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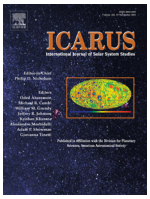

Planetary chaos and the (In)stability of Hungaria asteroids

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ABSTRACT

The Hungaria asteroid group is located interior to the main asteroid belt, with semimajor axes between 1.8 and 2 AU, low eccentricities and inclinations of 16–35 degrees. Recently, it has been proposed that Hungaria asteroids are a secularly declining population that may be related to the Late Heavy Bombardment (LHB) impactors (Cuk, 2012; Bottke et al., 2012). While Cuk (2012) and Bottke et al. (2012) have reproduced a Hungaria-like population that declined exponentially, the real Hungarias were never confirmed to be unstable to the same degree. Here we find that the stability of Hungarias is strongly dependent on the evolution of the eccentricity of Mars, which is chaotic and unpredictable on Gyr timescales. We find that the high Martian eccentricity chiefly affects Hungarias through close approaches with Mars, rather than planetary secular modes. However, current minimum perihelia of Hungarias (over Myr timescales) are not diagnostic of their long-term stability due to a number of secular and mean motion resonances affecting the Hungaria region Milani et al., 2010. We conclude that planetary chaos makes it impossible to determine the effective lifetimes of observed Hungarias. Furthermore, long-term changes of Martian eccentricity could lead to variable Hungaria loss over time. We speculate that some of the most stable Hungarias may have been placed in their present orbit when the eccentricity of Mars was significantly higher than today.

1. Introduction

Hungarias are a dynamical group of asteroids interior to the asteroid belt but exterior to the orbit of Mars (in the 1.8-2 AU range). Most stable Hungarias have high inclinations (16-35°) and low eccentricities (< 0.1). Hungarias are bracketed in inclination by multiple secular resonances, and are separated from the main asteroid belt by the ν_6 secular resonance and the 4:1 mean-motion resonance with Jupiter. Hungarias have a less well-defined inner boundary that is being enforced by close encounters with Mars (Warner et al., 2009; Milani et al., 2010). While they all inhabit the same island of relative dynamical stability, Hungarias are not compositionally uniform, with most common asteroid types being S and E (Warner et al., 2009; Lucas et al., 2017). A significant fraction of Hungarias belong to an E-type genetic family centered on 434 Hungaria (Warner et al., 2009), which has been proposed as the main source of aubrite meteorites (Gaffey et al., 1992; Ćuk et al., 2014).

Unlike the asteroids in the main belt, Hungarias are thought not to be stable over the age of the Solar System, but are constantly escaping into the Mars-crossing region (Milani et al., 2010; McEachern et al., 2010). The present-day reverse evolution of Mars-crossers into Hungarias has been found insufficient for replenishing the Hungaria population (McEachern et al., 2010). The implication is that the proto-Hungarias were orders of magnitude more numerous in the early Solar System, and may have been the main source of the Late Heavy Bombardment (Ćuk, 2012; Bottke et al., 2012). Hungarias are proposed to be depleted remnants of primordial Mars-crossers (Ćuk, 2012), or survivors from the extinct innermost part of main asteroid belt perturbed by late planetary migration (Bottke et al., 2012). Ćuk (2012) showed that a primordial population consisting solely from Mars-crossers can give rise to a quasi-stable Hungaria-like population, which eventually has a half-life of 600 Myr. Bottke et al. (2012) started with an initially dynamically cold "E-belt" that was perturbed by late giant planet migration, but the end results was similar in terms of creating quasi-stable Hungarias that slowly declined over next few Gyr (Nesvorný et al., 2017).

Given that the idea of a exponentially declining Hungaria population is established in the literature based on modeling of synthetic bodies, we wanted to test this concept on real asteroids. Previously, Migliorini et al. (1998) have reported a 960-Myr half-life for largest Hungarias, which may be significantly different from Ćuk (2012) prediction of 600 Myr, while

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Galiazzo and Schwarz (2014) found 5% loss over 100 Myr, implying half-life beyond 1 Gyr. Additionally, it would be very interesting to determine if there is a difference in dynamical stability between different spectroscopic types of Hungarias. Currently, 80% of background Hungarias (i.e. excluding the E-type family centered on 434 Hungaria) are S-type asteroids (Lucas et al., 2017). While the E-type Hungarias are very likely enstatite achondrites (i.e., aubrites Gaffey et al., 1992; Ćuk et al., 2014), S-type Hungarias have been suggested to contain more primitive achondrites than ordinary chondrites than the main-belt S-type asteroids (Lucas et al., 2017). Additionally, some of the few rare A-type (olivine-rich) asteroids are found among Hungarias. Different dynamical half-lives may indicate that the some of the spectral types may have been more of less common in the past, with implications for the primordial distribution of small bodies in the Solar System.

2. Billion-Year numerical experiments

Before moving on to purely gravitational dynamics of Hungarias, we must address the radiative Yarkovsky and YORP effects (Rubincam, 1995, 2000; Bottke et al., 2006, and references therein). Because none of the Hungarias are very large, almost all of them should experience some semimajor axis mobility due to the Yarkovsky effect, which is dependent on the objects' rotations, which are themselves affected by the YORP effect. An ideal simulation of Hungarias' stability would (in addition to perturbations from all eight planets) include Yarkovsky and YORP effects and close approaches with Mars (when needed). Another requirement is more subtle: we need all of the particles to interact with planets on the same orbits. Integrators such as swift-rmvs3 (and its Yarkovsky variant, swift-rmvsy; Levison and Duncan, 1994; Brož, 2006) which are both efficient and handle close encounters between planets and test particles well, have a peculiarity that the evolution of planetary orbits depends on the motion of otherwise massless particles. This is because the special handling of close approaches introduces time-step changes, the timing of which depends on what the test particles are doing. A large set of Hungarias (and their clones) would need to be integrated on many CPUs, and given the serial nature of swift (constrained by the nature of a n-body problem) every node would in practice integrate a different version of the planetary system. Our integrations are not optimized to follow planetary orbits as precisely as possible, but even state-of-the-art numerical experiments cannot predict planetary orbits more than 50–60 Myr in the future (Laskar et al., 2011a, 2011b). On the other hand, swift-rmvs4, while not including Yarkovsky effect, is designed to integrate close approaches without having the test particles affect planetary orbits in any way, so that all nodes will experience the same planetary system. A more primitive symplectic integrator simpl that one of the authors (M.Ć.) used in Ćuk et al. (2015) can include arbitrary forces like the Yarkovsky effect, but does not include close encounters, which makes it unsuited to this study but also happens to eliminate the problem of planetary divergence.

In order to be able control for the evolution of planetary orbits, we have decided to primarily use swift-rmvs4 for our numerical experiments. We wanted to retain the ability to accurately integrate close approaches with Mars, and decided that the accurate treatment of the Yarkovsky effect is not important to the same degree. To partially account for the Yarkovsky-related semimajor axis drift, we cloned each body 21 times (including the nominal orbit) and spread the clones within the range of semimajor axis expected from Yarkovsky drift in 100 Myr, using estimates based on Bottke et al. (2006) (Table 1). We generally find little correlation between fates of neighboring particles so we do not think that Yarkovsky-driven semimajor axis spreading is a major effect on the stability of largest Hungarias on the sub-Gyr timescale.

Table 1
Results of our 1 Gyr simulations for 14 Hungarias. The albedos and magnitudes shown here were used for determining Δa. These vales were obtained from Jet Propulsion Laboratory's HORIZONS system in November 2014 and may be outdated (we used albedo of 0.3 when neither spectral class nor albedo were known). The spread in semimajor axes Δa is determined after the fact from the simulation output (as the spread was introduced very roughly by changing the Hungaria's heliocentric ditance), and represents range from smallest to largest a (with the nominal orbit in the center and other clones distributed uniformly troughout the range). N_{HIGH} and N_{LOW} give the number of clones still in the simulation (i.e. that have not been lost to collisions or ejection) at 1 Gyr.

Asteroid	H mag.	Albedo	Δa [AU]	N_{HIGH}	N_{LOW}	Class
(434) Hungaria	11.21	0.428	1.4×10^{-3}	19	21	E
(3447) Burckhalter	12.2	(0.3)	3.0×10^{-3}	11	18	(u)
(1103) Sequoia	12.25	0.4	2.1×10^{-3}	11	18	E
(1025) Riema	12.4	0.4	3.9×10^{-3}	15	17	E
(1600) Vyssotsky	12.5	0.25	2.8×10^{-3}	13	21	A
(1453) Fennia	12.5	0.2495	2.8×10^{-3}	20	21	S
(1019) Strackea	12.63	0.2265	2.3×10^{-3}	21	21	S
(1509) Esclangona	12.64	0.2327	3.0×10^{-3}	7	21	S
(3940) Larion	12.7	(0.3)	2.7×10^{-3}	14	19	(u)
(3169) Ostro	12.73	0.4	3.1×10^{-3}	9	20	Xe
(3266) Bernardus	12.8	(0.3)	7.2×10^{-3}	19	20	(u)
(2001) Einstein	12.85	0.4	5.7×10^{-3}	6	15	E
(5806) Archieroy	12.9	(0.3)	3.5×10^{-3}	21	21	(u)
(5639) Cuk	14.7	(0.3)	9.5×10^{-3}	3	17	(u)

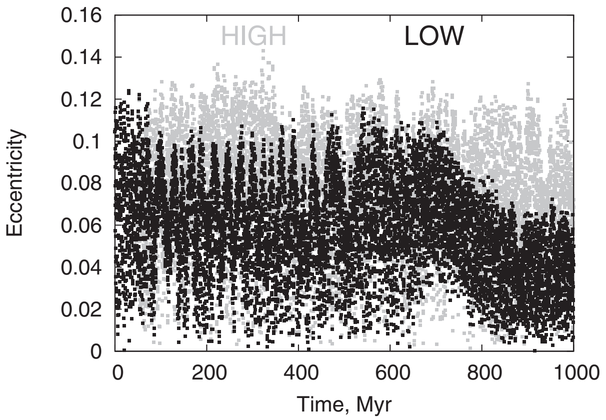

Fig. 1. The evolution of Martian eccentricity over next 1 Gyr in our two cases of the dynamical evolution of the Solar System, high and low. The two simulations differ only by a small shift in the initial position of the planet Mercury.

The importance of variations in Martian eccentricity for the stability of Hungarias was first indicated by inconsistent results we were getting for their stability when using slightly different initial conditions or different integrators. Ever since Laskar (1994) it was known that Martian eccentricity can experience large variation over the age of the Solar System, and Ćuk et al. (2015) recently found a major effect of the variation in Martian eccentricity on the dynamics of Mars Trojans. This suggested that we may need to separately explore Hungarias' stability in different "parallel Solar systems" with different histories of Martian eccentricity. We first set up ten different simulations of the planetary system alone using swift-rmvs4, with identical initial conditions[1], except that in each next integration (starting with the second) Mercury was 10^{-7} AU further from the Sun in the x-direction. After 1 Gyr, we compared the behavior of Martian eccentricity in all ten simulations, and chose two of them as initial conditions for our two cases of Hungaria stability, which we will term high and low (Fig. 1).

We then ran 1 Gyr simulations of the clones of 14 different, mostly brightest, Hungarias (Table 1; we also included 5639 Cuk as

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[1] Just like the nominal orbits of the Hungarias, planetary initial conditions were based on vectors obtained from JPL's HORIZONS system.

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