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Dynamical evolution of the Hungaria asteroids

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ABSTRACT

The Hungarias are a stable asteroid group orbiting between Mars and the main asteroid belt, with high inclinations (16–30°), low eccentricities ($e < 0.18$), and a narrow range of semi-major axes (1.78–2.06 AU). In order to explore the significance of thermally-induced Yarkovsky drift on the population, we conducted three orbital simulations of a 1000-particle grid in Hungaria a–e–i space. The three simulations included asteroid radii of 0.2, 1.0, and 5.0 km, respectively, with run times of 200 Myr. The results show that mean motion resonances—martian ones in particular—play a significant role in the destabilization of asteroids in the region. We conclude that either the initial Hungaria population was enormous, or, more likely, Hungarias must be replenished through collisional or dynamical means. To test the latter possibility, we conducted three more simulations of the same radii, this time in nearby Mars-crossing space. We find that certain Mars crossers can be trapped in martian resonances, and by a combination of chaotic diffusion and the Yarkovsky effect, can be stabilized by them. Therefore, some Hungarias (around 5% of non-family members with absolute magnitudes $H < 15.5$ and 10% for $H < 17$) may represent previously transient Mars crossers that have been adopted in this manner.

1. Introduction

The Hungarias are a distinct population of asteroids located in a swath between 1.78 and 2.06 AU. Bounded by the ν_5 and ν_{16} secular resonances,[1] the 4:1 mean motion resonance with Jupiter, and Mars-crossing orbital space (Gradie et al., 1979; Milani et al., 2010), its members have relatively high inclinations ($16° < i < 34°$) and eccentricities typically less than 0.18. The Hungarias make up the closest distinct region of the asteroid belt to the Sun, lying interior to the inner main belt by at least 0.1 AU. The region derives its name from its largest and earliest known member, (434) Hungaria. This asteroid has also been identified as the largest fragment of what is likely to be the region's sole asteroid family, created by a catastrophic collision about 0.5 Gyr ago (Warner et al., 2009). A majority of the approximately 5000 bodies in the region are thought to be part of this family. Almost all known Hungarias are brighter than absolute magnitude $H = 18$, meaning they are about 1 km in diameter or larger.

A noteworthy feature of the Hungaria group is their range of taxonomic classes. E and X spectral types are the most common, followed by S types, Cs, and As (Warner et al., 2009). All these bodies are found in the main belt with different spatial distributions and prevalence. The abundance of E types among the Hungarias is fascinating because E types are very rare in other asteroid populations. Clark et al. (2004) listed only 10 known E-type asteroids outside the Hungaria region. E-type asteroids have extremely high albedos (>0.34, with the majority >0.4; Tedesco et al., 1989; Gaffey and Kelley, 2004) and exhibit a range of curious spectra. Many spectra are consistent with aubrite meteorites[2] suggesting they might be the mantle material of parent bodies that differentiated in highly reducing conditions (Gaffey and Kelley, 2004). Based on their current distribution, it is most likely that they originated from the terrestrial planet zone, interior to most other asteroid types.

2. Preliminary experiment

Before examining long-term evolution of various-sized bodies in the Hungaria region, we decided to use a simple integration to test if the largest Hungarias could have been stable over the age of the Solar System, when taking into account the Yarkovsky effect.[3] In a preliminary experiment, we integrated the orbits of some 30 large asteroids in the Hungaria region (which turned out to in-

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[1] The ν_5 is the secular resonance at which the apsidal motion of an asteroid (i.e. the precession of its pericenter) is equal to the fifth secular apsidal frequency. Across the asteroid belt this occurs at a proper inclination around 30°. The ν_{16} is the secular resonance at which the nodal motion of an asteroid (i.e. the precession of its node) is equal to the sixth secular nodal frequency. This resonance lives near 2.0 AU.

[2] Aubrites are differentiated stony meteorites consisting primarily of enstatite with very low Fe content. Also known as enstatite achondrites.

[3] The Yarkovsky effect is a perturbation of an asteroid's orbit resulting from the recoil from its thermal radiation. The integrated momentum carried by thermal photons is offset from the Sun–asteroid line due to thermal inertia, resulting in a along-orbit force modifying the semi-major axis (see Bottke et al. (2006a,b) for a recent review).

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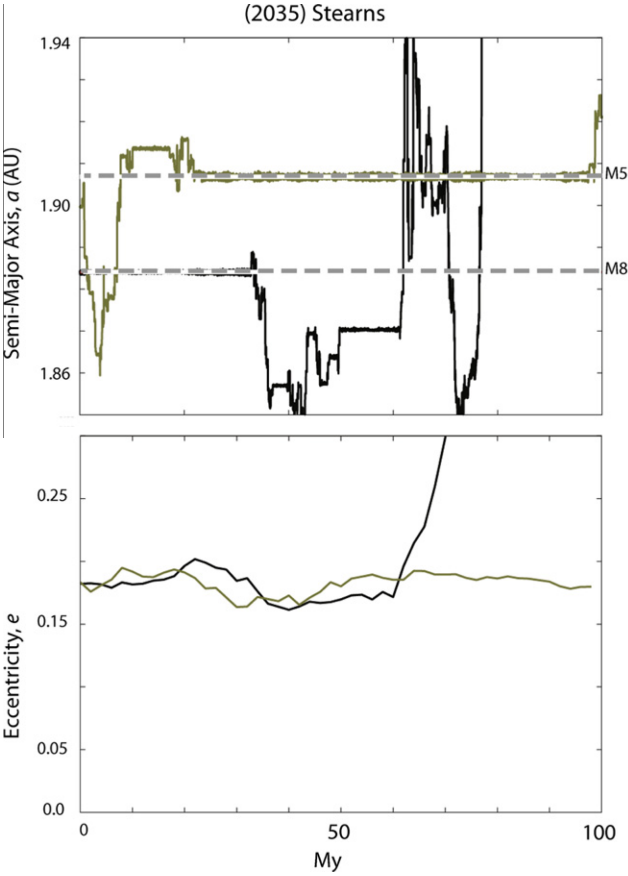

Fig. 1. Martian resonances catch Mars crossers for long durations. Osculating semi-major axis (top panel) and averaged eccentricity (bottom panel) of Asteroid (2035) Stearns over 100 Myr. Black plot is with today's initial conditions. Gray plot is with same initial conditions but with a shift in semi-major axis. Both get stuck to martian resonances for tens of millions of years. Eccentricities are plotted as running averages over a 5 Myr box.

clude some transient Mars crossers) from present initial conditions to 100 Myr in the future, using Rauch and Hamilton's symplectic integrator, HNBody (Rauch and Hamilton, 2002). These 30 large asteroids all had taxonomic classes listed on the JPL small-body database following the conventional Tholen classification (Tholen, 1984). We also conducted four nearly identical simulations, but with the 30 orbits shifted in semi-major axis. The shift was based on expected Yarkovsky drift over 0.5 and 1.0 Gyr, using parameters taken from Bottke et al. (2006b). All eight planets were included into the integration and the timestep was 1 day. Our primary aim was to study the future dynamical behavior of these asteroids and to characterize the region's general limits of stability. Some of our asteroids were incidentally shifted onto martian resonances, which proved to have significant dynamical effects.

Fig. 1 demonstrates how Mars crossers can stick to martian resonances (here "Mars crossers" means objects exhibiting kicks in the semi-major axis caused by close approaches to Mars). The Mars crosser (2035) Stearns stays in the martian 8:11 resonance for over 30 Myr during the nominal, unshifted simulation (black plot). This is because an asteroid is protected from encountering the planet it is in resonance with, even if the asteroid's eccentricity is high (Murray and Dermott, 1999). When shifted, Stearns randomly walks in semi-major axis through martian encounters (gray plot,) until it gets stuck to the 5:7 resonance, staying for as long as 70 Myr. Because of (2035) Stearns' chaotic nature, these simulations are not to be taken as definitive predictors of behavior, but nevertheless show how Mars crossers, although unstable, can remain in the Hungaria region for long periods due to resonance sticking.

Asteroids can chaotically jump from being near a resonance to being in a resonance and vice versa. In Fig. 2, a shifted orbit of (1355) Magoeba (gray plot) begins near, but not in, the 3:4 resonance. This situation continues for the first half of the simulation, but by 50 Myr Magoeba librates around 1.8458 AU, indicating that it has become resonant. The resonance also causes Magoeba's variations in semi-major axis and eccentricity to be more pronounced, the latter staying above the average eccentricity of the nominal unshifted simulation (black plot) for nearly the entire 100 Myr. Like Magoeba, (1727) Mette's eccentricity is greatly affected by the 3:4 resonance; its value dips significantly above and below the nominal eccentricity of the non-resonant simulation.

This preliminary numerical experiment was purely gravitational, and having shown that the local resonances could noticeably impact the Hungarias, it was necessary to do more comprehensive simulations: particularly, ones that incorporated the Yarkovsky effect. The Yarkovsky effect is especially important for the dynamical evolution of the Hungarias for several reasons. Firstly, because Yarkovsky is insolation-driven, the orbital migration among the Hungarias than in the more distant main belt (this might be partially offset by higher albedos in the case of numerous E-type Hungarias). Secondly, the region's small size allows asteroids to drift across significant fractions of its 0.2 AU width, not only leading them into resonances, but in some cases out of the stable region entirely. The combination of Yarkovsky drift and resonances is known to deplete asteroids from the main belt (Bottke et al., 2006b), and the same process has likely lead to the loss of many Hungarias. Finally, the Yarkovsky effect may play a role in population exchange between Mars crossers and Hungarias, which we will explore later in this paper.

3. Experiment 1: Hungaria grid

We conducted three simulations of 1000 test asteroids starting in stable Hungaria space ($1.8 < a < 1.98$ AU, $16° < i < 25°$, and perihelia outside 1.66 AU). The simulations tested asteroid radii of 0.2, 1.0, and 5.0 km (with randomized obliquities), and were run for 200 Myr. We used the symplectic integrator SWIFT-rmvs3y by Miroslav Brož to evolve the orbits (Brož, 2006). Brož's package is a modification of a widely used integrator, SWIFT (by Duncan et al. (1998)) in a number of ways, most notably in including Yarkovsky drift.

Our simulations are significantly longer than the natural eigenperiods of the Solar System. Therefore, if a body remains stable over the course of the simulation, it is likely (except in cases of very slow chaotic diffusion) that its orbit is indeed stable against gravitational perturbations. For example, Tabachnik and Evans (2000) used 100-Myr simulation to sufficiently characterize the stability of inner Solar System asteroid repositories. Yarkovsky effect can cause instability on longer timescales (by slowly drifting asteroids into resonances), so in principle running longer simulations would be useful if computationally expensive. However, we expect even 5-km bodies to significantly change their rotational state over 200 Myr, making Yarkovsky evolution on longer timescales somewhat of a stochastic process. While the SWIFT-rmvs3y is fully cabale of taking YORP reorientation into account, we decided to simply extrapolate our results to longer timescales assuming our 200-Myr simulations are typical of the long-term history of the bodies in question. The last assumption may not be correct for some of our largest bodies, as discussed below.

We used a timestep of three days, outputting orbital elements of each body every 100,000 years. The simulations in this paper

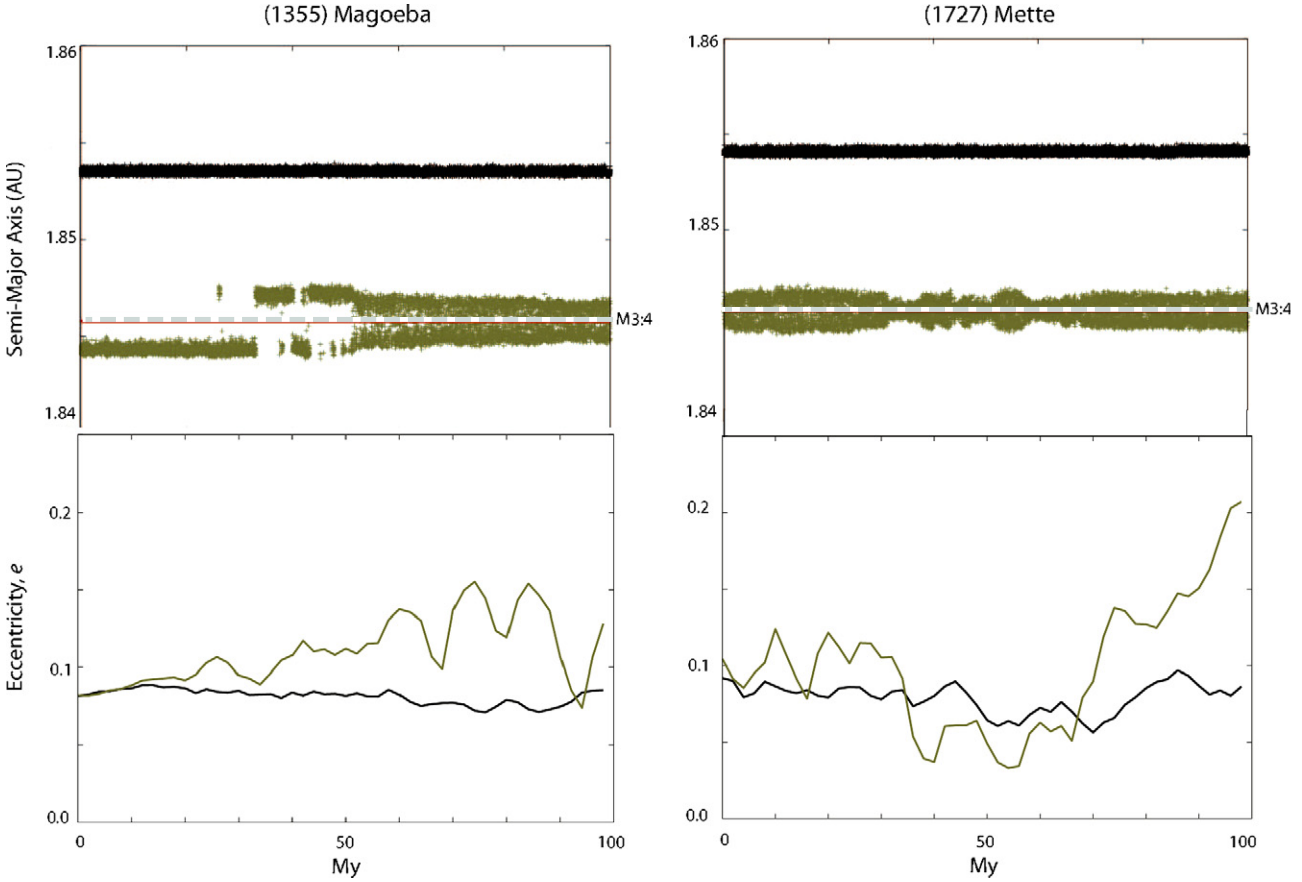

Fig. 2. Eccentricity fluctuations due to martian resonance. The semi-major axes and eccentricities of (1355) Magoeba and (1727) Mette over 100 Myr are shown in black. Gray plots are their corresponding evolutions when one is shifted near and the other onto the Mars 3:4 resonance.

were run on the Odyssey cluster operated by the Harvard FAS Research Computing Group, taking approximately one month to complete.

See the relevant columns of Table 1 for a summary of the physical and thermal parameters specified for these simulations.

3.1. Results

Fig. 3 shows the time evolution of the asteroids in semi-major axis and eccentricity. The asteroids drift from their initial semi-major axes, and—for the two smallest radii—become indistinguishably mixed by the end of the simulations. The 5 km asteroids migrate slowly and do not diverge far from their starting positions. Each asteroid group disperses in eccentricity as well, with some bodies becoming lost altogether.

Table 1
Summary of simulation parameters.

Parameter	Experiment 1			Experiment 2		
Radius (km)	0.2	1.0	5.0	0.2	2.0	10.0
Number of test particles	1000	1000	1000	1000	1000	1000
Simulation length (Myr)	200	200	200	100	100	100
Timestep (days)	3	3	3	3	3	3
Bulk density (kg/m^3)	2500	2500	2500	2500	2500	2500
Surface density (kg/m^3)	1700	1700	1700	1700	1700	1700
Thermal conductivity (W/K/m)	0.01	0.01	0.01	0.01	0.01	0.01
Thermal capacity (W/kg/K)	680	680	680	680	680	680
Albedo	0.4	0.4	0.4	0.4	0.4	0.4
Infrared emissivity	0.8	0.8	0.8	0.8	0.8	0.8
Rotation period (h)	1.0	1.0	10.0	1.0	1.0	10.0
Reorientations	No	No	No	No	No	No
Disruptions	No	No	No	No	No	No

We observe numerous examples of these losses resulting from the effects of martian mean motion resonances. Fig. 4 shows 0.2 km asteroids drifting into the M3:4 and M9:13 resonances (panels (a) and (b), respectively). Both asteroids' eccentricity increase or fluctuate dramatically while resonant, until they chaotically escape. Since their eccentricities have been elevated into Mars-crossing a–e space, they encounter Mars immediately upon escaping. Morbidelli and Nesvorny (1999) demonstrated this chaotic diffusion for asteroids in inner main belt resonances.

Similar examples are exhibited in Fig. 5, which demonstrate the destabilization of 1.0-km bodies in M7:9: and M10:13 resonances. Chaotic diffusion of eccentricity and resulting escape is observed to occur in martian resonances as weak as fifth order, and for both prograde and retrograde spinning bodies.

While martian resonances account for the majority of resonance losses, we do witness examples of other mean motion resonances causing instabilities, including those of Jupiter, Saturn, Earth, and even Venus. Jupiter's 5:1 resonance at 1.7798 AU is an important example, as it is a common departure point for asteroids migrating at the inner edge of the Hungarias.

Table 2 shows the population count of the Hungaria grid as it decreases with time. The smallest group ($R = 0.2$ km) decay the fastest as they strong encounter resonances more frequently (owing to faster drift speeds). Two hundred and ninety out of 1000 asteroids are destabilized in 200 Myr, with an overall half-life of 350 Myr. Meanwhile, 229 of the 1.0-km bodies and 194 of the 5.0-km bodies are lost, amounting to longer half-lives of 440 Myr

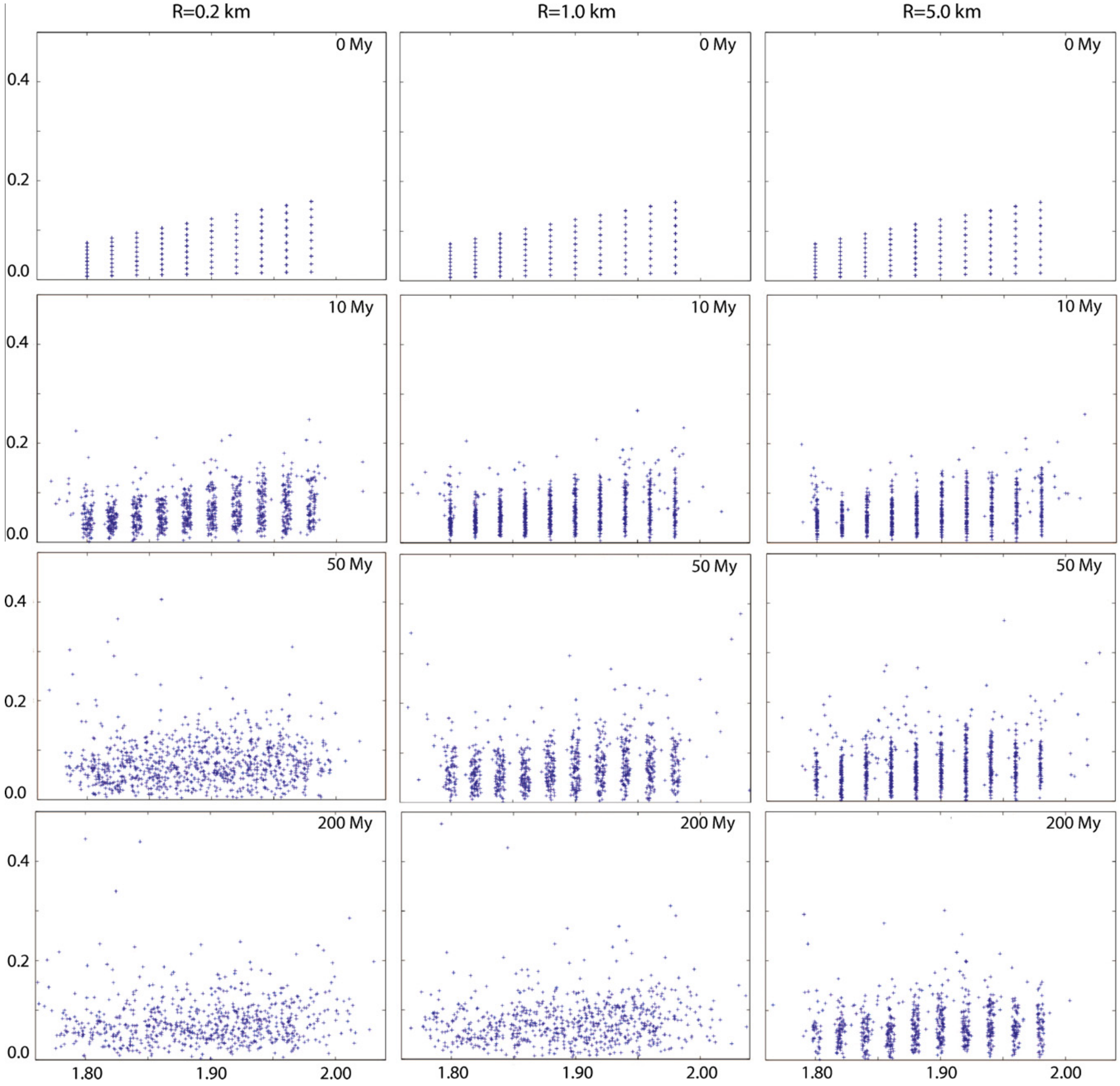

Fig. 3. Eccentricity (y-axis) vs. a (x-axis; in AU) time evolution for 1000 test asteroids starting in Hungaria space.

and 475 Myr respectively. These values lie intermediate between Migliorini et al.'s Hungaria half-life of 137.2 Myr (Migliorini et al., 1998) and Milani et al.'s 960 Myr (Milani et al., 2010). Large uncertainties are to be expected as the former study was based on only 56 asteroids of $D > 5$ km, while the latter study extrapolated the half-life from 10-Myr simulation which included many (relatively stable) Hungaria family members (Yarkovsky effect was not included by either study). While our calculated lifetimes for 0.2-km and 1-km bodies are dominated by the Yarkovsky drift into resonances, loss of 5-km bodies is more affected by purely gravitational chaos and probably reflects our choice of initial conditions more than the realistic loss rate of Hungarias. In order to calculate the lifetime of 5-km Hungarias against the Yarkovsky drift into resonances, one needs to do integrations significantly longer than 200 Myr. For this reason we will not be using the above listed lifetime for 5-km bodies for any further estimates.

Splitting our initial grid into two separate groups, the inner half decays faster, which is consistent across all three radii (Table 2). This can be attributed to the fact that 4 out of the 6 most destabilizing resonances are located below 1.9 AU. Table 3 lists the main resonances found in the Hungaria region, their order, and their observed loss rates. Loss rate is the number of asteroids a resonance was observed to destabilize divided by the number of times asteroids encountered it. The most destabilizing resonances include M3:4, M2:3, M7:9, M5:7, M10:13, and J5:1. Higher loss rates correlate well with lower orders, with a few exceptions such as the fourth order M13:17, presumably because it is coupled with V1:4. Furthermore, loss rates for a specific resonance are generally higher for the larger asteroids (Table 3—last column), as they migrate more slowly and are less likely to pass through a resonance unaffected. In reality, any relative depletion of Hungarias below 1.9 AU is impossible to distinguish from the contribution of the

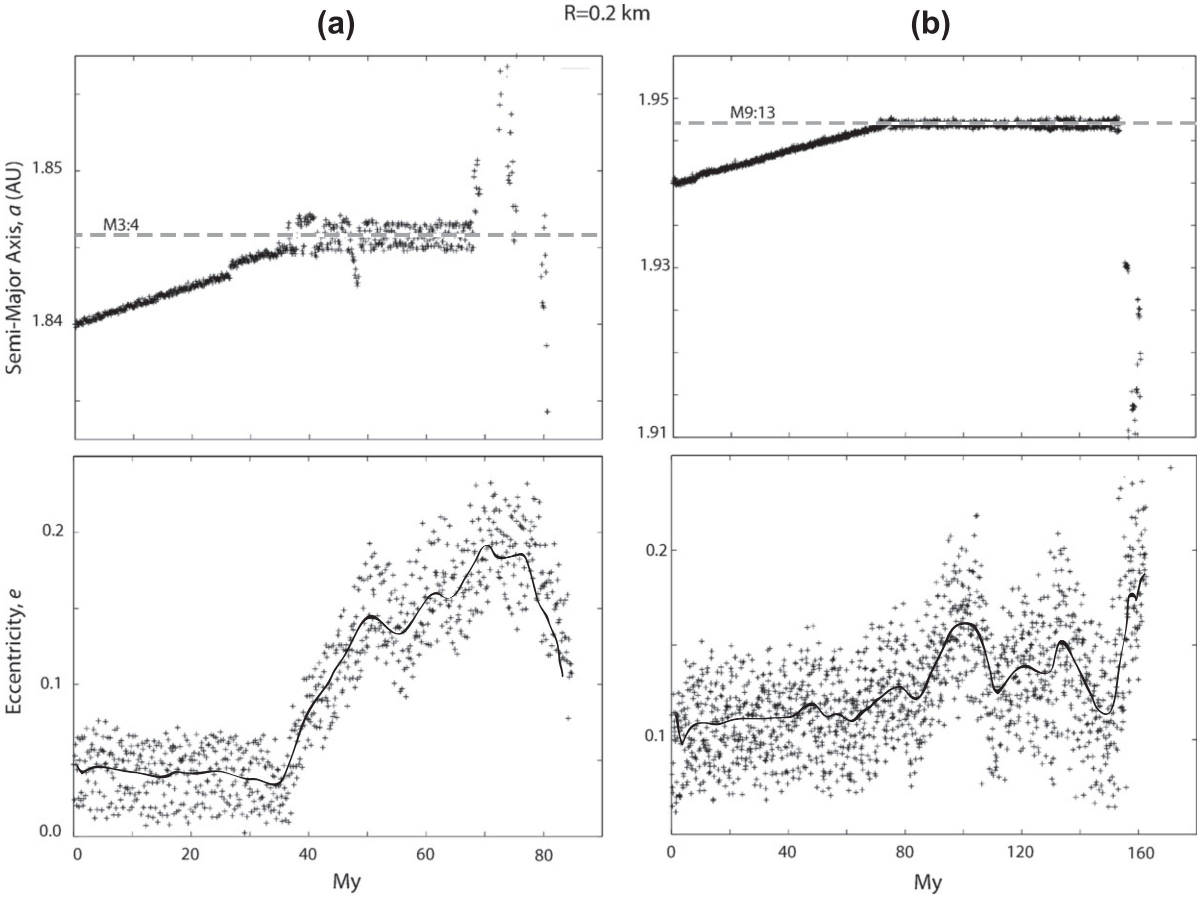

Fig. 4. Two 0.2-km Hungaria test bodies becoming unstable by the M3:4 and M9:13 resonances, respectively.

large Hungaria family centered on 1.94 AU (Warner et al., 2009; Milani et al., 2010).

Of the one thousand 0.2-km bodies, 801 encountered a resonance during the simulation, and of those, 227 (28%) were destabilized directly as a result of a mean motion resonance. Most (i.e. 76%) of these losses were due to martian resonances. A similar picture emerges from the 1.0 km group: 673 asteroids encountered a resonance. Of these, 115 (about 17%) were destabilized by a resonance, 90 of which were by martian resonances in particular. An analogous chart was not made for the 5 km group as they had not diffused far enough across the region by 200 Myr to provide reliable results.

4. Experiment 2: Mars-crosser grid

Considering that resonances have surely contributed to the demise of many past Hungarias, we were interested in exploring mechanisms of asteroid influx to counteract such losses. In our preliminary experiment, we noticed that strong martian resonances not only increase eccentricity but can also cause substantial drops in eccentricity. When (1727) Mette was shifted onto the powerful 3:4 resonance (Fig. 2), for example, the variations in eccentricity became greater (gray plot), and for about 40 Myr, Mette's eccentricity dropped well below the value of the nominal, non-resonant simulation (black plot). We suggested that such behavior—in concert with the Yarkovsky effect—could facilitate the conversion of transient Mars crossers into stable Hungarias. The preconditions for such 'adoption' would be: (i) landing on/near a martian resonance strong enough to lower the asteroid's eccentricity to non-Mars-crossing values; (ii) escaping the resonance while eccentricity is low; and (iii) drifting far enough away such that the asteroid does not get stuck to the resonance again and risk the excitation of its eccentricity back to unstable levels.

In order to explore the adoption potential of Mars crossers in the Hungaria region, we again utilized Brož's Yarkovsky-capable SWIFT-rmvs3y package to evolve the orbits of 1000 test asteroids for 100 Myr, starting in unstable near-Hungaria space ($1.8 < a < 1.98$ AU, $16^\circ < i < 25^\circ$, and perihelia $1.38 < q < 1.66$ AU, i.e. between Mars' minimum perihelion and maximum aphelion). Like in Experiment 1, three different asteroid radii were studied, but the sizes were not the same as in the previous simulation (now they are 0.2 km, 2 km and 10 km). See Table 1 for a summary of the physical and thermal parameters specified for these simulations.

4.1. Results

Fig. 6 displays the a–e evolution of the 1000 Mars crosser grid from start to finish. Mostly only lower eccentricity asteroids remain, although there are still some at high eccentricities that are unstable but have not yet left the region. These are transient.

Out of an initial population of 1000, 768, 769, and 752 bodies were lost from the 0.2 km, 2.0 km, and 10.0 km groups, respectively. Fitting an exponential decay curve to these data (Fig. 7), we obtain half-lives of 39.9, 40.5, and 42.4 Myr. They are close in value because the loss of Mars crossers is dominated by encounters with Mars, a gravitational process unaffected by small differences in the Yarkovsky drift.

The majority of asteroids decoupled from Mars at the end of our simulations were either borderline stable to begin with (as $q < 1.66$ AU does not guarantee close approaches), or are long-term

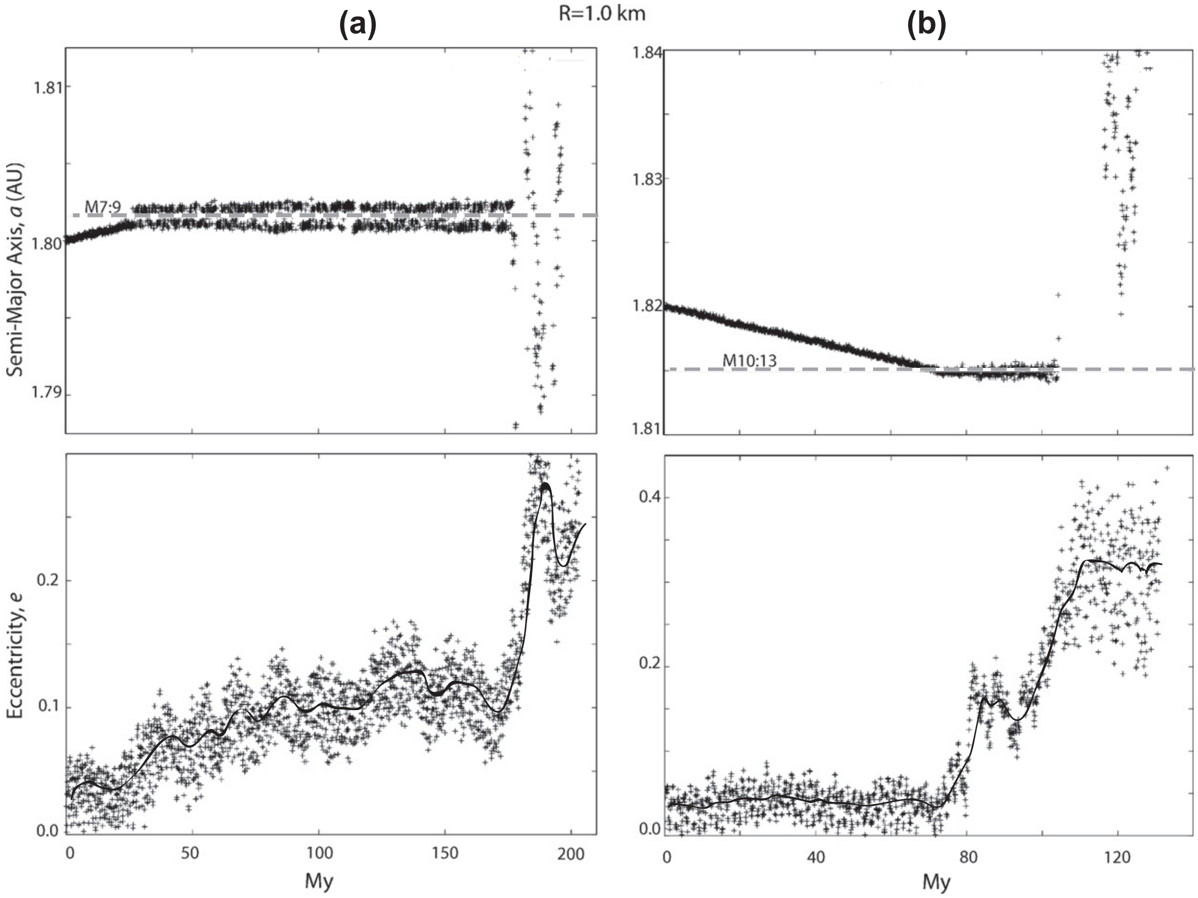

Fig. 5. Two 1.0-km Hungaria test bodies becoming unstable by the M7:9 and M10:13 resonances, respectively.

Table 2
Summary of the decay of the Hungaria test population, both in the inner and outer halves of the region.

Orbital region	$1.8 < a < 1.9$ AU			$1.9 < a < 1.98$ AU			All particles		
Radius (km)	0.2	1.0	5.0	0.2	1.0	5.0	0.2	1.0	5.0
Losses	175	120	115	115	106	79	290	226	194
Loss rate (Myr^{-1})	−.84	−0.61	−0.62	−0.61	−0.53	−0.43	−1.43	−1.14	−1.05
Half-life (Myr)	305	412	405	410	470	574	350	440	475

Mars crossers temporarily detached form Mars. About 5 or 6 asteroids of each radius, however, are clearly stabilized by resonances in accordance with our adoption hypothesis. Histories of the suspected "adoptees" were inspected individually and all were found to have undergone close approaches before encountering resonance (i.e. they were not stable to begin with).

The Mars crosser in Fig. 8 is unstable for 15 Myr, rapidly being scattered by Mars until it lands on the M2:3 resonance. It sticks to the resonance for 20 Myr, decreasing in eccentricity from an average of 0.25 to 0.1, after which it drifts off the resonance. It preserves a lower eccentricity for the rest of the simulation, comfortably far from the resonance to no longer be affected by it. This asteroid is doomed because it will eventually drift out of the region into J4:1, but this is merely a stochastic outcome and is not determined by the adoption process. The asteroid in Fig. 9 is adopted by M2:3 as well, but will not suffer the same fate because its retrograde spin is bringing it closer to the interior of the stable region, as can be seen in the last 25 Myr. While in the resonance the eccentricity fluctuates dramatically, but crucially gets unstuck as the eccentricity plummets for the last time between 70 and 80 Myr. What is the cause of this escape? A small body can chaotically jump out of a resonance at any time, so candidates for adoption would be those that, by chance, jump out of a resonance during a low swing of eccentricity. However, a resonance decreases in width/strength at lower eccentricities (Murray and Dermott, 1999), thereby making it easier for the asteroid to escape. There is no doubt adoption can only happen at lowered eccentricity, but whether or not such lowered eccentricity is a necessary happenstance or the very instigator of the process is harder to distinguish.

5. Discussion

From Experiment 1 we derived a half-life of 439.5 Myr for 1-km Hungaria bodies. Bowell et al. (1989) show that $\log D(\text{km}) = 0.5(6.259 - 0.4H - \log P)$, where D stands for diameter, H for absolute magnitude, and P for geometric albedo. Assuming an albedo of $P = 0.28$ (intermediate between those for E and S types), a radius of 1 km corresponds to an absolute magnitude of 15.5. According to Warner et al.'s (2009) background size distribution of the

Table 3

Mean motion resonances in the Hungarias. Resonances are given as ratio of resonant frequency to planet's orbital frequency. Semi-major axes are rounded to the 4th decimal. Loss rate is the observed proportion of encounters (i.e. asteroids sticking to, getting stuck in, librating around, passing through, etc.) with a resonance that result in destabilization. Data taken from Experiment 1.

Planet	Resonance	Order	Semi-major axis	Encounters[1]	Loss rate[1]	Encounters[2]	Loss rate[2]
Mars	3:4	1	1.8458	161	0.18	68	0.22
Mars	2:3	1	1.9966	39	0.62	0	–
Mars	7:9	2	1.8016	102	0.15	44	0.41
Mars	5:7	2	1.9068	170	0.10	47	0.23
Mars	10:13	3	1.8149	147	0.09	47	0.21
Mars	8:11	3	1.8841	163	0.08	45	0.04
Mars	7:10	3	1.9327	173	0.05	46	0.07
Mars	13:17	4	1.8221	158	0.04	72	0.15
Mars	11:15	4	1.8737	144	0.05	44	0.07
Mars	9:13	4	1.9470	172	0.05	34	0.09
Mars	14:19	5	1.8677	156	0.01	35	0.03
Mars	13:18	5	1.8928	172	0.02	42	0.02
Mars	12:17	5	1.9219	186	0.05	51	0.06
Mars	11:16	5	1.9560	162	0.05	38	0.05
Venus	2:9	7	1.9716	129	0.05	40	0.03
Earth	2:5	3	1.8420	170	–	56	0.09
Earth	3:8	5	1.9230	186	0.05	51	0.06
Earth	5:12	7	1.7926	79	0.08	25	0.08
Earth	4:11	7	1.9629	160	0.04	44	0.09
Earth	5:13	8	1.8908	180	0.01	45	0.00
Earth	5:14	9	1.9866	77	0.04	34	0.09
Jupiter	5:1	4	1.7798	45	0.53	9	–
Jupiter	9:2	7	1.9093	170	–	45	0.02
Jupiter	13:3	10	1.9580	171	–	58	0.07
Jupiter	14:3	11	1.8636	164	0.03	38	0.05
Saturn	11:1	10	1.9373	196	–	62	0.02
Saturn	12:1	11	1.8281	168	–	61	0.03

[1] $R = 0.2$ km.

[2] $R = 1$ km.

Hungarias, there are at least 200 bodies of this size or larger (most of them, given their size, we assume to be independent of the Hungaria family). As the YORP spin-axis reorientation time for kilometer-size asteroids is much shorter than the age of the system (resulting in frequent semi-major axis drift reversals), we will assume that the long-term decay is exponential, with a constant half-life. Since about 10 half-lives have elapsed since the beginning of the Solar System, by our estimate there were 200,000 bodies with radius greater or equal to 1.0 km. A similar calculation estimates 30,000$R \geqslant 5.0$-km bodies. If the loss to collisions with the main-belt asteroids is included, the projected initial Hungaria population becomes several times larger (Warner et al., 2009). These estimates suggests the original population was enormous or, more realistically, the current attrition rate cannot be accurately extrapolated back to estimate the original population. We predict that several family-creating events have occurred in the past and created spikes in the population, making the present number of asteroids largely representative of however many half-lives have occurred since the last breakup. Such ancient families would be hard to identify (since Yarkovsky and YORP tend to mix them thoroughly over time), but may have been crucial for sustaining the Hungarias. This way an enormous primordial population of Hungaria suggested by our estimate could be avoided.

Another reason against extrapolating today's Hungaria population back to the early Solar System is that not all asteroids found there today—even if they are independent, non-family members (i.e. not collisional fragments)—are guaranteed to be originally part of the Hungaria group. In Experiment 2 we found that about 6 out of 1000 Mars crossers became stable Hungarias in 100 Myr. Given a half-life of about 40 Myr, this equates to an adoption rate for a single Mars crosser of 1.26×10^{-4} Myr^{-1}. A search on JPL's small-body database search engine reveals 107 Hungaria-neighboring Mars crossers of $H < 15.5$ (defining the Hungaria-neighborhood of Mars crossers to be $1.78 < a < 2.06$ AU, $q < 1.7$ AU, and $16° < i < 30°$). Since the Mars crosser population is believed to be in steady state (Morbidelli and Nesvorny, 1999), we thus anticipate 0.0135 Mars crossers of this magnitude to become adopted every 1 Myr—a total of about 60 over the age of the Solar System. As these adoptees would be subject to the same decay rates as other Hungarias, then the current number of ex-Mars crossers among the Hungarias is bound to be less than this total. Specifically, if 0.0135$H < 15.5$ Mars crossers are converted to stable Hungarias every million years, and 0.1% of a Hungaria population is lost in that time (assuming a half-life of approximately 450 Myr), then the population of adopted asteroids would reach equilibrium at 12. Thus, we suspect over 5% of the 200 independent $H < 15.5$ bodies in the Hungarias to be former Mars crossers. The proportion is possibly larger because the true number of Mars crossers in the given parameter ranges we specified is likely higher than the 107 JPL listings. It also may be higher for smaller radii, as a similar calculation of the 400$H < 17$ background Hungarias (using the same adoption rate of 1.26×10^{-4} Myr^{-1}, a Hungaria half-life of 400 Myr, and a Mars crosser population of 417 of this magnitude range) suggests about 10% are ex-Mars crossers. Thirdly, the half-life of stable Hungarias may be longer than our simulations derived because the grid that we designed was uniform in asteroid density whereas the real Hungaria distribution may favor pockets of more deeply stable areas. The adopted population may therefore reach equilibrium at a higher number. Finally and perhaps most importantly, the number of independent $H < 15.5$ Hungarias might be much less than 200, closer to the several dozen identified by Milani et al. (2010), making a population of 12 adoptees a significant fraction of the overall background population.

Considering the distribution of large asteroids in the Hungarias today, is it possible that some have been adopted? Are some close enough to a resonance such that they might have originated from one? Fig. 10 shows the distribution of 4th and lower order martian resonances in the Hungaria region, along with the present day

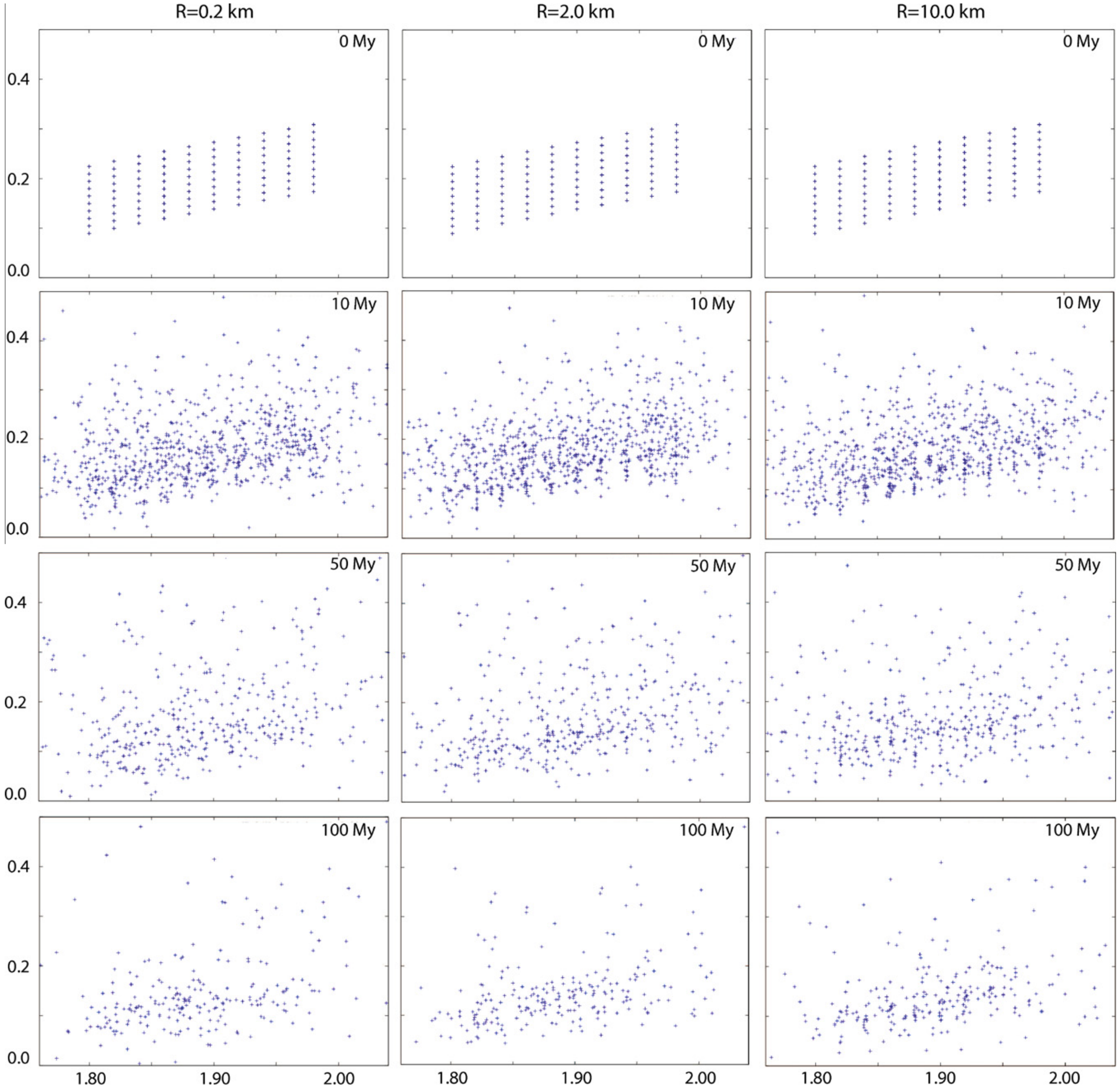

Fig. 6. Eccentricity (y-axis) vs. a (x-axis; in AU) time evolution for 1000 test asteroids starting in Mars crosser space.

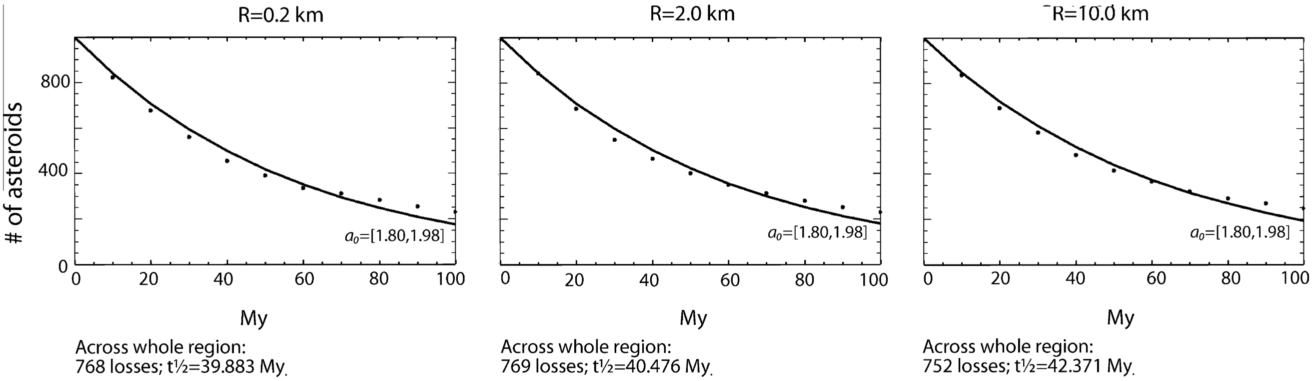

Fig. 7. Population of test Mars crossers over time.

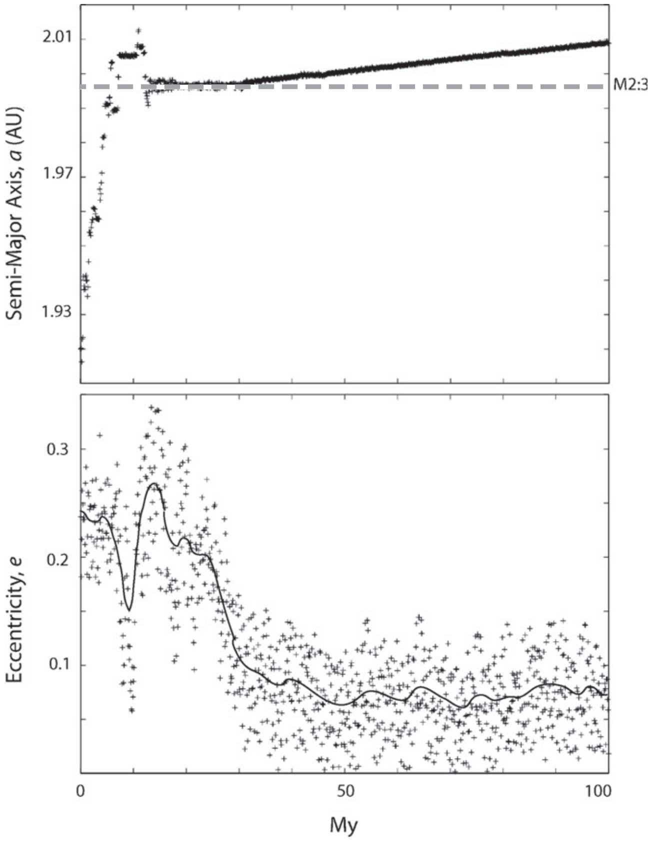

Fig. 8. Mars crosser ($R = 0.2$ km) being adopted via the M2:3 resonance.

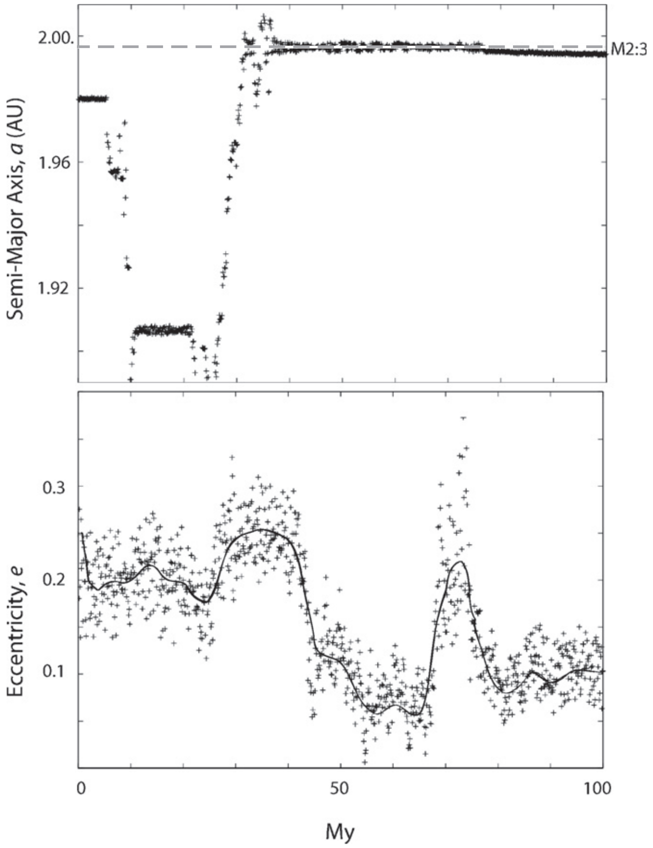

Fig. 9. Mars crosser ($R = 2.0$ km) being adopted via the M2:3 resonance.

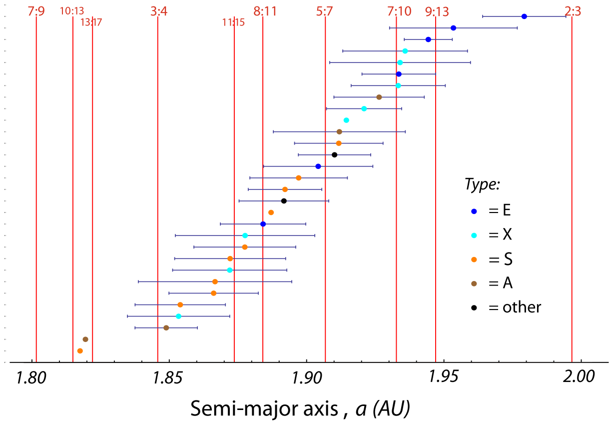

Fig. 10. Martian resonances up to 4th order between 1.80 AU and 2.00 AU and the 30 asteroids studied in the preliminary experiment. The asteroids are separated vertically for clarity. Colors represent taxonomic type, and "error" bars show the distance each asteroid may have traveled in the last 1 Gyr by Yarkovsky (in either direction), in the absence of resonances. Deep Mars crossers have no "error" bars as their past movement is indeterminable.

semi-major axes of 30 of its largest asteroids. The "error" bars are the estimated distances the asteroids have migrated in the last 1 Gyr (assuming inefficient YORP evolution). The same is even true for half that distance, representing 0.5 Gyr, which is a typical YORP timescale for asteroids of these sizes (Čapek and Vokrouhlický, 2004). The bars extend on either side of each asteroid because most of their spin directions are not known. Regardless, Fig. 10 emphasizes that strong martian resonances are common enough such that most of the asteroids we studied in our preliminary experiment are within their reach. We do not claim all or even most of these 30 asteroids have been adopted, but merely state that the length scales of Yarkovsky drift are appropriate for any subset of these asteroids to have come from a resonance. In order to predict which subset that is, we must review the types of asteroids residing in the region.

5.1. Taxonomic classes in the Hungarias

The Hungarias consist of primarily E, X, and S-type asteroids, with some C types and even fewer A's. Of 362 Hungarias classified by Warner et al. (2009), 76.8% were found to be type X (inferred to be E),[4] 17.2% type S, and 6.0% type C. The predominance of E/X types is a function of the multitude of bodies belonging to the Hungaria family, the result of a larger E parent body breakup. Outside the family, however, Warner et al. note that the numbers of E/X and S types are about the same.

If our proposed mechanism of adoption has indeed lead to some Mars crossers becoming stable Hungaria members, we suggest that the S types are the likeliest candidates. Of course, given our estimation that adoptees are a relatively minor fraction of the Hungarias, there must be S type bodies that are not adopted; these probably scattered in during planet formation and migration (Bottke et al., 2006a). Nevertheless, of the adopted population, we believe S types dominate. S types are the second most common asteroid class and the most abundant in the inner belt. More importantly, most Mars crossers are S types (Angeli and Lazzaro, 2002). Mars crossers are supplied by slow chaotic diffusion of asteroids from small mean motion resonances in the inner main belt (Morbidelli and Nesvorny, 1999). The asteroids slowly increase in eccentricity until their perihelia encounter Mars, at which point they begin to

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[4] X types are a degenerate class, including E, M, and P-type asteroids. In the context of the Hungarias, the X types are likely to be E types (Warner et al., 2009).

randomly walk in semi-major axis. Some of these asteroids will randomly walk into the Hungarias, having acquired a semi-major axis between 1.78 and 2.06 AU. The number of asteroids leaking from the inner belt by chaotic diffusion is apparently enough to keep the population of Mars crossers at steady state, despite their short dynamical lifetime (Morbidelli and Nesvorny, 1999). Therefore, not only is there a large potential source of S asteroids nearby, these asteroids are reliably delivered to the Hungarias as Mars crossers.

In contrast to S and C types, E types are rare everywhere except among the Hungarias. From a statistical perspective it is unlikely any of them are adopted. Secondly, the properties of E type asteroids are symptomatic of melting and differentiation, which is more likely to occur close to the inner Solar System where strong solar winds and faster accretion times (that incorporated short-lived radionuclides) caused heating (Grimm and McSween, 1993). These facts suggest that E types formed in or near their current concentration. If the E types are native, and no new E types are being adopted into the Hungarias (for lack of another source population), the E types must be gradually leaking away. The near Earth Asteroid (3103) Eger, an E type, may be a recent casualty of this loss (Gaffey et al., 1992). The proportion of S types to E types is likely growing slowly and might be even larger than current tallies show, because detection is biased in favor of high-albedo E types.

Given that the Hungaria population was likely periodically refreshed through family-forming events (of which the present Hungaria *family* is just the youngest instance), there might have been past Hungaria population "bottlenecks". By "bottlenecks" we mean that few bodies (or a single body) could have produced a large fraction of the Hungaria population through collisions, skewing the compositional makeup of the whole population. If one of the prominent past disruptions was of an "adoptee", significantly more than 5–10% of present "background" Hungarias may be its descendants. If this hypothesis is correct and there are members of multiple ancient families among Hungarias, more detailed spectroscopy may be able to resolve past relationships even if almost all dynamical clustering is gone.

6. Conclusion

In our preliminary experiment, we characterized the dynamical behavior of 30 large asteroids in the Hungaria region with strictly gravitational simulations (using shifts in initial semi-major axis as a proxy for Yarkovsky drift). We found that mean motion Mars resonances cause pronounced fluctuations in eccentricity and can trigger asteroids to escape the resonances chaotically. We also observed Mars crossers getting stuck to resonances, surviving in the region for tens of millions of years despite being unstable.

For a more realistic treatment of the region's dynamics, we simulated three sets of 1000 bodies (corresponding to radii of 0.2, 1 and 5 km) in stable Hungaria space using the Yarkovsky-enabled SWIFT-rmvs3y integrator. The results confirmed our hypothesis that Mars resonances are primary aggravators of stability in the region. We derived half-lifes of our Hungaria grid population between 350 Myr and 475 Myr, increasing in timescale with larger radii. Larger bodies hit resonances less frequently due to slower drift speeds, and thus get lost more slowly (which outweighs the fact that larger radii suffer higher loss rates per resonance encounter, as seen in Table 3). These short lifetimes imply that either a very high original population, or, more realistically, periodic repopulations of the Hungaria region through past family-forming events.

To explore the potential for Mars crossers to be stabilized by resonances, we also integrated three sets of 1000 asteroids with the similar initial conditions as the Hungaria grid, now with eccentricities in Mars-crossing space. About 5–6 asteroids of each radius were stabilized by martian resonances in 100 Myr. The adopted population today is expected to be about 5–10% of the background, non-family Hungaria population, and possibly larger. The adoptees are likely to be represented among the S types in the Hungarias, as S types pervade the Mars crosser population and are a viable source for adoption. This contrasts with E types, which are common in the Hungarias but rare in the overall asteroid belt; they have probably been local residents since they were scattered in during the early stages of the Solar System (as *in situ* formation on high-incination orbits is usually considered implausible).

In conclusion, the Hungarias are an intriguing population where martian mean motion resonances and the Yarkovsky effect result in significant loss rates, while at the same time feeding some Mars crossers back into the population. As we think that many of the present "background" Hungarias are likely to be ancient collisional fragments, a more detailed model of dynamical and collisional evolution over the age of the Solar System is needed to correctly determine the possible contribution from resonant adoption. Lastly, there may be observational clues to look for evidence of adoption, such as a slight predominance in the number of asteroids moving away from the important resonances.

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