Three new stable $L_5$ Mars Trojans

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ABSTRACT

Mars was second to Jupiter in being recognized as the host of a population of Trojan minor bodies. Since 1990, five asteroids – 5261 Eureka, (101429) 1998 VF$_{11}$, (121514) 1999 UJ$_7$, 2001 DH$_{47}$ and (311999) 2007 NS$_2$ – have been identified as Mars Trojans, one $L_4$ and four $L_5$. Dynamical and spectroscopic evidence suggests that some Mars Trojans may be remnants of the original planetesimal population that formed in the terrestrial planets region. Here, we revisit the long-term dynamical evolution of the previously known Mars Trojans and show that 2011 SC$_{191}$, 2011 SL$_{25}$ and 2011 UN$_{63}$ are also trailing ($L_5$) Mars Trojans. They appear to be as stable as Eureka and may have been Trojans over the age of the Solar system. The fact that five Trojans move in similar orbits and one of them is a binary may point to the disruption of a larger body early in the history of the Solar system. Such a catastrophic event may also explain the apparently strong asymmetry in terms of number of objects (one versus seven) between the $L_4$ and $L_5$ regions. Future spectroscopic observations should be able to reject or confirm a putative common chemical signature that may lend further support to a collisional scenario.

Key words: celestial mechanics – minor planets, asteroids: individual: 2011 SC$_{191}$ – minor planets, asteroids: individual: 2011 SL$_{25}$ – minor planets, asteroids: individual: 2011 UN$_{63}$ – planets and satellites: individual: Mars.

1 INTRODUCTION

Trojans are minor bodies that share the semimajor axis of their host body but they may have different eccentricity and inclination. In a frame of reference rotating with the host, they move in the so-called tadpole orbits around the Lagrangian equilateral points $L_4$ and $L_5$. $L_4$ is located on the orbit of the host object at some 60° ahead or east of the host, and $L_5$ is some 60° west. In other words and for a Trojan object, the relative mean longitude $\lambda_t = \lambda - \lambda_H$ oscillates around the values $+60^\circ$ ($L_4$) or $-60^\circ$ (or 300°, $L_5$), where $\lambda$ and $\lambda_H$ are the mean longitudes of the Trojan and the host body, respectively. The first Trojan object, 588 Achilles, was discovered by M. Wolf in 1906 at Jupiter’s $L_1$ point (Einarsen 1913). Since 1990, Mars is second to Jupiter in being recognized as the host of a population of Trojan minor bodies (see, for example, Marzari et al. 2002 for a review). The list of Mars Trojans currently includes 5261 Eureka (Bowell et al. 1990; Holt et al. 1990; Mikkola et al. 1994), (101429) 1998 VF$_{11}$ (Ticha et al. 1998; Tabachnik & Evans 1999), (121514) 1999 UJ$_7$ (Rivkin et al. 2003), 2001 DH$_{47}$ (Scholl, Marzari & Tricarico 2005) and (311999) 2007 NS$_2$ (Rodriguez et al. 2007; Izidoro, Winter & Tsuchida 2010; Schwarz & Dvorak 2012). Right after the discovery of Eureka, it was suggested that Mars Trojans may have been captured fairly late in Solar system history (Bowell et al. 1990) but soon after, the primeval Mars Trojan scenario started to gain support from both dynamical (long-term integrations) and spectroscopic data (Mikkola et al. 1994; Howell et al. 1995). Today, it is widely accepted that some Mars Trojans may be primordial bodies, perhaps the only surviving examples of the planetesimal population that formed in the terrestrial planets region (e.g., Connors et al. 2005; Scholl et al. 2005).

Any claim regarding the putative ancient nature of all or part of the current Mars Trojan populations must be supported by dynamical stability analyses. The stability of Martian Trojans was first studied by Mikkola & Innanen (1994). For a simulated time of 100 Myr, they found two regions of stability depending on the orbital inclination, $i$; only orbits with $i \in (15, 30^\circ)$ or $i \in (32, 44^\circ)$ appeared to be long-term stable. Tabachnik & Evans (1999, 2000) found that the inclination ranges in Mikkola & Innanen (1994) ensured stability around the Lagrangian point $L_4$ but that around $L_5$, the range of stable inclinations was $i \in (15, 40^\circ)$. In their 100 Myr simulations, both Eureka and 101429 were deeply settled into the $L_5$ stable region; they also suggested a primordial origin for these two objects. Focusing on the role of secular resonances in the dynamical evolution of Mars Trojans, Brasser & Lehto (2002) found that several secular resonances with Earth, Mars and Jupiter were able to explain the unstable inclination ranges found by previous studies. Scholl et al. (2005) further explored this topic to conclude that secular resonances make Mars Trojan orbits with $i < 15^\circ$ as well as those with $i \sim 30^\circ$ unstable. Orbits with $i > 35^\circ$ are also unstable due to the Kozai resonance (Kozai 1962). In their 4.5 Gyr calculations, they also found that the dynamical half-life of Mars Trojans in the most stable regions is of the order of the age of the Solar system and that the Yarkovsky effect has negligible role for objects larger...
than about 10 m. All known Mars Trojans have relatively small sizes with diameters of the order of 1 km (Trilling et al. 2007). Numerical modelling (Tabachnik & Evans 1999, 2000) predicts that the number of Mars Trojans with diameter > 1 km could be as high as 30.

Here, we search for Mars Trojan candidates among known asteroids with relative semimajor axis $|a - a_{\text{Mars}}| < 0.001$ au, then perform $N$-body calculations to confirm or reject their Trojan nature. In this Letter, we show that the minor bodies 2011 SC$^{191}$, 2011 SL$^{25}$ and 2011 UN$^{63}$ are stable trailing (L$_5$) Mars Trojans.

This Letter is organized as follows: in Section 2, we briefly outline our numerical model. Section 3 focuses on currently known Mars Trojans, reviewing their dynamical status. Section 4 presents our results for the objects studied here. These results are discussed and our conclusions summarized in Section 5.

2 NUMERICAL MODEL

In order to confirm the current Trojan nature of our candidates, we perform $N$-body calculations in both directions of time ($\pm 2$ Myr) with the Hermite integrator (Makino 1991; Aarseth 2003), in a model Solar system which includes the perturbations by the eight major planets and treat the Earth and the Moon as two separate objects; it also includes the barycentre of the dwarf planet Pluto–Charon system and the five largest asteroids, 1 Ceres, 2 Pallas, 4 Vesta, 10 Hygiea and 31 Euphrosyne. Our calculations consider point, constant mass objects orbiting in a conservative system; therefore, relativistic effects are ignored and no modelling of the Yarkovsky and Yarkovsky–O’Keefe–Radzievskii–Paddack effects (see, e.g., Bottke et al. 2006) is attempted. The standard version of this direct $N$-body code is publicly available from the IoA website,$^1$ additional details can be found in de la Fuente Marcos & de la Fuente Marcos (2012). In order to validate our results, we have also calculated the evolution of the previously known Mars Trojans (see Figs 1 and 2). Our orbital integrations use initial conditions (positions and velocities in the barycentre of the Solar system referred to the JD 245 6200.5 epoch) provided by JPL’s HORIZONS system (Giorgini et al. 1996; Standish 1998). In all the figures, $t = 0$ coincides with the JD 245 6200.5 epoch. Relative errors in the total energy at the end of the simulations are $< 5 \times 10^{-15}$. In addition to the calculations completed using the nominal orbital elements in Tables S1 and 1, we have performed 20 control simulations (for each object) using sets of orbital elements obtained from the nominal ones within the accepted uncertainties (3$\sigma$). The sources of the

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$^1$ http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm

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Table 1. Heliocentric Keplerian orbital elements of the new objects studied in this research. Values include the 1$\sigma$ uncertainty when available. (Epoch = JD 245 6200.5, 2012-Sep-30.0; J2000.0 ecliptic and equinox. Source: JPL Small-Body Database and AstDyS-2.)
Heliocentric Keplerian osculating orbital elements and uncertainties are the JPL Small-Body Database\(^2\) and the AstDyS-2 portal.\(^3\) The results of these control calculations are consistent with those from the nominal ones. In order to study the long-term stability of these newly found Trojans, we use the Regularized Mixed Variable Symplectic (RMVS) integrator (SWIFT-RMVS3) which is a part of the SWIFT package (Levison & Duncan 1994). The SWIFT package is available from H. Levison website.\(^4\) The physical model here is similar to the previous one but the Earth and the Moon are replaced by the barycentre of the system. One group of calculations does not include Mercury or the Pluto–Charon system, uses a time step of 9 d and has been followed for ±4.5 Gyr with six control orbits per object; the second group includes Mercury and the Pluto–Charon system, uses a time step of 3 d and runs for ±2.25 Gyr. Relative errors in the total energy are now <1.5 \(\times\) 10\(^{-8}\). Results from RMVS and Hermite are consistent within the applicable time frame (±2 Myr).

### 3 KNOWN MARS TROJANS

In this section, we present the results of the short-term integrations of the orbits of the known Mars Trojans (nominal orbital elements in Table S1). These calculations are presented here because there are no references including a dynamical analysis of all of them; these results are also used to validate our simulations against previous work. Our results are consistent with those from other authors.

#### 5261 Eureka

Discovered by D. H. Levy and H. E. Holt on 1990 June 20 during the course of the Mars and Earth-crossing Asteroid and Comet Survey conducted by E. M. and C. S. Shoemaker (Holt et al. 1990), the first known images of this object date back to 1979 November and its dynamics has been studied in detail for more than 20 years. Its diameter is 1.3–2.6 km (Trilling et al. 2007; Burt 2012), its rotational period is 2.69 h and it has a secondary companion with an amplitude of 11\(^{\circ}\) from the years 2003, 2009 and 2011 with an arc length of 3146 d. Our calculations confirm that it is an L\(_5\) Mars Trojan as well as those in inclination by Jupiter. Fig. 1 clearly shows that 101429 is not a dynamical analogue of Eureka; the evolution of its \(\lambda_5\), \(\alpha\) and \(e\) is not similar to that of Eureka. The intrinsically different nature of these two objects has been further confirmed by spectroscopic results (Rivkin et al. 2007; Lim et al. 2011). Its origin points to a possible capture event 3.9 Gyr ago (Rivkin et al. 2007).

**121514 1999 UJ\(_7\)**

This object is first mentioned as an L\(_5\) Mars Trojan by Rivkin et al. (2003); they also point out that its visible spectrum is different from those of Eureka or 101429. It is likely a P-asteroid and the largest of the known Mars Trojans with a rotational period of 21.2 h (Burt 2012). Our calculations confirm that this object is following a tadpole orbit east of Mars so it is an L\(_5\) Mars Trojan. Its \(\lambda_5\) oscillates around +60\(^{\circ}\) in very wide, asymmetric loops with an amplitude of 77\(^{\circ}\), the largest of all the objects, and it has a libration period of 1500 yr, see Fig. 2. Simulations (Mikkola et al. 1994) show that, for Mars, stable excursions about L\(_5\) and L\(_3\) as large as 80\(^{\circ}\) occur on time-scales of millions of years which is consistent with our own findings. Oscillations in both eccentricity and inclination are also observed.

**2001 DL\(_{17}\)**

We also confirm that this object is a robust L\(_3\) Mars Trojan. Its \(\lambda_3\) oscillates around +60\(^{\circ}\) with an amplitude of 11\(^{\circ}\) and a libration period of 1365 yr. Together with Eureka, it has the smallest libration amplitude of all the objects studied here. Its orbital behaviour is also very similar to that of Eureka, see Fig. 1.

**311999 2007 NS\(_2\)**

Again, we face a robust L\(_3\) Mars Trojan. Its \(\lambda_3\) oscillates around +60\(^{\circ}\) with an amplitude of 14\(^{\circ}\) and a libration period of 1310 yr. Its orbit is similar to that of Eureka and 2001 DL\(_{17}\), see Fig. 1. Out of all Mars Trojans, it currently has the smallest relative (to Mars) semimajor axis, 5.9 \(\times\) 10\(^{-5}\) au.

### 4 NEW MARS TROJANS

The three new Trojans follow tadpole orbits around Mars’ L\(_5\) and, as in previous cases, they exhibit oscillations in both eccentricity and inclination, see Fig. 3. Their distances to Earth are always >0.4 au and their arguments of perihelion \(\omega\) circulate.

**2011 SC\(_{19}\)**

It was originally discovered on 2003 March 21 by the Near-Earth Asteroid Tracking project at Palomar and named 2003 GX\(_{20}\), then was lost but re-discovered on 2011 October 31 by the Mt. Lemmon Survey (Pettarin et al. 2011). Its orbit is robust; 45 observations from the years 2003, 2009 and 2011 with an arc length of 3146 d have been used to compute it. Its orbital inclination is significant (≈19\(^{\circ}\)) but its eccentricity is low (0.04); both values are similar to those of known Mars Trojans. It is a relatively bright object, suitable for spectroscopy, with a typical apparent visual magnitude of nearly 20. Our calculations indicate that it is a stable L\(_5\) Mars Trojan, see Fig. 3. Its relative mean longitude oscillates around −60\(^{\circ}\) with an amplitude of 18\(^{\circ}\) and a libration period of 1300 yr, see Fig. 4. These values are comparable to those of the first Mars Trojan, Eureka (see Section 3); the evolution of their orbits is also very similar, see Fig. 1. The orbit appears to be very stable on Myr time-scales. As
Figure 3. Same as Figs 1 and 2 but for 2011 SC$^{191}$, 2011 SL$^{25}$ and 2011 UN$^{63}$.

Figure 4. Left-hand panels: details of the evolution of the relative mean longitude for the three objects presented here in the time interval (−10 000, 10 000) yr. Right-hand panels: one tadpole loop starting at $t = 0$ yr in the coordinate system corotating with Mars; tadpole loops are the superposition of multiple epicyclic loops.

in the case of Eureka, $\lambda_t$ is modulated with a major periodicity of nearly 200 000 yr.

2011 SL$^{25}$

It was discovered on 2011 September 21 at the Alianza S4 Observatory on Cerro Burek in Argentina. Its orbit has been computed using 76 observations with an arc length of 42 d; even if somewhat reliable, it is in need of further observations in order to make it as robust as that of 2011 SC$^{191}$. Because of its larger eccentricity, it can get brighter than 2011 SC$^{191}$ at nearly 19 mag. Our calculations indicate that it is a stable L$_3$ Mars Trojan, see Fig. 3. Its $\lambda_t$ oscillates around $-60^\circ$ with an amplitude of $18^\circ$ and a libration period of 1400 yr, see Fig. 4.

2011 UN$^{63}$

It was originally discovered on 2009 September 27 by the Mt. Lemmon Survey and named 2009 SA$^{170}$. After being lost, it was re-discovered on 2011 October 21, again by the Mt. Lemmon Survey. Its orbit is well known; 64 observations with an arc length of 793 d. Its orbital behaviour is similar to that of 2011 SC$^{191}$. Our calculations also indicate that it is a stable L$_3$ Mars Trojan, perhaps the most stable of this set of three, see Fig. 3. Its $\lambda_t$ oscillates around $-60^\circ$ with an amplitude of $14^\circ$ and a libration period of 1350 yr, see Fig. 4, which are comparable to those of Eureka (see Section 3).

5 DISCUSSION AND CONCLUSIONS

The simulated time span studied so far (4 Myr) is not long enough to answer the astrophysically critical question of whether the newly found Trojans may have been trapped at the Lagrangian L$_3$ point of Mars since the formation of the Solar system. To investigate the long-term stability of the three objects we use the SWIFT-RMVS3 integrator. Our ±4.5 Gyr integrations indicate that the lifetime of the Trojan orbits of the new objects is equivalent to or longer than the Solar system age (see Fig. 5). They all could be primordial objects. We also confirm the long-term stability of the four Mars Trojans studied by Scholl et al. (2005) and conclude that 311999 is...
also stable on Gyr time-scales. However, our calculations (including control orbits) suggest that 101429 and 121514 are not primordial but were captured about 4 Gyr ago. Some of the control orbits associated with 2011 SL₂₅ are not stable over the entire simulated time. Our ±2.25 Gyr integrations show stability for all the eight objects.

In this Letter, we have presented solid dynamical evidence in the form of N-body numerical integrations for three new stable Mars Trojans and also provided a comprehensive summary of the dynamics of the previously known objects. After this study, the list of robust Mars Trojans includes eight objects. Unfortunately and with the exception of the first three objects, there is no consensus among Solar system researchers on the robust Trojan nature of 2001 DH₂₅ and 311999 in spite of both having reliable orbits. Even the MPC still lists just three objects as genuine Mars Trojans. The N-body calculations completed for this research clearly show that the eight objects are long-term stable, at least for several Gyr. We also conclude that 101429 is by no means a dynamical analogue of Eureka – their orbital evolution being too different – which is consistent with the rather different spectroscopic signature found by Rivkin et al. (2007). Two of the three new L₅ Trojans move in orbits very similar to that of Eureka which, in the absence of surface composition data, may point to them (and several of the previously known Trojans) being the by-products of the disruption of a larger body. Eureka and 101429 could be collisional fragments of larger bodies as they are highly differentiated bodies (Rivkin et al. 2007). The binarity and relatively fast rotation of Eureka (Burt 2012) as well as the apparently strong asymmetry between the size of the L₄ and L₅ populations (one versus seven) also point in that direction. Although our calculations indicate that most of the currently known and new Mars Trojans are dynamical analogues of Eureka, spectroscopy should settle the question of them also having a common chemical signature with Eureka, an R chondrite (Lim et al. 2011). If, as suggested, they are fragments of a large body, further objects with similar properties should be found (Marzari et al. 1997). Strategies to search for additional Mars Trojans have been recently discussed by Todd et al. (2012).

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NOTE ADDED IN PRESS

After this work was accepted by MNRAS Letters, a relevant paper was submitted by A. A. Christou to astro-ph (astro-ph/1303.0420). He arrives to similar conclusions regarding the three objects discussed here but using different techniques.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. Heliocentric Keplerian orbital elements of known Mars Trojans. Values include the 1σ uncertainty. (Epoch = JD 245 6200.5, 2012-Sep-30.0; J2000.0 ecliptic and equinox. Source: JPL Small-Body Database and AstDyS-2.0) (http://mnrasl.oxfordjournals.org/lookup/suppl/doi:10.1093/mnrasl/slt028/-/DC1)

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