomes which we have observed among the clones. We expect a special sensitivity to effects from Jupiter, which are 80 times stronger than those of Earth when Jupiter is at the same celestial longitude as the L_3 point. The overall Trojan behaviour is dictated by 1:1 orbital resonance with Earth, but large nonresonant effects such as those of Jupiter are important in influencing the asteroid's chaotic behaviour. This is illustrated by the fact that the horizontal "banding" in *a* shown in Fig. 2 has a period near that of Jupiter. Many clone orbits make repeated transitions between the Lagrange points, so that the chaos can be stable[27], with L_4 and L_5 each defining permitted regions of phase space. Knowledge of the orbit will improve as it is observed over the years, but its chaotic nature dictates that dynamics-based discussions of the origin, fate, and genetic relationships of 2010 TK_7 will necessarily remain statistical in nature.

Earth Trojan asteroids have been proposed as natural candidates for spacecraft rendezvous missions[11]. However, the inclination of 2010 TK_7 results in a delta-v of 9.4 km/s required, where other near-Earth asteroids have values below 4 km/s[11]. The reported absolute magnitude of H=20.7 puts the diameter of 2010 TK_7 at 300m with an assumed albedo of 0.1[29], which makes it relatively large among the Near-Earth asteroid population. No spectral or colour information is as yet available to determine whether the asteroid is in any other way unusual.

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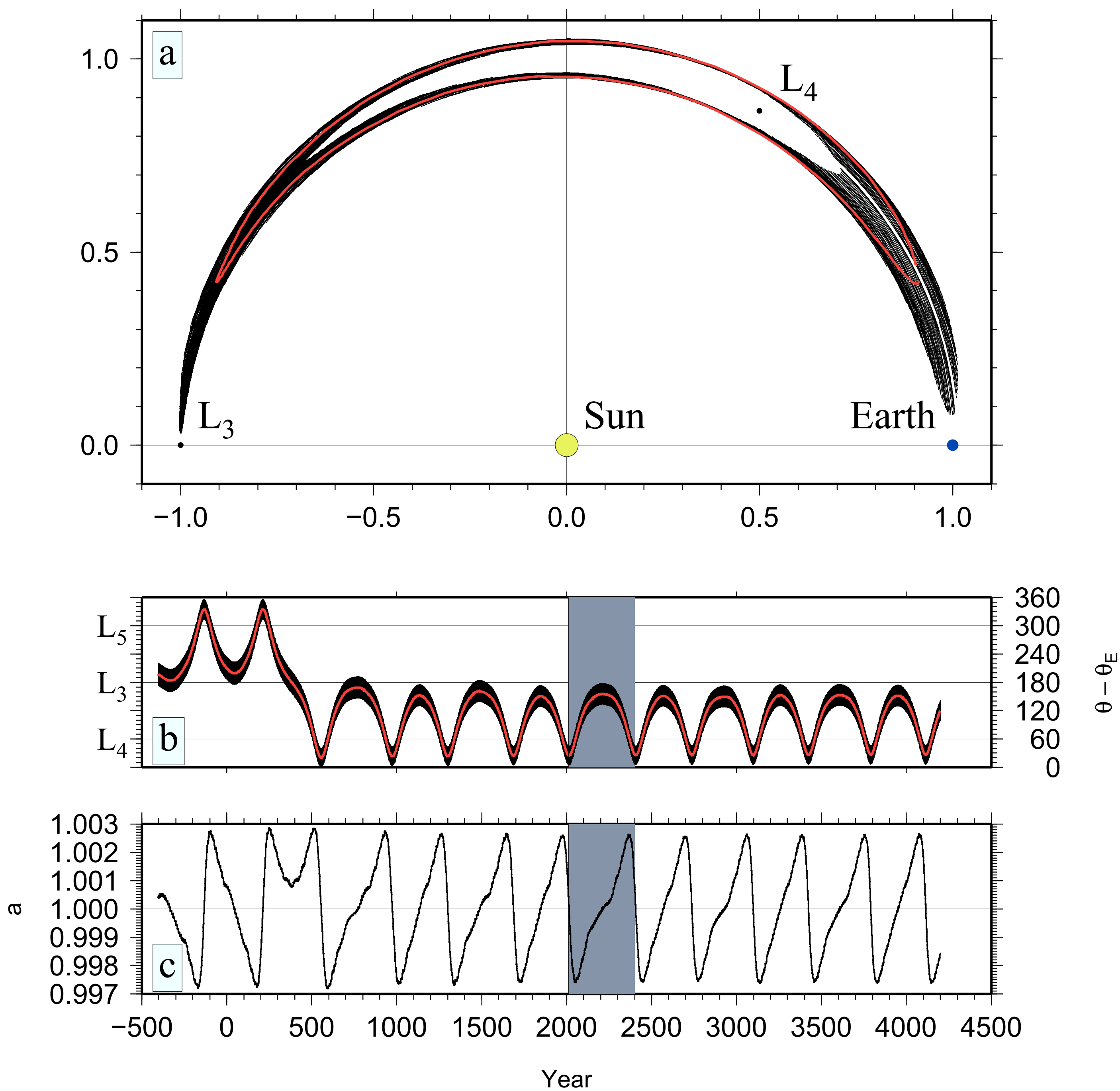
Figure 1 | Orbital parameters of asteroid 2010 TK$_7$. a. Path over one Trojan libration from 2010 to 2400 A.D. in the corotating frame. In this frame, Earth is stationary, while the average position of the asteroid as it moves around the Sun librates about the L_4 point in a "tadpole orbit". The radial distance of the asteroid's semimajor axis *a* from a circle of radius 1 AU is multiplied by a factor of 20 for clarity, and Earth and Sun are not to scale. Black lines indicate *a* and longitude relative to Earth daily, red curve the annual average. **b**. Longitude relative to Earth as in **a**, over the period 420 B.C. to 4200 A.D. A "jump" from L_5 libration to the present L_4 libration took place near 500 A.D. Grey band is the time for the present libration. **c**. Semimajor axis *a* daily values. We used the Mercury integrator[21] verified in the near-present with the JPL Horizons system[22]. Results in the figures were obtained using the RADAU option and 1-day spacing with 8 planets, Pluto, and the Earth-Moon barycenter approximation. Initial conditions (best orbital solution) are given in Table 1. Clone studies included 8 planets but Earth and Moon separately, with variations of the orbital elements from those of the nominal orbit of order the last significant digit in Table 1.

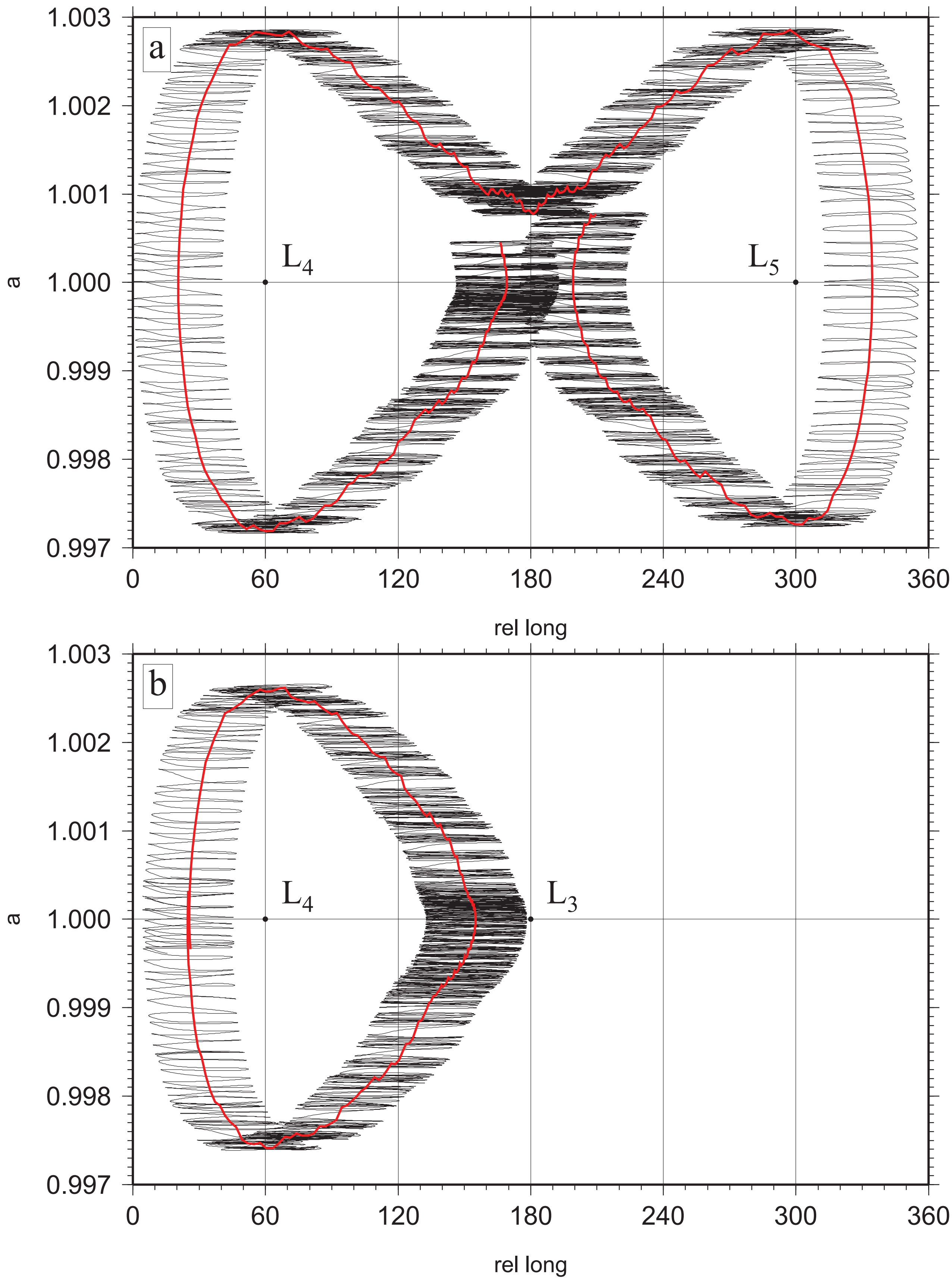
Figure 2 | Semimajor axis versus relative longitude for 2010 TK$_7$. a. Libration during the period 1 to 800 A.D., featuring a "jump" from libration initially about L_5 (right) to the present libration around L_4. When the asteroid is near L_3 (not labeled in panel **a**: see panel **b**), the annual excursions in relative longitude cross L_3. This crossing of the relative longitude through 180° appears to trigger the rapid transition or "jump" between librational modes. **b**. Present (2010-2410 A.D.) libration about L_4. The location of the L_3 point is shown for reference but the relative longitude in the era after 800 A.D. does not cross it, which results in the current stability of the orbit. The apparent banding is due to changes in semimajor axis *a*, and has a predominant period of roughly 12 years, so is likely mainly due to Jupiter perturbations.

Table 1 | Heliocentric orbital elements of 2010 TK$_7$.

Epoch	JD 2455600.5
Semimajor axis *a*	1.0004078 AU
Eccentricity *e*	0.1908177
Inclination *i*	20.87984°
Argument of perihelion	45.86009°
Longitude of ascending node	96.54190°
Mean anomaly	20.30069°



a
L4
L3
Sun
Earth
1.0
0.5
0.0
−1.0
−0.5
0.0
0.5
1.0
b
L5
L3
L4
360
300
240
180
120
60
0
θ − θE
c
a
1.003
1.002
1.001
1.000
0.999
0.998
0.997
−500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Year


a
b
L4
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rel long
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60
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