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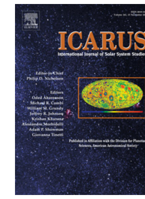

# Is the Eureka cluster a collisional family of Mars Trojan asteroids?

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ABSTRACT

We explore the hypothesis that the Eureka family of sub-km asteroids in the $L_5$ region of Mars could have formed in a collision. We estimate the size distribution index from available information on family members; model the orbital dispersion of collisional fragments; and carry out a formal calculation of the collisional lifetime as a function of size. We find that, as initially conjectured by Rivkin et al. (2003), the collisional lifetime of objects the size of (5261) Eureka is at least a few Gyr, significantly longer than for similar-sized Main Belt asteroids. In contrast, the observed degree of orbital compactness is inconsistent with all but the least energetic family-forming collisions. Therefore, the family asteroids may be ejecta from a cratering event sometime in the past $\sim$ 1 Gyr if the orbits are gradually dispersed by gravitational diffusion and the Yarkovsky effect (Ćuk et al., 2015). The comparable sizes of the largest family members require either negligible target strength or a particular impact geometry under this scenario (Durda et al., 2007; Benavidez et al., 2012). Alternatively, the family may have formed by a series of YORP-induced fission events (Pravec et al., 2010). The shallow size distribution of the family is similar to that of small MBAs (Gladman et al., 2009) interpreted as due to the dominance of this mechanism for Eureka-family-sized asteroids (Jacobson et al., 2014). However, our population index estimate is likely a lower limit due to the small available number of family asteroids and observational incompleteness. Future searches for fainter family members, further observational characterisation of the known Trojans' physical properties as well as orbital and rotational evolution modelling will help distinguish between different formation models.



## 1. Introduction

Trojan asteroids are objects confined by solar and planetary gravity to orbit the Sun 60° ahead, or behind, a planet's position along its orbit (see e.g. Murray and Dermott, 1999). Trojans of Jupiter, Neptune and Mars are stable over the age of the solar system, dating from its formation. The taxonomies of Jupiter Trojans are indicative of primitive, geologically unprocessed bodies (Grav et al., 2012). By contrast, the much smaller population of Martian Trojans exhibits a wide range of taxonomies, suggesting diverse origins (Rivkin et al., 2003, 2007).

As capture of asteroids into a stable Trojan configuration with Mars is implausible in the present solar system (Schwarz and Dvorak, 2012), these objects were likely deposited at their present locations when the solar system had not yet reached its final configuration (A. Morbidelli, in Scholl et al., 2005). Rivkin et al. (2003) proposed that the collisional lifetime of Mars Trojans is longer than asteroids in the main belt and, therefore, that the objects we observe today are near their original sizes. Recently, Christou (2013) identified a compact orbital cluster of Martian Trojans (the "Eureka family" after its largest member, 5261 Eureka) containing most of the known population, including newly-identified Trojans. In the same work, Christou argued that a collision plausibly formed this cluster but it could also have been produced by YORP-induced rotational fission (Pravec et al., 2010). In Ćuk et al. (2015), the orbits of a compact group of Trojan test particles ejected from Eureka were propagated in time under planetary gravitational perturbations and the Yarkovsky effect. Those authors found that the group is likely a genetic family formed roughly in the last Gyr of the solar system's history. Here, we focus on the problem of the family's formation. Specifically, we address the question of whether the cluster could have formed by collisional fragmentation of a progenitor body. Our approach is three-pronged: Firstly, we exploit a recent increase in the size of the known population and perform an appraisal of the size distribution of observed family members as a clue to the formation mechanism. Then, we apply models of collisional fragmentation,

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**Table 1**
Mean orbital elements and physical properties of Eureka family asteroids.

| Designation | *D* (deg) | *e* | *I* (deg) | *H* | Diam.[a] (km) |
|---|---|---|---|---|---|
| (5261) Eureka | 5.63 | 0.0593 | 22.22 | 16.1 | 1.79 |
| (385250) 2001 $DH_{47}$ | 5.90 | 0.0572 | 22.80 | 18.9 | 0.49 |
| (311999) 2007 $NS_2$ | 7.40 | 0.0468 | 20.95 | 18.1 | 0.71 |
| 2011 $SC_{191}$ | 9.52 | 0.0734 | 19.14 | 19.3 | 0.41 |
| 2011 $SL_{25}$ | 7.97 | 0.0850 | 21.75 | 19.5 | 0.37 |
| 2011 $UB_{256}$ | 5.89 | 0.0565 | 22.64 | 20.1 | 0.28 |
| 2011 $UN_{63}$ | 7.44 | 0.0512 | 21.60 | 19.7 | 0.34 |

Orbital elements are from Ćuk et al. (2015). Absolute magnitudes were retrieved from the Minor Planet Center Database on 26 July 2016.
[a]Calculated from *H* assuming a visible albedo of 0.2.

seeking to reproduce the observed orbital distribution of family members with plausible kinematical properties of the family formation event. Finally, we perform a rigorous calculation of the collisional lifetime of Martian Trojans to determine if, and when, collisional disruption is likely to have occurred.

This paper is organised as follows: In the following Section, we review the currently available information on Martian Trojans and the Eureka family. In Section 3 we look at the size distribution of family members confirmed to-date. In Section 4 we construct a probabilistic model of the collisional dispersion and escape of Trojan fragments and apply it to the case at hand. In Section 5 we perform a calculation of the lifetime of objects in the Martian Trojan clouds against collisional disruption. Finally, in Section 7 we carry out a synthesis of results from the different lines of investigation and present our conclusions in Section 7.

## 2. The observed population of Martian Trojans

Although Mars plays host to a population of co-orbital objects (Connors et al., 2005), here we are concerned with *stable* Trojans, in other words asteroids that have librated around the $L_4$ and $L_5$ Lagrangian equilibrium points of Mars for an appreciable fraction of the age of the solar system. Scholl et al. (2005) showed by numerical integration that there are at least three such objects: (5261) Eureka & (101429) 1998 $VF_{31}$ at $L_5$ and (121514) 1999 $UJ_7$ at $L_4$. New simulations by Christou (2013) and by de la Fuente Marcos and de la Fuente Marcos (2013) added a further four: (311999) 2007 $NS_2$, (385250) 2001 $DH_{47}$, 2011 $UN_{63}$ and 2011 $SC_{191}$. Finally, Ćuk et al. (2015) reported two additional objects, 2011 $SL_{25}$ and 2011 $UB_{256}$, recovered during the 2013/14 opposition and consequently confirmed as stable Trojans by integrating their orbits. Table 1 lists their orbital elements. The quantity *D* refers to the half-amplitude of libration of the mean longitude $\lambda$ around $L_5$. Remarkably, all 6 asteroids identified as Trojans in 2013 and 2015 are Eureka family members.

Compositional information on the three brightest Trojans shows that Eureka belongs to the rare, olivine-dominated, A-type taxonomic class while 1998 $VF_{31}$ shows a spectrum dominated by pyroxene and not directly related to Eureka (Rivkin et al., 2003; 2007). 1999 $UJ_7$'s featureless spectrum (Rivkin et al., 2003) and low albedo ($p_v = 0.048 \pm 0.012$; Mainzer et al., 2012) suggest a primitive taxonomy, typical of bodies in the Outer Main Belt and Jupiter Trojan clouds (Grav et al., 2012). Assuming albedos of 0.2, 0.23 & 0.06 for the respective classes within the Bus-DeMeo taxonomy (5261: A class; 101429: S class; 121514: C/D class; DeMeo et al., 2009; DeMeo and Carry, 2013) yields, through the formula

$$D = \frac{1329}{\sqrt{p_v}} 10^{-H/5},$$

diameters of 1.8, 1.1 & 2.2 km respectively. Therefore the three brightest Trojans are similar in size, 1-2 km across. Analysis of

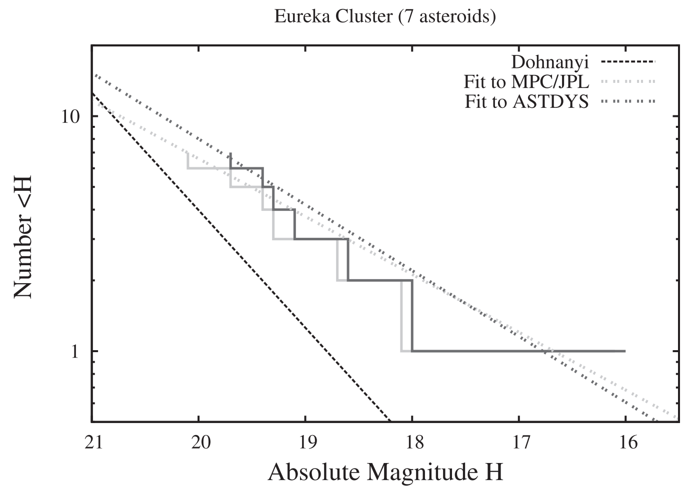


**Fig. 1.** Cumulative distribution of absolute magnitudes for Eureka family asteroids, using data from MPC/JPL (light grey line) and ASTDYS (dark grey line). The straight double-dotted lines represent power law fits to the respective distributions. The black dashed line indicates the slope expected for a collisionally-evolved population according to Dohnanyi (1969).

observations during year one of the WISE reactivation mission gave $D = 1.88 \pm 0.23$ km, $p_v = 0.18 \pm 0.05$ for Eureka (Nugent et al., 2015), consistent with our above estimates of size & albedo for that asteroid and within the range of albedo values obtained by WISE (Masiero et al., 2011) and IRAS (Tedesco et al., 2004) for other so-called monomineralic olivine asteroids (Sanchez et al., 2014).

Recently, it was confirmed that asteroids (311999) 2007 $NS_2$ and (385250) 2001 $DH_{47}$, the second and third largest members of the Eureka family, share the same spectral reflectance properties as (5261) Eureka. In particular, all three objects display features that are diagnostic of an olivine-dominated surface composition (Borisov et al., 2017; Polishook et al., 2016). Since the implied taxonomy is uncommon, it further strengthens the case for a common origin of the members of this group. In other words, we have here a real *family* of objects sharing a common parent body, rather than a cluster of unrelated asteroids.

## 3. Size distribution of the family

The small sample size notwithstanding, the size distribution of family members is diagnostic of the formation mechanism (Tanga et al., 1999; Jacobson et al., 2014). Assuming that the size distribution of the objects has the form

$$N(>s) = As^{-\alpha} \quad (1)$$

where *s* is the asteroid diameter and $\alpha$ and *A* are constants, it is simple to show that the corresponding distribution of absolute magnitudes is

$$N(<H) = B\,10^{\beta H} \quad (2)$$

where $\alpha = 5\beta$ and *B* is related to *A*, $\alpha$ and the albedo. In this case, the magnitude distribution appears as a line in the plane $\log(N(<H))$ vs *H*. A nonlinear least-squares fit utilising the Marquardt–Levenberg algorithm with inverse-variance weights yields $\beta = 0.25 \pm 0.02$ & $0.28 \pm 0.03$ for the JPL/MPC and AstDys data respectively or, equivalently, 1.25 & 1.4 for $N(>D)$. Note that AstDys *H* values for the fainter objects are systematically higher than JPL's. MPC magnitudes tend to be underestimated for the fainter objects (Jurić et al., 2002). In any case, the slopes are considerably shallower than the $\beta = 0.5$ expected for a population of collisional fragments (Dohnanyi, 1969, Fig. 1). Interestingly, Gladman et al. (2009) found an exponent of $\sim 0.3$ for the distribution of asteroids with