ORIGIN AND EVOLUTION OF NEAR EARTH ASTEROIDS

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Abstract. The present paper reviews our current understanding of the origin and evolution of NEAs, at the light of the results of recent quantitative numerical simulations that have revolutioned the previously accepted scenario.

1. Introduction

With the discovery of 433 Eros in 1898, the existence of a new population of asteroid–like bodies on orbits intersecting those of the inner planets was established. Explaining the origin of these Near Earth Asteroids (NEAs) was difficult because, at that time, it was not evident which mechanisms could have forced them to evolve from an orbit bounded by those of Mars and of Jupiter –typical of the main asteroid belt– to a planet–crossing orbit. Still in 1976, Wetherill was claiming that most of NEAs must be extinct cometary nuclei.

However, a close look to the distribution of the asteroids in the main belt shows that the belt is structured by several resonances: the existence of the Kirkwood gaps (Kirkwood, 1866) is associated with the main mean–motion resonances with Jupiter (resonances between the orbital periods of the asteroid and of the planet), among which particularly evident are the 3/1, the 5/2 and the 2/1 resonances; the upper bound of the asteroid distribution, when plotted in the semimajor axis a vs. inclination i plane, corresponds with the location of the ν_6 secular resonance, which occurs when the mean precession rates of the longitudes of perihelia of the asteroid and of Saturn are equal to each other (Fig. 1). This implies that somehow the asteroids must be removed from resonant locations, and suggests that this phenomenon could be related to the origin of NEAs.

The first indication that resonances can force bodies to cross the orbits of the planets came from J.G. Williams, in a diagram reported by Wetherill (1979), showing the amplitude of eccentricity oscillations as a function of the distance from the ν_6 resonance: at distances smaller than 0.025 AU, the amplitudes exceed 0.25, forcing the resonant bodies to cross the orbit of Mars at the top of their eccentricity oscillation. Shortly afterwards, Wisdom (1983) showed that the 3/1 mean motion resonance has a similar effect: the eccentricity of resonant bodies can have, at irregular time intervals, rapid and large oscillations whose amplitudes exceed 0.3, the threshold value to become Mars–crosser at the 3/1 location.

Following these pioneering works, several studies confirmed, both analytically and numerically, the role that resonances have in increasing asteroid eccentricities to Mars–crossing or even Earth–crossing values. For a review of the studies on mean motion resonances we recommend the paper by Moons (1997), while a compendium of the investigations on secular resonances can be found in Froeschlé and Morbidelli (1994).

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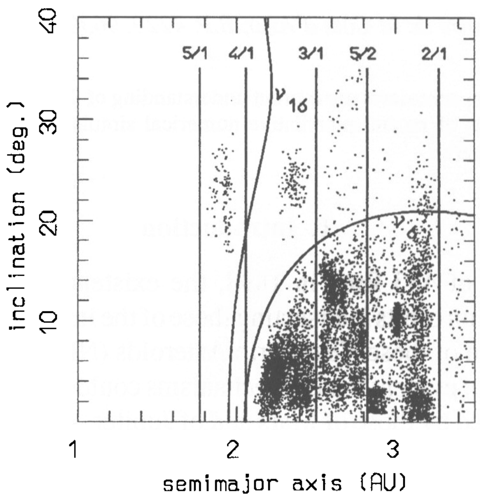

Fig. 1. Orbital distribution of the numbered asteroids that do not cross the orbits of any planet. The two bold curves denote the location of the ν_6 and ν_{16} secular resonances, while the vertical lines mark the position of the main mean motion resonances with Jupiter associated to evident Kirkwood gaps.

The improved knowledge of resonant dynamics allowed to design a generally accepted scenario on the origin of Near Earth Asteroids, that we will call hereafter "the classical scenario".

2. The Classical Scenario on the Origin of NEAs

G.W. Wetherill is the author who most contributed to outlining a coherent scenario for the origin and evolution of NEAs and meteoroids in a long series of papers (Wetherill 1979, 1985, 1987, 1988). His results were reviewed, in an interpreted form, by Greenberg and Nolan in two papers (1989, 1993) that gave a well defined and concised portrait to the classical scenario (Fig. 2).

According to this scenario, collisions in the main belt continuously produce new asteroids by fragmentation of larger bodies. Some of these new asteroids are injected into the ν_6 or the 3/1 resonance by the collisions that liberated them from their parent bodies. Once inside one of these resonances, their average semimajor axes stay constant, while their eccentricities suffer large oscillations, reaching, after a typical time-scale of 1 Myr, values that make the asteroids intersect the orbit of Mars and/or of the Earth.

At this point, close encounters with a planet may occur. Close encounters provide an impulse velocity to the asteroid's trajectory, causing a "jump" of its semimajor

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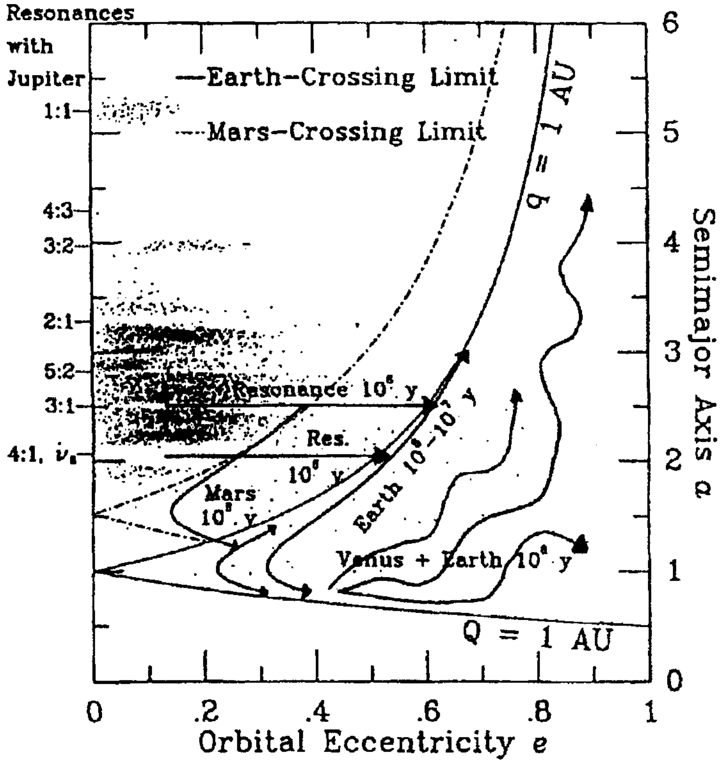

Fig. 2. Schematic representation of the origin and evolution of NEAs according to the classical scenario (from Greenberg and Nolan, 1993). The dash curves denote the set of orbits with perihelion distance q or aphelion distance Q equal to the value of the Martian semimajor axis. Solid curves denote the orbits with $q = 1$ or $Q = 1$ AU. The arrows with labels "Mars 10^8y" and "Earth 10^6–10^7y" sketch curves of constant Tisserand parameter with Mars and the Earth respectively. See text for further comments.

axis and eccentricity by a quantity depending on the geometry of the encounter and on the mass of the planet. If the jump in semimajor axis is large enough, the asteroid is removed from the resonant location and liberated from the control of the resonance, and then evolves mainly under the solely effects of the subsequent close encounters with the planet.

Repeated encounters with random geometry force the asteroid to random walk on the (a, e)–plane. This random walk, however, must follow preferential directions, approximately preserving the so–called Tisserand parameter

$$T = \frac{a_p}{a} + 2\sqrt{\frac{a(1-e^2)}{a_p}}\cos i$$

relative to the dominating planet with semimajor axis a_p. In fact, if the planet is on a circular orbit the Tisserand parameter is equal to $3 - U^2$, where U is the norm

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of the relative velocity between the asteroid and the planet, which is not changed by the encounter as is well known from the theory of scattering dynamics (Öpik, 1976). Setting the inclination to a constant value, the constancy of the Tisserand parameter defines curves on the (a, e)–plane. A few of these curves are sketched in Fig. 2.

If the asteroid has been extracted from the resonance by Mars on a solely Mars–crossing orbit, due to the small mass of the planet its random walk evolution is very slow and eventually may reach, after a typical time of 10^8 y, an Earth–crossing orbit. If, on the contrary, it has been extracted on an Earth–crossing orbit, its subsequent evolution is faster, requiring 10^6–10^7 years to reach a Jupiter crossing or a Venus–crossing orbit. Combined encounters with the Earth and Venus break the constancy of the Tisserand parameter, since neither planet really may dominate as the "main perturber". This allows the asteroid to go all over the Earth/Venus–crossing space, on a typical time-scale of order 10^8 y. Encounters with Jupiter, conversely, quickly eject the body from the Solar System.

Undergoing this kind of evolution, a NEA survives as long as it does not collide with a planet or undergo encounters with Jupiter that eject it on an unbound orbit from the Solar System. Monte Carlo codes, which treat in a statistical way the effects of close planetary encounters (Arnold, 1965; Wetherill, 1988), predict that the median lifetime of NEAs, from their original injection into resonance, is of order several tens of Myr (Gladman, personal communication).

3. The Solar Sink

The first indication that some qualitatively important dynamical features are missing from the classical scenario came from Farinella *et al.* (1994), who showed that, among the bodies in the ν_6, 3/1 or 5/2 resonances, the collision with the Sun is a fairly common fate. The collision with the Sun happens because the eccentricity increases up to values close to unity, so that the perihelion distance becomes smaller than the solar radius.

The reasons for which the main resonances pump the eccentricity of resonant bodies to unity were quickly understood. The ν_6 resonance location is almost independent of the eccentricity (Williams and Faulkner, 1981), so that the eccentricity may have an infinite regular growth (Morbidelli, 1993). Inside the 3/1 and 5/2 resonances, conversely, secular resonances are present and overlap each other, making most of the resonant phase space chaotic. This allows the eccentricity to evolve in an irregular manner without upper bound (Moons and Morbidelli, 1995).

Farinella *et al.* also showed that NEAs with very large orbital eccentricity –like the Taurids asteroids– may also easily collide with the Sun, despite not being inside any notable resonance. Actually, they may be forced to collide with the Sun by non–resonant secular oscillations of the eccentricity, which are particularly large when all secular arguments are in phase (Levison and Duncan, 1994; Valsecchi *et al.*, 1995).

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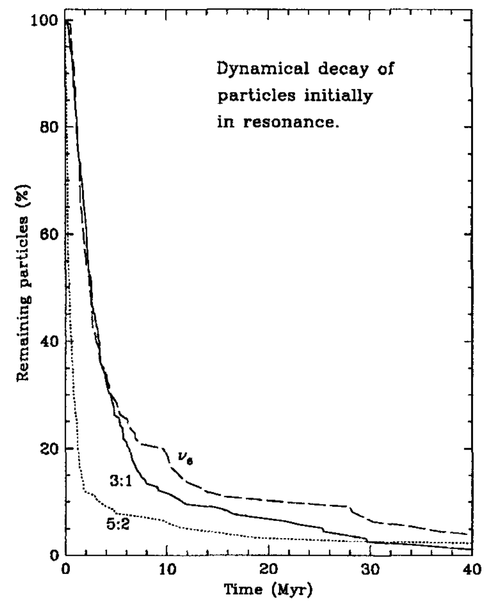

Fig. 3. Decay of populations of particles initially placed in the 3/1, 5/2 and ν_6 resonances (Gladman *et al.*, 1997). The median dynamical lifetime is of order 2 Myr for the 3/1 and ν_6 resonances and less than 1 Myr for the 5/2 resonance.

The Farinella *et al.* simulations, however, were based on too few bodies to conclude on the statistical importance of solar collisions in the overall scenario of the origin and evolution of NEAs. The improvements in computer technology and, in particular, the availability of a new integration algorithm (Wisdom and Holman, 1991; Levison and Duncan 1994) a few years later allowed Gladman *et al.* (1997) to numerically simulate the dynamical evolution of several hundred test particles, initially placed into the ν_6, 3/1 and 5/2 resonances. They found that the median lifetime of the simulated particles is about 2 Myr, while only $\sim$10% of them survive longer than $\simeq$10 Myr (Fig. 3).

This happens precisely because the resonances tend to pump the eccentricity of almost all the resonant bodies to unity on a Myr time-scale. As a result of the rapid growth of e, Mars is able to extract only a few percent of resonant bodies before an Earth-crossing orbit is achieved. Of all the simulated particles extracted by Mars, none was transported to Earth–crossing orbit by successive Martian encounters, conversely to what was expected in the classical scenario. The reason for this is that the 'kicks' provided by Martian encounters are so small that the particles cannot jump over the resonances and (after a typical time ranging from 1 to a few 10 Myr) always find themselves again injected into some resonant mechanism which takes them to Earth-crossing orbits.

In the Gladman *et al.* simulation, Earth and Venus are found to be much more

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efficient than Mars in extracting bodies from resonances. However, the "mortality" of the extracted particles is still very high. Those which are driven by close encounters to $a > 2.5$ AU are usually ejected by Jupiter on hyperbolic orbits. Many others are injected again into the 5/2, 3/1 or ν_6 resonances and subsequently are forced to collide with the Sun. Only the bodies that reach semimajor axes <1.8 AU may live much longer than the median lifetime because, in this region, although many resonances exist and influence the dynamics (Michel and Froeschlé 1997, Michel 1997), no statistically significant dynamical mechanisms have been found which pump the eccentricities up to Sun–grazing values. Therefore, these bodies die only by colliding with a planet (rare), or after being driven back to $a > 1.8$ AU (after a typical 1-10 Myr journey) and then usually being pushed by a resonance into the Sun.

Finally, the Gladman *et al.* simulations show that particles extracted from the resonances do not evolve by closely following lines of constant Tisserand parameter, as described by the classical scenario. In reality the dynamics is much more complicated: there are many high-order resonances which force the orbits to evolve transversally with respect to the curves of constant Tisserand parameter (see Michel *et al.* 1996), so that the Tisserand parameter is very poorly conserved on a Myr or longer time scale and, in practice, extracted particles are quickly spread all over the Earth- and Venus-crossing region.

Despite the fact that collisions with the Sun quantitatively change the classical scenario regarding dynamical paths and typical lifetime, the basic concept that NEAs are asteroid fragments pushed to Earth–crossing orbits after being injected into the 3/1 or ν_6 resonances could still be considered valid. The resonant bodies' median lifetime of 2 Myr simply implies that, to sustain the NEA population in steady state, the number of asteroids injected into resonance per Myr needs to be roughly equal to 1/4 of the total number of NEAs. This is plausible for small to km–sized bodies. For instance, 2000 NEAs are estimated to exist with diameter of order of 1 km (Morrison, 1992), while the number of 1–km bodies injected into the 3/1 or ν_6 resonances per Myr is estimated to be $\sim$400 by Menichella *et al.* (1996). Moreover, the orbital distribution of NEAs seems to be consistent with the one expected on the basis of the Gladman *et al.* simulations, once observational biases are quantitatively taken into account (Bottke, Jedicke and Morbidelli, work in progress). To have a decent fit between the expected and observed orbital distributions of NEAs, the number of bodies injected into the 3/1 resonance per unit time should be about 5 times larger than the number of bodies injected into the ν_6 resonance (Fig. 4). This ratio is close to the one found by Morbidelli and Gladman (1998) in order to explain the observed orbital distribution of fireballs of chondritic origin, and is reasonable from the point of view of the location of the source asteroids (Farinella *et al.*, 1993).

However, the short dynamical lifetime of 3/1 and ν_6 resonant particles produces inconsistencies for the classical scenario concerning the origin of multi–kilometer NEAs. About 10 bodies larger than 5 km exist on Earth–crossing orbits. To sustain

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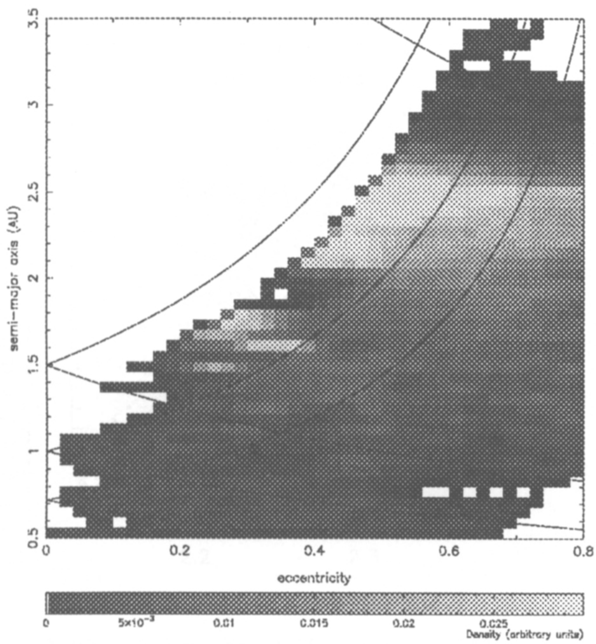

Fig. 4. Expected unbiased orbital distribution of NEAs ($q < 1.3$ AU) coming from the 3/1 and ν_6 resonances, assuming that 5 times more particles are injected into the 3/1 than in the ν_6 resonance per unit time. The grey scale denotes the relative density of NEAs on the (e, a)–plane.

this population, 2–3 bodies of this size should be injected into 3/1 or ν_6 resonance per Myr. However, bodies of this size can be injected into resonance only during very energetic and rare break–up events, such as those leading to the formation of asteroid families (Menichella *et al.*, 1996; Zappalá *et al.*, 1998).

4. A New Scenario on the Origin of Large NEAs

A hint for a better understanding of the origin of multi–kilometer Earth–crossers comes from the observation that Mars–crossing asteroids of similar size are much more numerous. Taking into account in the Mars–crossing population also the bodies that will intersect the orbit of Mars within the next 300,000 y (namely during their next secular eccentricity cycle), the number of Mars–crossers with diameter larger than 5–km is ~350, i.e. 35 times larger than the number of Earth–crossers of comparable size (Migliorini *et al.*, 1998). Numerical integrations done by Migliorini *et al.* show that Mars–crossers evolve to Earth–crossing orbits on a typical (median) time-scale of 20–25 Myr; this suggests that Mars–crossing asteroids might constitute the intermediate reservoir of Earth–crossers, but moves the fundamental question from the origin of multi–kilometer Earth–crossers to the

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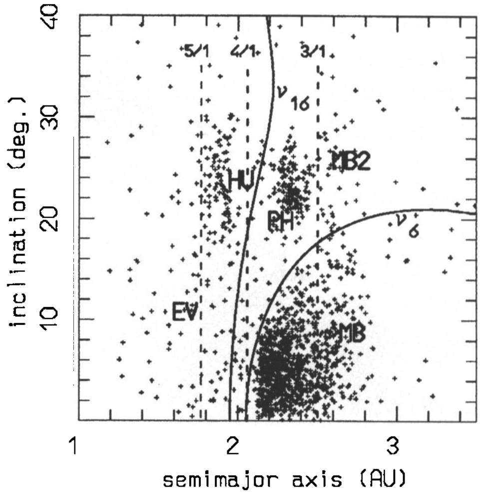

Fig. 5. Orbital distribution of Mars–crossers. Note the similarity with the (a, i) distribution of non planet–crossing main belt asteroids (Fig. 1).

origin of multi–kilometer Mars–crossers.

The orbital distribution of Mars–crossing asteroids shows no concentration around the 3/1 and ν_6 resonances (Fig.5). It reveals the existence of four main groups –denoted by Migliorini *et al.* as MB, MB2, HU and PH– with values of semimajor axis a and inclination i (compare with Fig. 1) similar to those of four populations of non–planet–crosser asteroids: the main belt below the ν_6 resonance, the main belt beyond the 3/1 resonance and above the ν_6, the Hungarias and the Phocaeas. This similarity suggests that these populations continuously lose objects to the Mars–crossing region, sustaining the MB, MB2, HU and PH groups. Only 2% of Mars–crossers larger than 5 km have a and i very different from those of non–planet–crossing asteroids and therefore must have evolved relative to the orbit that they had when they first crossed the orbit of Mars: for this reason they have been denoted as EV.

In order to better understand the mechanism by which the main belt sustains the MB Mars–crossing population, Migliorini *et al.* numerically integrated a sample of 412 asteroids with osculating perihelion distance smaller than 1.8 AU, semimajor axis in the range 2.1–2.5 AU, inclination smaller than 15 degrees and which are not Mars–crosser in the first 300,000 y. Fig. 6 shows the evolution of the proper semimajor axis and eccentricity of the integrated bodies. Very few asteroids exhibit regular dynamics (those which appear as dots in Fig. 6); the vast majority exhibit macroscopic diffusion in eccentricity –that is, a relevant change of proper eccentricity– in agreement with the result of Morbidelli and Nesvorný (1998) that

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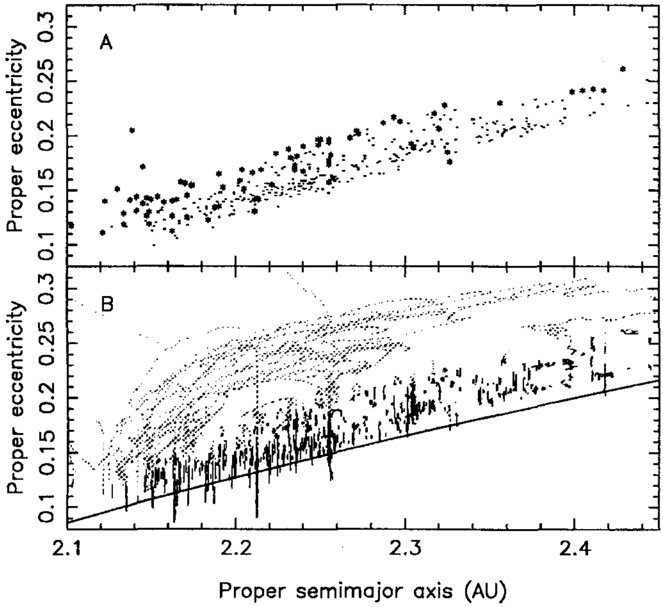

Fig. 6. Origin of MB Mars–crossers from the main belt. (A) the initial proper semimajor axis and eccentricity of the integrated asteroids. Asterisks denote the bodies that will become Mars–crossers within the integration time span. (B) The trace left by their time evolution. Proper elements are constant for regular asteroids, whose orbital elements have quasi–periodic evolution, while change over time for those evolving chaotically. If all asteroids were regular, panel B and panel A would be identical, so that the comparison between the two plots allows to appreciate that most of the asteroids chaotically migrate in the proper element plane. Before becoming Mars–crossers (black), asteroids migrate in proper eccentricity, keeping the proper semimajor axis close to its initial value. During the Mars–crossing regime (grey) asteroids migrate also in proper semimajor axis, as a result of close encounters with Mars which force them to evolve along curves of quasi–constant Tisserand invariant. The solid curve denotes proper perihelion distance equal to 1.92 AU (from Migliorini *et al.*, 1998).

most of the bodies in the inner belt are chaotic, mainly due to the dense location of mean motion resonances with Mars.

In the Migliorini *et al.* simulations, 17% of the integrated bodies become MB Mars–crossers in the first 25 Myr by diffusing to larger eccentricity. Scaling to the number of asteroids larger than 5 km existing in the population sampled by the integrated bodies, this implies that 44 new multi–kilometer asteroids should become MB Mars–crossers in the next 25 Myr. This number could probably be doubled, if one took into account that the chaotic process which leads to the origin of Mars–crossers concerns basically all the asteroids with proper perihelion distance smaller than 1.92 AU (Fig. 6) and that, according to the 1994 update of the proper elements catalog (see Milani and Kneževič, 1994), about 1000 asteroids

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larger than 5 km in the inner belt have proper perihelion distances smaller than this threshold, including parts of the Flora and the Nysa families. On the other hand, in the same time interval (25 Myr), the MB Mars–crossing population should lose $\sim$ 90 bodies (50% of the total population), which evolve to the Earth–crossing region and subsequently collide with the Sun or another planet or are ejected on an hyperbolic orbit. Therefore, the diffusion process should be sufficient to keep the MB Mars–crosser population in a steady state, at least for the next 25 Myr.

If chaotic diffusion is able to sustain the MB and HU populations in steady state, by liberating to the Mars–crossing region a sufficiently large number of asteroids from the main belt and the Hungaria region, then the Migliorini *et al.* simulations show also that the number of asteroids larger than 5 km that should be expected on Earth–crossing orbits and on EV Mars–crossing orbits is very close to that presently observed (10 and 7, respectively). Therefore, the new scenario for the origin of multi–kilometer NEAs appears to be quantitatively able to supply both the Mars–crossing and the Earth–crossing asteroids.

It should be qualified, however, that the Migliorini *et al.* simulations concerned only approximately 1/3 of the known total Mars–crossing population; the integration of the remaining bodies is presently undergoing. It is therefore possible that the numbers provided by Migliorini *et al.* have an uncertainty of a factor 2. Moreover, our knowledge of the Mars–crossing population is probably not complete even for large objects. Most surveys for NEAs, in fact, don't pay care to follow the discovered asteroids that do not appear to be Earth–crosser (Jedicke, private communication), and this could severely reduce the number of Mars–crossers that are eventually listed in the asteroid catalogue. Future work, both from the dynamical and from the observational viewpoint, needs to be done to refine the Migliorini *et al.* scenario.

5. Perspectives

While the Migliorini *et al.* scenario brings a credible solution to problem the origin of multi–kilometer NEAs, it also opens new dilemmas. Is the diffusion process from the main belt the dominating mechanism for the origin of NEAs of all sizes? Or do near–Earth bodies smaller than some threshold come mostly from 3/1 and ν_6 resonances, into which they have been collisionally injected? What is this threshold? These questions are intimately related to the size distribution of NEAs (extremely poorly known), because the size distribution of NEAs should be main belt–like in the size–range where the diffusion process is the dominating mechanism, while it might become steeper at sizes such that the contribution of bodies collisionally injected into the main resonances becomes substantial.

A significant advancement in this direction may be achieved by quantitatively fitting the observed orbital distribution of Earth–crossers by the simulated orbital distributions of bodies coming out from ν_6 resonance, 3/1 resonance and Mars–crossing intermediate reservoir. This however requires a reliable knowledge of the

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observational biases. In principle, this procedure could allow the determination of the relative weight of the ν_6, 3/1 and Mars–crossing sources. On the other hand, an improved knowledge of the collisional mechanisms in the main belt could refine the estimates of the number of bodies injected into the main resonances, as a function of body size.

Another new open question raised by the Migliorini *et al.* results is that the escape rate of asteroids from the main belt seems to decrease, after the first 10 Myr, to about 10% of the population per 100 Myr. This escape rate would be insufficient to keep the present Mars–crossing population in steady state on a 10^8 y time-scale. In the Migliorini *et al.* simulation this happens because the bodies in the main diffusion tracks escape in majority in the first 10 Myr, so that these tracks result depleted of objects; subsequently, only the bodies in the "diffusion background" contribute to sustain the Mars–crossing population, but can do so only at a much lower rate. However, in reality the main diffusion tracks are not associated with gaps in the distribution of asteroids; this indicates that they must be resupplied with new objects on a $\sim$10 Myr time–scale by some process(es) that are not taken into account in the Migliorini *et al.* simulation. The important processes that could bring new bodies to the considered large–eccentricity parts of the main diffusion tracks could be *(i)* diffusion from the low eccentricity portion of the belt, *(ii)* injection into resonance by collisions and/or encounters among asteroids, *(iii)* migration in semimajor axis due to some non–conservative force, such as that given by the Yarkovsky thermal re–emission effect (Burns *et al.*, 1979 ; Rubincam, 1995; Farinella *et al.* 1998) which could allow for a 0.01 AU mobility of multi–kilometer asteroids over their collisional lifetime (Farinella and Vokrouhlický, 1998). Until a quantitative analysis of these processes is done, a realistic understanding of the long–term evolution of the asteroid belt will not be achieved, limiting in turn our understanding of the NEA origin process.

The picture of the origin of NEAs is getting more complex, but this is because it is getting more realistic.

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