LETTER

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Earth's Trojan asteroid

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It was realized in 1772 that small bodies can stably share the same orbit as a planet if they remain near 'triangular points' 60° ahead of or behind it in the orbit[1]. Such 'Trojan asteroids' have been found co-orbiting with Jupiter[2], Mars[3] and Neptune[4]. They have not hitherto been found associated with Earth, where the viewing geometry poses difficulties for their detection[5], although other kinds of co-orbital asteroid (horseshoe orbiters[6] and quasi-satellites[7]) have been observed[8]. Here we report an archival search of infrared data for possible Earth Trojans, producing the candidate 2010 TK$_7$. We subsequently made optical observations which established that 2010 TK$_7$ is a Trojan companion of Earth, librating around the leading Lagrange triangular point, L$_4$. Its orbit is stable over at least ten thousand years.

The existence of Trojan asteroids of other planets raises the question of whether such companions could exist for Earth. Despite studies showing that such bodies could be relatively stable[9] and may wander relatively far from the Lagrange points[5], they would dwell mostly in the daylight sky as seen from Earth, making detection difficult. Indeed, they hitherto have not been observed[10,11]. The launch of the Wide-field Infrared Survey Explorer (WISE) by NASA in 2009[12] provided improved viewing circumstances that made possible new detections of over 500 near-Earth objects[13]. WISE searched large areas of sky always 90° from the Sun, with high efficiency for asteroidal bodies and good astrometric accuracy. Examining WISE discoveries in the expectation that Earth co-orbital objects, possibly including a Trojan, could be found, resulted in two promising candidates, 2010 SO$_{16}$ and 2010 TK$_7$. Both are larger than most co-orbital objects, being several hundred metres in diameter, and 2010 SO$_{16}$ is a horseshoe orbiter[14]. We identified 2010 TK$_7$ as probably being an Earth Trojan, on the basis of positions measured over a six-day arc in late 2010. Observations made at the University of Hawaii (D. Tholen, personal communication) and the Canada–France–Hawaii Telescope[15] in April 2011, after the object had for months been in an unfavourable position as seen from Earth, so greatly improved the knowledge of its orbit that we can state with certainty that 2010 TK$_7$ is an Earth Trojan.

The 'tadpole' motion of 2010 TK$_7$, which is characteristic of Trojan asteroids, is shown in Fig. 1 in the frame co-rotating with Earth (see Supplementary Information for three-dimensional depictions of the motion). The 1-yr-averaged curve shows the centre of motion librating about L$_4$, the Lagrange point 60° ahead of Earth. The period of this motion is at present 395 yr. Superposed on this is an annual motion or epicycle[2,16,17] (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 Earth, to the far 'tail', where it is nearly on the opposite side of the Sun from the Earth. The relatively large eccentricity, of $e = 0.191$, results in an annual heliocentric radial motion between roughly 0.81 and 1.19 AU. The inclination of 2010 TK$_7$ is about $i = 20.9°$, so there is significant motion perpendicular to Earth's orbital plane. The asteroid's eccentricity and inclination produce a large epicycle, which is responsible for the visibility of the object at the solar elongation of 90°, as observed by WISE; and it is now at the near-Earth end of the tadpole. 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 a rapid decrease in the object's semimajor axis, a, making it increase its angular speed (Kepler's third law) and outpace Earth. This is currently taking place. Slow resonant interaction at the other parts of the tadpole increases a, making the object slow gradually such that it again approaches Earth. In the current cycle, this will take place in the years AD 2050–2350, approximately. Repetition of this cycle leads to a sawtooth pattern in a as a function of time (Fig. 1c).

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 the accuracy of computations of this asteroid's position over timescales[18] greater than about 250 yr. 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 1,800 yr in the past, and more than 5,000 yr in the future, the 100 clone orbits we

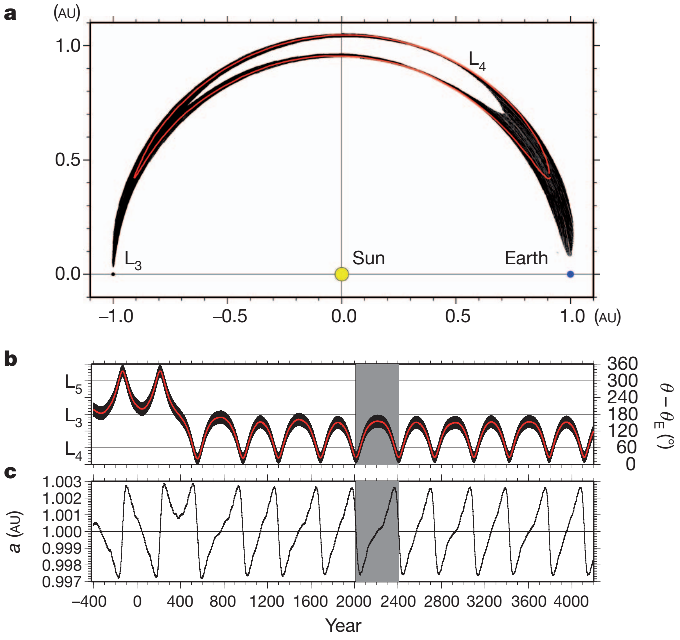

Figure 1 | Orbital parameters of asteroid 2010 TK$_7$. a, Path over one Trojan libration from AD 2010 to 2405 in the co-rotating reference frame. In this frame, Earth is stationary and the average position of the asteroid librates about L$_4$ in a 'tadpole' orbit. Both Earth and the asteroid revolve about the Sun with periods close to 1 yr, and slow changes in their relative positions are best seen in the co-rotating frame. The difference between the asteroid's semimajor axis, a, and a circle of radius 1 AU (an astronomical unit (AU) is the Earth–Sun distance) is multiplied by a factor of 20 for clarity, and Earth and the Sun are not shown to scale. Black lines indicate a and longitude relative to Earth daily; the red curve shows the annual average. **b**, Longitude relative to Earth, $\theta - \theta_E$, over the period 420 BC to AD 4200. A 'jump' from L$_5$ libration to the present L$_4$ libration took place in around AD 400. Black and red lines indicate daily and averaged values, as in **a**. The grey band is the period of the present libration. **c**, Semimajor axis daily values. Initial conditions (best orbital solution) are given in Table 1.

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computed diverged sufficiently that we must say that the asteroid's precise behaviour cannot be predicted with certainty outside that ~7,000-yr span. The range of behaviour shown by the clones and, thus, possible for the real object includes making transitions to horseshoe modes and 'jumping' between Lagrange points. Short-term unstable libration about L_3, the Lagrange point on the other side of the Sun from Earth, can occur as a result of the asteroid's large inclination. Such orbits were theorized as early as 1920[17], but no real object had until now been suspected to enter them.

Jumping from one Lagrange point to the other is a behaviour previously attributed to the Jupiter Trojan 1868 Thersites[19], and was found in about half of the clone orbits. Here, the large eccentricity leads to longitudinal excursions (Kepler's second law), including when near L_3. In Fig. 2, these are shown to have allowed (in about AD 500) 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[16] Trojan pattern, although of large amplitude.

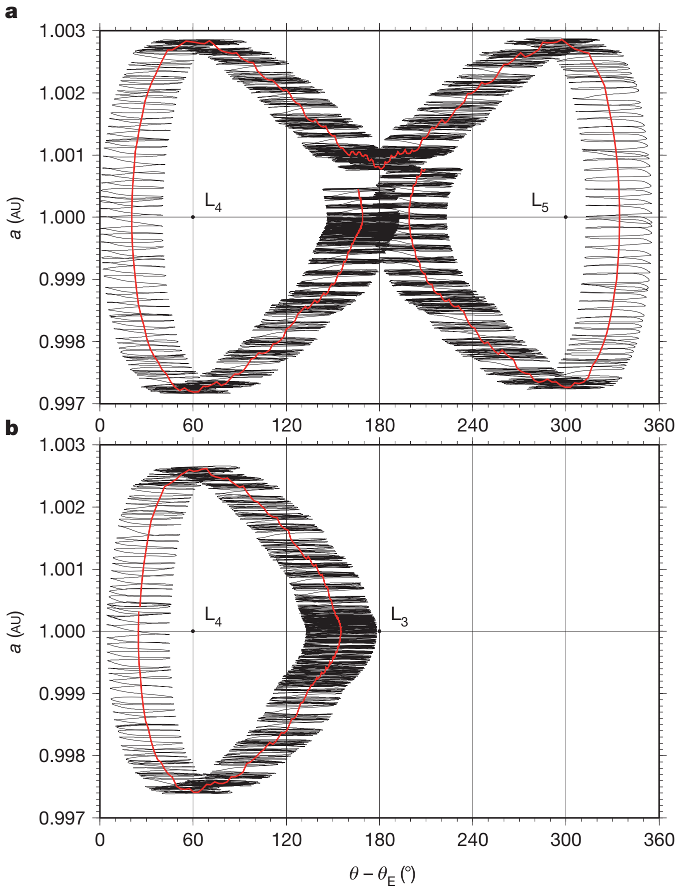

Figure 2 | Semimajor axis versus relative longitude for 2010 TK$_7$. **a**, Libration during the period AD 1–800, featuring a 'jump' from libration initially about L_5 (right) to the present libration around L_4. As in Fig. 1, black lines indicate daily values and red lines indicate the annual averages. When the asteroid is near a relative longitude, $\theta - \theta_E$, of about 180°, the annual excursions in relative longitude can cause it to cross L_3. This crossing can trigger a rapid transition or 'jump' between librational modes. Clone studies show that the chaotic behaviour of the asteroid is due mainly to a great sensitivity to non-resonant perturbations when near L_3. Libration about L_5 results in an average longitude 120° different from that for libration about L_4. Such a large change resulting from small perturbations (when near L_3) is characteristic of chaos. **b**, Present (AD 2010–2405) libration about L_4. The location of L_3 is shown for reference but the relative longitude in the era after AD 800 does not cross it, resulting in the current stability of the orbit. The apparent banding in both panels is due to changes in semimajor axis and has a predominant period of roughly 12 yr; therefore, it is probably mainly caused by 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°

Results in the figures were obtained using these initial conditions in the Mercury integrator[24] (verified in the near-present using the JPL Horizons system[25]). The RADAU[26] option was used with 1-d spacing for the eight planets, Pluto and the Earth–Moon barycentre. Clone studies included the eight planets and the Moon[27], with variations[7] among the orbital elements of the order of the last significant digit shown. The Julian date (JD) shown corresponds to 0:00 UT on 8 February 2011.

Chaotic effects have a large role in the behaviour of this asteroid. Its sensitivity to small influences when in the vicinity of L_3 allows the range of outcomes seen among the clones. The overall Trojan behaviour is dictated by 1:1 orbital resonance with Earth, but non-resonant effects of Jupiter are 80 times stronger than those of Earth when Jupiter is at the same celestial longitude as L_3. Such influences, demonstrated by the 'banding' seen in Fig. 2, alter the asteroid's chaotic behaviour. Many clone orbits make repeated transitions between the Lagrange points, such that the chaos can be stable[20], 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 and fate of 2010 TK$_7$, and its relationship to other bodies, will necessarily remain statistical in nature.

Earth Trojan asteroids have been proposed as natural candidates for spacecraft rendezvous missions[21]. However, the large inclination of 2010 TK$_7$ results in a Δv of 9.4 km s^{-1} being required, whereas other near-Earth asteroids have values of Δv less than 4 km s^{-1}. The reported absolute magnitude, 20.7 mag, puts the diameter of 2010 TK$_7$ at 300 m with an assumed albedo of 0.1 (ref. 22), 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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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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