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Yarkovsky-driven spreading of the Eureka family of Mars Trojans

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ABSTRACT

Out of nine known stable Mars Trojans, seven appear to be members of an orbital grouping including the largest Trojan, Eureka. In order to test if this could be a genetic family, we simulated the long term evolution of a tight orbital cluster centered on Eureka. We explored two cases: cluster dispersal through planetary gravity alone over 1 Gyr, and a 1 Gyr evolution due to both gravity and the Yarkovsky effect. We find that the dispersal of the cluster in eccentricity is primarily due to dynamical chaos, while the inclinations and libration amplitudes are primarily changed by the Yarkovsky effect. Current distribution of the cluster members orbits is indicative of an initially tight orbital grouping that was affected by a negative acceleration (i.e. one against the orbital motion) consistent with the thermal Yarkovsky effect. We conclude that the cluster is a genetic family formed either in a collision or through multiple rotational fissions. The cluster's age is on the order of 1 Gyr, and its long-term orbital evolution is likely dominated by the seasonal, rather than diurnal, Yarkovsky effect. If confirmed, Gyr-scale dominance of the seasonal Yarkovsky effect may indicate suppression of the diurnal Yarkovsky drift by the related YORP effect. Further study of Mars Trojans is essential for understanding the long-term orbital and rotational dynamics of small bodies in the absence of frequent collisions.

1. Introduction

A Trojan (or "tadpole") coorbital companion is a small body that has the same mean orbital distance as a planet, and librates around the so-called triangular Lagrangian points, which are located 60° ahead and behind the planet. Trojans' orbits can in principle be stable for star-planet (or planet-satellite) mass ratios above about 25 (Murray and Dermott, 1999). In our Solar System, only Jupiter, Neptune and Mars are known to have long-term stable Trojan companions (Dotto et al., 2008). Additionally, Saturn's moons Tethys and Dione also have two Trojan coorbitals each (Murray and Dermott, 1999; Murray et al., 2005). Giant planets are thought to have acquired their Trojans during a violent early episode of planetary migration and/or scattering (Morbidelli et al., 2005; Nesvorný and Vokrouhlický, 2009; Nesvorný et al., 2013). Any primordial Saturn and Uranus Trojans would have been subsequently lost through planetary perturbations (Nesvorný and Dones, 2002; Marzari et al., 2002, 2003; Dvorak et al., 2010; Hou et al., 2014), with the known Uranus Trojans thought to be temporarily captured from among the Centaurs (Alexandersen et al., 2013; de la Fuente Marcos and de la Fuente Marcos, 2014). Some hypothetical Trojans of Earth would have been long-term stable, with the situation at Venus being less clear (Tabachnik and Evans, 2000; Scholl et al., 2005; Ćuk et al., 2012; Marzari and Scholl, 2013); however, so far only temporary coorbitals of these planets are known (Christou, 2000; Christou and Asher, 2011; Connors et al., 2011). To date, only one coorbital dynamical family has been identified, among Jupiter Trojans (Brož and Rozehnal, 2011).

The first Mars Trojan to be discovered was 5261 Eureka in 1990 (Bowell et al., 1990). Since then, a total of nine Mars Trojans have been discovered and were found to be stable (Mikkola et al., 1994; Mikkola and Innanen, 1994; Connors et al., 2005; Scholl et al., 2005; de la Fuente Marcos and de la Fuente Marcos, 2013, and references therein). The three largest Mars Trojans do not form any kind of cluster: Eureka and 1998 VF_{31} are both in L_5 but have very different orbits, and 1999 UJ_7 is in L_4. Recently, Christou (2013) proposed that some of the smaller L_5 Trojans form an orbital cluster together with Eureka. Subsequently, multiple teams of researchers recognized a likely 6-member orbital cluster (de la Fuente Marcos and de la Fuente Marcos, 2013; Christou, 2014, personal communication): Eureka, 2001 DH_{47}, 2007 NS_2, 2011 SC_{191}, 2011 SL_{25} and 2011 UN_{63}, to which we add 2011 UB_{256} (based on latest orbital elements listed on JPL Solar System Dynamics

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web-page; Table 1).[1] In this paper, we will consider these seven objects only, as orbits of more newly discovered objects are likely to have large errors. This is especially true of Mars Trojans' libration amplitudes, which can vary a lot due to relatively small changes in the solutions for their semimajor axes. While one of us (Christou) has developed a method to compute the Trojan mean elements, based on Milani (1993) (cf. Christou, 2013), we found little difference between proper elements and much simpler averaged elements, we decided to only use the latter in this paper.

Separately from orbital clustering, spectroscopy can resolve relationships between potential family members. Eureka and 1998 VF_{31} both have high albedos (Trilling et al., 2007), but are not of the same surface composition (Rivkin et al., 2003). Rivkin et al. (2007) find Eureka to be closest to angrite meteorites, while Lim et al. (2011) find it to be better matched by olivine-rich R-chondrites. Non-cluster member 1998 VF_{31} is likely to be a primitive achondrite (Rivkin et al., 2007), while the sole L_4 Trojan 1999 UJ_7 has a much lower albedo, and presumably very different composition (Mainzer et al., 2012).

In this paper, we explore if the Eureka cluster's orbital distribution could result from a initially compact collisional family spreading due to planetary perturbations and the radiative Yarkovsky effect.

2. Gravitational dynamics of Mars Trojans

Orbits of asteroid families born in collisional disruptions spread due to both gravitational and non-gravitational (usually radiative) forces (Bottke et al., 2001). In the main belt, the Yarkovsky effect (Rubincam, 1995; Farinella et al., 1998; Farinella and Vokrouhlický, 1999; Bottke et al., 2006) is by far the most important radiative force on the observable asteroids. The details of a collisional family dispersal are likely to be different among Mars Trojans than for main-belt asteroids (MBAs). The coorbital relationship with Mars prevents the Trojans from drifting in semimajor axis, making their libration amplitudes, eccentricities and inclinations the only relevant parameters in which we can identify potential families (this is true of resonant families in general; Brož and Vokrouhlický, 2008; Brož and Rozehnal, 2011; Brož et al., 2011). Additionally, they are largely free of collisions, allowing for the YORP radiation torques (Rubincam, 2000; Bottke et al., 2006) to fully dominate the evolution of their spins, with implications for the long-term behavior of the Yarkovsky drift (sub-km Mars Trojans are expected to have their spins completely re-oriented by YORP in less than a Myr). It is possible that YORP would evolve Trojans into a stable rotation state, which could be very long-lived in the absence of collisions. All these factors make it hard to use the lessons from MBA families for studying a potential family among Mars Trojans, and independent numerical modeling is clearly needed. In order to separate the effects of (purely gravitational) planetary perturbations and the radiation forces, we decided to first model spreading of a family due to gravity alone. Such a simulation is certainly unlikely to reflect a real-life Mars Trojan family consisting mostly of sub-km bodies, but is valuable in providing a control for our Yarkovsky simulations.

We used the SWIFT-rmvs4 symplectic integrator which efficiently integrates perturbed Keplerian orbits, and is able to resolve close encounters between massless test particles and the planets (Levison and Duncan, 1994). While in previous versions of SWIFT the timestep used for integrating planets depended on the timing of particle-planet encounters, SWIFT-rmvs4 propagates planets using constant timestep, not dependent on the fate of test particles. Once each planet-particle encounter is over, changes of planetary orbits during the encounter are discarded and the post-encounter planetary orbits depend solely from "regularly scheduled" force evaluations. This enabled all of the 100 test particles to experience the same history of the chaotic inner planets, despite the computation being divided between five different processors. The initial conditions for the eight planets and Eureka are based on vectors for January 1st, 2000, downloaded from JPL's horizons ephemeris service.[2] Test particles had the same initial positions as Eureka, with their velocities differing slightly from that of Eureka. Small kicks to y and z components of the particle's velocity (in the ecliptic coordinate system) were assigned according to a 5×20 grid. The size of the grid step was 10^{-4} of the relevant velocity component, amounting to 1 m/s in the y-direction, 0.5 m/s in the z-direction (comparable to Eureka's likely escape velocity). This was beyond a realistic collisional fragment dispersion, but enabled us to sample a larger phase space (for comparison, escape from the Trojan region would require about 30 m/s). The simulations were run for 10^9 years with a 5-day timestep.

Table 1
Dynamical properties and absolute magnitudes H of known Eureka cluster members. Eccentricities and inclinations are mean values computed over 10^7 year, using initial conditions from JPL Solar System Dynamics site, retrieved on 08/15/2014 (we used the same source for absolute magnitudes). Here and elsewhere in the paper, the mean libration amplitudes are computed as $\frac{\pi}{2n}\sum_1^n \mid \lambda_M - \lambda - 60^\circ \mid$ (summed over output intervals), where λ is mean longitude, and subscript M refers to Mars. All inclinations in this paper are measured relative to the J2000 ecliptic. Assuming an albedo of 0.4, absolute magnitudes of $H = 16$ and $H = 19$ correspond to diameters of $D = 1.3$ km and $D = 0.33$ km, respectively.

Trojan	Amplitude (°)	Eccentricity	Inclination (°)	H (mag)
(5261) Eureka	5.63	0.0593	22.22	16.1
(385250) 2001 DH_{47}	5.90	0.0572	22.80	18.7
(311999) 2007 NS_2	7.40	0.0468	20.95	18.1
2011 SC_{191}	9.52	0.0734	19.14	19.3
2011 SL_{25}	7.97	0.0850	21.75	19.4
2011 UB_{256}	5.89	0.0565	22.64	20.1
2011 UN_{63}	7.44	0.0512	21.60	19.7

At the end of the simulation, 98 of the hundred particles were still Mars Trojans (the remaining two were destabilized). This agrees with the results of Scholl et al. (2005), who find that Eureka is most likely long-term stable, with only ≃20% chance of escape over 4.5 Gyr. Also, just like Scholl et al. (2005), we find that it is the eccentricity that disperses most rapidly due to planetary perturbations (Fig. 1). The eccentricity dispersion of our synthetic cluster reaches that of the actual cluster in at most a few hundred Myr. This is contrasted by the much slower dispersion in inclination; the inclination dispersion of the synthetic family does not approach the size of the Eureka cluster by the end of the integration. This discrepancy between the eccentricity and inclination dispersals is independent of which bodies we include in the Eureka cluster. If we exclude outlying 2001 SC_{191} from the cluster, inclinations could be explained by a gravity-only dispersal over the Solar System's age. However, the age of the family according to the scatter of member eccentricities would be only 10^8 years or so, clearly indicating that this cannot be a collisional cluster that has been spreading due to gravity alone (Fig. 2).

Our choice of initial conditions produced a relatively large dispersal in libration amplitudes (2–20°), which has not changed

[1] The recovery of this and other potential Mars Trojans was the result of a targeted campaign by Christou, Vaduvescu and the EURONEAR collaboration (Vaduvescu, 2013; Christou et al., 2014).

[2] Vectors used for test-particle simulations were obtained in 2013, while those used to produce Table 1 are from August 2014, leading to slight differences between the orbit of Eureka and the centers of the simulated clusters.