Origin of Multikilometer Earth- and Mars-Crossing Asteroids: A Quantitative Simulation

Fabio Migliorini,* Patrick Michel, Alessandro Morbidelli,†
David Nesvorny, Vincenzo Zappalà

Orbital dynamic simulations show that many asteroids in the main asteroid belt are driven toward Mars-crossing orbits by numerous weak mean motion resonances, which slow down the orbital ellipticity of the asteroids. In addition, half of the Mars-crossing asteroids (MCAs) transition to Earth-crossing asteroids (ECAs) in less than 20 million years. This scenario quantitatively explains the observed number of large ECAs and MCAs.

Most ECAs and MCAs are fragments of larger main belt asteroids. According to the classic scenario (1), they were injected by the collisions that formed them into a resonance (2), which increased their eccentricities until they started to cross the terrestrial planets’ orbits. The encounters with the planets then spread them all over the region where they are now observed and categorized as ECAs or MCAs (3).

Recent simulations (4) showed that the median dynamical lifetime of bodies initially placed in the 3/1 or 2/1 resonances is only 2 My (million years), because these resonances pump the eccentricity to unity, forcing most of the resonant bodies to collide with the sun. As a consequence, in order to sustain the observed planet-crossing population in steady state, the number of bodies injected into resonance per million year would need to be about 25% of the total population. This indicates that the classic scenario cannot explain the origin of multikilometer ECAs and MCAs. In fact, 10 ECAs and 354 MCAs with diameters larger than 5 km are currently known (5) despite the fact that bodies of this size can be injected into resonance only during very energetic and rare breakup events, such as those leading to formation of asteroid families (6). Also, the classic scenario would predict a lower MCA/eca ratio than is observed because asteroids in the 3/1 and 2/1 resonances experience such a rapid increase in their eccentricity that they quickly become ECAs or graze the sun before encounters with Mars can extract the asteroids from these resonances into MCAs.

The orbital distribution of MCAs consists of four groups—hereafter denoted by MB, MB2, HU, and PH—with values of semimajor axis $a$ and inclination $i$ similar to those of four populations of non–planet-crosser asteroids: the main belt below the $v_2$ resonance, the main belt above the $v_2$ resonance and beyond 2.5 AU, the Hungarias, and the Phocaeas. This similarity suggests that these populations continuously lose objects to the MCA region due to an increase in eccentricity, sustaining the MB, HU, and PH groups. Only 2% of MCAs larger than 5 km have $a$ and $i$ different from those non–planet-crosser asteroids and therefore must have evolved relative to the orbit they had when they first crossed the orbit of Mars: we denote them EV (Fig. 1).

To better understand the process by which non–planet-crossing asteroids become MCAs, and in particular the dynamical link between the main belt and MB populations, we have numerically integrated (7) the evolution of 412 main belt asteroids, a representative sample of the population with $a = 2.1$ to 2.5 AU, $i < 15°$, perihelion distance $q < 1.8$ AU and not intersecting the orbit of Mars during the first 300,000 years. The integrations covered a time span of 100 My, along which we numerically computed the time evolution of proper elements to distinguish between regular and chaotic asteroids (8).

Integrations show that the majority of the asteroids are on chaotic orbits and 25% of them become MBs (Fig. 2). We find that this process is mainly due to mean motion resonances with Mars (3/5, 7/12, 4/7, 5/9, 7/13, and 1/2), mean motion resonances with Jupiter (7/2 and 10/3), and three-body mean motion resonances between Jupiter, Saturn, and the asteroid or Mars, Jupiter, and the asteroid (9). Although the most important source region of MBs is the one with $a < 2.17$ AU, where high-order mean motion resonances with Mars are particularly dense, in practice, asteroids are removed from the main belt all over the 2.1- to 2.5-AU range, driven by numerous weak mean motion resonances. It is possible that a similar process also drives Hungary and Phocaea asteroids to Mars-crossing orbits, sustaining the HU and PH populations.

To quantify the exchange of asteroids among non–planet-crossers, MCAs and ECAs, we have also integrated the evolution of 511 MCAs, a representative sample of their total population. MCAs become ECAs.
by random walking in a semimajor axis under the
effects of close encounters with Mars until
entering into some resonance that increases
the eccentricity to within the ECA range \(100\). The median time to become an
ECA is about 20 My for MBs, and it is longer
for HUs and PHs because of the reduced
strength of martian encounters at large incli-
nations. The MBs are also the Mars-crossing
population with the shortest dynamical life-
time (about 25 My); their most typical end
states are collision with the sun or ejection
beyond Saturn’s orbit (Table 1).

Our simulation of what happens to an
initial population of MCAs allows us to de-
terminize the number of bodies in ECA or EV
orbits as a function of time. We scale the
number of bodies down to reflect the results
we would expect if we had started with the
actual number of MCAs with diameters > 5
km \(11\). The number of ECAs larger than 5
km evolved from the initial MB, HU, and PH
populations increases rapidly with time, be-
cause a fraction of the MB population (those
members having \(q \sim 1\) AU or who are rap-
idly captured into 3/1 or \(v_n\) resonance) be-
comes ECA on a short time scale (Fig. 3A).

Then, between 15 and 60 My the number of
ECAs oscillates mainly between 5 and 10
bodies, with an average of 7 bodies. Finally,
the number of bodies slowly decays because
of the 25 My dynamical half-life of the MB
population. Four to five objects with diam-
eters greater than 5 km are sustained on orbits
typical of EVs between 20 and 60 My, with
equal contributions from the MB and HU
populations (Fig. 3B). The dynamical paths
of EVs from MBs and HUs are different.

MBs first become ECAs and then decrease
their semimajor axis below 2 AU due to
encounters with Earth and Venus, where the
eccentricity temporarily decreases under the
effect of some resonance \(12\), raising the
perihelion distance above the ECA limit. Few
MBs become EVs without first being ECAs.

Conversely, HUs become EVs by decreasing
their inclination, because of the proximity of
the \(v_n\) resonance \(13\). Few HUs become
ECAs without first being EVs.

The real numbers of bodies sustained on

Table 1. Statistics of MCA evolutions. Each class of objects is defined by its label. EV are crossing
asteroids either having current semimajor axis \(a < 1.77\) AU (location of the 5/1 resonance with Jupiter)
or \(1.77 < a < 2.06\) AU (between the 5/1 and 4/1 resonances with Jupiter) and inclination \(i > 15^{\circ}\); MBs
are MCAs with \(a > 2.06\) AU (location of the 4/1 resonance with Jupiter) and an inclination such that they
are below the \(v_n\) secular resonance; HUs have \(1.77 < a < 2.06\) AU and \(i > 15^{\circ}\); PHs have \(2.1 < a < 2.5\)
AU (between the 4/1 and 3/1 resonances with Jupiter) and are situated above the \(v_n\) secular resonance;
MB2s have \(a > 2.5\) AU and are situated above the \(v_n\) secular resonance. Diameters are estimated
assuming different albedos: 0.2 for EV asteroids and 0.3 for HU ones (taking into account that most are
bright E-type asteroids); they are 0.16 to 0.08 (depending on the semimajor axis) for the other classes
\(18\). The number of integrated bodies, the time spans covered by the integrations, and the number
of bodies that are ejected beyond Saturn or impact the sun (in parentheses the percentage that they
represent over the number of nonsurviving bodies) are shown. Time scales are shown for 50\% (half-life)
and 90\% decay of the integrated bodies and median times \(T_{med}\) for crossing the orbits of Earth and Venus.
The number (percentage) of objects that are temporarily in regions of particular interest and the median
time spent in these regions (\(T_{med}\)) are listed. Q indicates aphelion distance.

<table>
<thead>
<tr>
<th>Class</th>
<th>EV</th>
<th>MB</th>
<th>HU</th>
<th>PH</th>
<th>MB2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of bodies</td>
<td>105</td>
<td>1093</td>
<td>114</td>
<td>165</td>
<td>37</td>
</tr>
<tr>
<td>No. of bodies with &gt; 5 km (%):</td>
<td>7 (6.67)</td>
<td>240 (23.1)</td>
<td>17 (14.9)</td>
<td>78 (47.3)</td>
<td>12 (32.4)</td>
</tr>
<tr>
<td>Length (My):</td>
<td>147</td>
<td>200</td>
<td>147</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Outside Saturn (%):</td>
<td>7 (17.1)</td>
<td>76 (25.4)</td>
<td>2 (6.9)</td>
<td>6 (41.7)</td>
<td></td>
</tr>
<tr>
<td>Impact sun (%):</td>
<td>26 (63.4)</td>
<td>205 (68.6)</td>
<td>25 (86.3)</td>
<td>6 (50.0)</td>
<td></td>
</tr>
<tr>
<td>Half-life (My):</td>
<td>93.0</td>
<td>23.7</td>
<td>137.2</td>
<td>&gt;200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>90% decay (My):</td>
<td>&gt;147</td>
<td>114.2</td>
<td>&gt;147</td>
<td>&gt;200</td>
<td>144.7</td>
</tr>
<tr>
<td>No. of EC (%):</td>
<td>49 (92.5)</td>
<td>297 (92.2)</td>
<td>43 (76.8)</td>
<td>31 (47.0)</td>
<td>12 (85.7)</td>
</tr>
<tr>
<td>(T_{med}), Earth (My):</td>
<td>11.6</td>
<td>19.1</td>
<td>7.46</td>
<td>&gt;200</td>
<td>243</td>
</tr>
<tr>
<td>No. of VC (%):</td>
<td>43 (81.1)</td>
<td>285 (88.5)</td>
<td>36 (64.3)</td>
<td>31 (47.0)</td>
<td>12 (85.7)</td>
</tr>
<tr>
<td>(T_{med}), Venus (My):</td>
<td>25.4</td>
<td>20.0</td>
<td>86.0</td>
<td>&gt;200</td>
<td>25.2</td>
</tr>
<tr>
<td>(V_n) Earth (My):</td>
<td>53 (100)</td>
<td>109 (33.4)</td>
<td>55 (98.2)</td>
<td>14 (21.2)</td>
<td>0</td>
</tr>
<tr>
<td>(V_n) Venus (My):</td>
<td>72.4</td>
<td>6.5</td>
<td>105.7</td>
<td>6.2</td>
<td>—</td>
</tr>
<tr>
<td>(T_{med}), Earth (My):</td>
<td>13 (24.5)</td>
<td>16 (5.0)</td>
<td>3 (5.4)</td>
<td>1 (1.5)</td>
<td>0</td>
</tr>
<tr>
<td>(T_{med}), Venus (My):</td>
<td>12.7</td>
<td>10.7</td>
<td>10.2</td>
<td>8.3</td>
<td>—</td>
</tr>
<tr>
<td>(T_{med}), (Q) Earth (My):</td>
<td>45 (84.9)</td>
<td>29 (9.0)</td>
<td>33 (58.9)</td>
<td>1 (1.5)</td>
<td>0</td>
</tr>
<tr>
<td>(T_{med}), (Q) Venus (My):</td>
<td>30.7</td>
<td>11.0</td>
<td>20.5</td>
<td>15.4</td>
<td>—</td>
</tr>
</tbody>
</table>
ECA and EV orbits by the MB, HU, and PH populations depend on the number of MB, HU, and PH bodies supplied by the objects from the main belt, Hungary, and Phocaea regions. To be in steady state, half the MB population should be regenerated every 25 My. In that case, a low estimate of the average steady-state populations of ECAs and EVs can be obtained by adding to their average number in the 25- to 50-My range (seven and five bodies, respectively) (Fig. 3) half the average numbers supplied by the MB population during the first 25 My (two and one bodies, respectively). The resulting populations are similar to those currently observed (10 ECAs and 7 EVs), showing that the MBs, HUs, and PHs are sufficient to sustain ECAs and EVs. Extinct comets and asteroid fragments, collisionally injected into the main resonances of the main belt, are not required to provide significant contributions to the ECA population (14).

The number of MBs larger than 5 km in the 2.1- to 2.5-AU range is 183. Because of their half-life, 91 of these asteroids should be dynamically eliminated in 25 My. Of the original main belt asteroids that we have integrated, 17% become MBs within 25 My. Because there are 263 asteroids larger than 5 km in the main belt region represented by our initial population, we estimate that 44 asteroids are resupplied to the MB population. However, the chaotic process that leads to the origin of MCAs concerns basically all the asteroids with a proper perihelion distance smaller than 1.92 AU (Fig. 2). According to the 1994 update of the proper elements catalog (15), about 1000 asteroids larger than 5 km in diameter in the inner belt have proper perihelion distances smaller than this threshold, including parts of the Flora and the Nysa families. In summary, there is a strong presumption that chaotic evolution in the inner asteroid belt will ensure the existence of the next generation of MB Mars crossers with \( a < 2.5 \) AU.

Sustaining the MB population on time scales longer than 25 My is problematic. In our integrations, the first 10 My, the fastest transporting resonances are mostly depleted of objects, so that the escape process from the inner main belt becomes dominated by the action of the weakest resonances and consequently the escape rate decreases to an almost constant value of 10% of the population every 100 My. This rate would supply the MB population with about 100 bodies per 100 My, which seems to be insufficient to keep it in steady state. However, this result probably means that our simulation is too simplistic to describe the real evolution of the asteroidal populations on a 100-My time scale. Collisional processes, generating new multikilometer bodies on this time scale, should be taken into account as well as non-conservative dynamical phenomena, allowing the mobility of the proper semimajor axis of the asteroids in the main belt.

In past epochs, keeping the MBs in steady state during the last 3 Gyr requires the escape of 12,000 asteroids larger than 5 km from the main belt. This is comparable to the number of bodies larger than 5 km that are estimated to currently exist with \( a < 2.5 \) AU in the main belt (16). It might not be a coincidence that the distribution of asteroids with respect to proper perihelion distance peaks at 1.95 AU. Chaotic diffusion could have substantially eroded the part of the main belt with proper distance taken from the main belt. Conf. Series 107, 29 (1996)).

The Tisserand parameter shows the relative velocity at encounter between the body and the planet. If the planet is on a circular orbit, the encounter velocity vector is rotated during the encounter, and its norm is preserved [G. Valsecchi and A. Manara, Icarus 131, 245 (1998)]; extrapolating the size distribution of the asteroid families, this number is increased by 50% [V. Zappala and A. Cellino, in Completing the Inventory of the Solar System, ASP Conf. Series 107, 29 (1996)].

The Tisserand parameter shows the relative velocity at encounter between the body and the planet. If the planet is on a circular orbit, the encounter velocity vector is rotated during the encounter, and its norm is preserved [G. Valsecchi and A. Manara, Icarus 131, 245 (1998)]; extrapolating the size distribution of the asteroid families, this number is increased by 50% [V. Zappala and A. Cellino, in Completing the Inventory of the Solar System, ASP Conf. Series 107, 29 (1996)].

The Tisserand invariant is related to the relative velocity at encounter between the body and the planet. If the planet is on a circular orbit, the encounter velocity vector is rotated during the encounter, and its norm is preserved [G. Valsecchi and A. Manara, Icarus 131, 245 (1998)]; extrapolating the size distribution of the asteroid families, this number is increased by 50% [V. Zappala and A. Cellino, in Completing the Inventory of the Solar System, ASP Conf. Series 107, 29 (1996)].

15 June 1998; accepted 23 July 1998