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The Near Earth Objects: possible impactors of the Earth/Les astéroïdes geocroiseurs : impacteurs potentiels de la Terre

Origin and dynamics of Near Earth Objects

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Abstract

The population of Near-Earth Objects (NEOs) evolves on orbits which can cross the orbit of the Earth. Most NEOs come from the asteroid belt via unstable zones associated with powerful or diffusive resonances. Their evolutionary paths and the statistical properties of their dynamics have been determined by massive numerical integrations. A steady-state model of their orbital and magnitude distributions has been elaborated which indicates that 1000 NEOs are kilometre-size with an impact frequency with the Earth around 0.5 Myr. A non-gravitational mechanism, the Yarkovsky thermal drag, plays the dominant role in delivering material in the NEO source regions, explaining how this population is maintained in a steady-state and why its size distribution is shallower than expected if NEOs were created through the direct injection of fresh fragments from collisional break ups into resonances. ***To cite this article: P. Michel et al., C. R. Physique 6 (2005).***

Résumé

Origine et dynamique des objets croiseurs de la terre. La population des *Near-Earth Objects (NEOs)* évolue sur des orbites qui peuvent croiser celle de la Terre. La plupart des NEOs proviennent de la ceinture des astéroïdes depuis des zones instables associées à des résonances puissantes ou diffusives. Les routes utilisées et les propriétés statistiques de leur dynamique ont été déterminées par intégrations numériques massives. Un modèle stationnaire des distributions de leurs orbites et de leurs magnitudes a été élaboré. Il indique que 1000 NEOs sont plus grands qu'un kilomètre et ont une fréquence d'impact avec la Terre autour de 0.5 Ma. Un mécanisme non-gravitationnel, l'effet thermique Yarkovsky, joue le rôle dominant pour délivrer du matériel dans les régions sources des NEOs, expliquant comment cette population est maintenue dans un état stationnaire et pourquoi sa distribution des tailles est moins pentue que celle produite par l'injection directe dans les résonances de fragments produits par les collisions entre astéroïdes. ***Pour citer cet article : P. Michel et al., C. R. Physique 6 (2005).***

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Mots-clés : Astéroïdes ; Chaos ; Dynamique ; Impacts ; Rencontres planétaires ; Résonances

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1. Introduction

By definition, the population of NEOs contains small bodies on Earth-crossing orbits and more generally the ones whose orbits have perihelion distances $q \leqslant 1.3$ AU and aphelion distances $Q \geqslant 0.983$ AU. For observational reasons, the NEOs are by convention subdivided into three groups named Apollos ($a \geqslant 1.0$ AU; $q \leqslant 1.0167$ AU), a the orbital semi-major axis, Atens ($a < 1.0$ AU; $Q \geqslant 0.983$ AU), and Amors (1.0167 AU $< q \leqslant 1.3$ AU). A fourth group has been more recently defined, composed of the so-called Inner Earth Objects (IEOs) [1] which evolve entirely inside the orbit of the Earth. Note that from a dynamical point of view, an individual object can pass from one group to the other during its lifetime, due to different perturbations such as the planetary encounters that can modify its orbit.

Several pieces of evidence suggest that the population of NEOs is in some sort of steady-state. The analysis of lunar and terrestrial craters suggests that the impact flux on the Earth-Moon system has been more-or-less constant for the last 3 Gyr [2], thus supporting the idea of a gross steady state of the NEO population. Some short fluctuations may have occurred in certain periods, as indicated by the analysis of the asteroid belt, which shows that the formation of several asteroid families occurred over the age of the Solar System (see [3]). Such events may have temporarily injected a large amount of asteroids into the unstable zones that can transport them to the NEO region (see next section).

The identification of impact craters on the moon as well as on the terrestrial planets, including the Earth, have thus led to the conclusion that the NEOs represent a hazard of global catastrophe for human civilization. Moreover, their close proximity to the Earth make them easily reachable to space missions devoted to the exploration of the small bodies which kept the memory of the original composition of the nebula in which planets have been built. Thus, while the discovery of unknown NEOs is of primary concern, the theoretical understanding of the origin and evolution of NEOs is also of great importance. Observational data and theoretical models can be used together to estimate the complete orbital and size distributions of the NEO population, and consequently to quantify the collision hazard and to optimize NEO search strategies. In this section, a review on our current knowledge on the NEO population in these aspects is presented. In Section 2, we present the different mechanisms that can allow a small body to be transported to the NEO region from the main asteroid belt or from the cometary region. Section 3 describes the typical dynamical evolutions of NEOs and possible end-states. In Section 4, we present the method used to elaborate a quantitative model of the NEO population on the basis of our current knowledge on the origin and evolution of NEOs. Section 5 describes the debiased NEO orbital and magnitude distributions resulting from this modelling effort which in turn allows the estimate of the collision probability of NEOs with the Earth. The determination of the main mechanisms which provide a continuous supply of new bodies to the transportation resonances of the asteroid belt is exposed in Section 6. Finally, open problems and future perspectives are discussed in Section 7.

2. Dynamical origin of NEOs

The asteroid versus comet origin of the NEO population has been debated throughout the last 40 years. An historical review on this topic is beyond the scope of this paper and can be found in, e.g. [4]. The first studies were confronted to a very poor understanding of resonant dynamics and to the very limited computer performances. Thus, direct numerical integrations of asteroid orbits could not be used to determine the evolutionary paths of NEOs. NEO modellers could only consider the collisions as the only viable mechanism for moving asteroids from the main belt directly into the NEO region, even though the typical ejection velocities of asteroid fragments generated in collisions do not exceed 100 m/s, which is still far too small in most cases to achieve planet-crossing orbits [5].

In the 1990s, the availability of cheap and fast workstations allowed the first direct simulations of the dynamical evolution of test particles, initially placed in the NEO region or in the transport resonances, over million year timescales. Using a Bulirsch–Stoer integrator, a breakthrough result was obtained by [6], who showed that NEOs with orbital semi-major axis $a < 2.5$ AU can easily collide with the Sun, and that this limits their typical dynamical lifetime to a few million years. The introduction of a new numerical integration code [7], which extended a numerical symplectic algorithm proposed by [8], opened for the first time the possibility of integrating numerically a much larger number of particles, so to quantify the statistical properties of NEO dynamics. The subsequent studies have contributed to build up our current understanding of NEOs origin, evolution and orbital distribution.

A large amount of research activity, both theoretical and numerical, has allowed the demonstration that asteroids become planet crosser by increasing their orbital eccentricity under the action of a variety of resonant phenomena. Two kinds of resonances have been characterized and can be qualified as ‘powerful resonances’ and ‘diffusive resonances’. The former have first been identified as they are related to gaps in the main-belt asteroid distribution, known as the Kirkwood gaps. The most notable resonances in the ‘powerful’ class are the ν_6 secular resonance at the inner edge of the asteroid belt, and the mean motion resonances with Jupiter (3:1, 5:2 and 2:1 at 2.5, 2.8 and 3.2 AU respectively). The properties of the two main ones (ν_6 and 3:1) are detailed below. The diffusive resonances are so numerous that they cannot be effectively enumerated. Therefore, we will discuss only their generic dynamical effects (see [9] for a more technical discussion of the dynamical structure of the main asteroid belt).

The ν_6 secular resonance occurs when the precession frequency of the asteroid's longitude of perihelion is equal to the sixth secular frequency of the planetary system. The latter can be identified with the mean precession frequency of Saturn's longitude of perihelion, but it is also relevant in the secular oscillation of the eccentricity of Jupiter (see chapter 7 in [10]). This secular resonance essentially marks the inner edge of the main belt and its effect depends on the location of the small body in this zone. In the powerful region the resonance causes a regular but large increase of the eccentricity of the asteroids. Earth- (or Venus-) crossing orbits can thus be reached, and in several cases the small bodies collide with the Sun, their perihelion distance becoming smaller than the solar radius. The median time required to become Earth-crosser, starting from a quasi-circular orbit, is about 0.5 Myr. Accounting also for the subsequent evolution in the NEO region (cf. Section 3), the median lifetime of bodies initially placed in the ν_6 resonance is ≈ 2 Myr, the typical end-states being collision with the Sun (80% of the cases) and ejection on hyperbolic orbit (12%) [11]. The mean time spent in the NEO region is 6.5 Myr [12], and the mean collision probability with the Earth, integrated over the lifetime in the Earth-crossing region, is ≈ 0.01 [13]. In the border region, the effect of the ν_6 resonance is less powerful and is only capable of forcing the asteroids to cross the orbit of Mars at the top of the secular oscillation cycle of their eccentricity. Therefore, these asteroids must first evolve under the effect of Martian encounters before entering eventually in the NEO region, and the required time increases sharply with the distance from the resonance [13]. The dynamics in this region is also complicated by the dense presence of mean motion resonances with Mars (see below).

The 3:1 mean-motion resonance with Jupiter occurs at approximately 2.5 AU from the Sun. Inside the resonance, two regions are dynamically distinct: a narrow central region where the asteroid eccentricity has regular oscillations that bring the objects to periodically cross the orbit of Mars, and a larger border region where the evolution of the eccentricity is wildly chaotic and unbound, so that the bodies can rapidly reach Earth-crossing and even Sun-grazing orbits. Under the effect of Martian encounters, bodies in the central region can easily transit to the border region and be rapidly boosted into the NEO space (see chapter 11 in [10]). For a population initially uniformly distributed inside the resonance, the median time required to cross the orbit of the Earth is ≈ 1 Myr, the median lifetime is ≈ 2 Myr, and the typical end-states are the collision with the Sun (70%) and the ejection on hyperbolic orbit (28%) [11]. The mean time spent in the NEO region is 2.2 Myr [12], and the mean collision probability with the Earth, integrated over the lifetime in the Earth-crossing region, is 0.002 [13].

In addition to these powerful resonances, the main belt is densely crossed by hundreds of thin resonances: high order mean motion resonances with Jupiter (where the orbital frequencies are in a ratio of large integer numbers), three-body resonances with Jupiter and Saturn (where an integer combination of the orbital frequencies of the asteroid, Jupiter and Saturn is equal to zero, [14–16]), and mean motion resonances with Mars [17]. Many – if not most – main-belt asteroids have a chaotic evolution due to this dense presence of resonances. The magnitude of this chaotic effect remains very weak so that the time required to reach a planet-crossing orbit (Mars-crossing in the inner belt, Jupiter-crossing in the outer belt) ranges from several 10 Myr to some Gyr, depending on the resonance and on the starting eccentricity [18]. To quantify these timescales, [17] performed numerical integrations of real objects' orbital evolutions in the inner belt ($2 < a < 2.5$ AU) for 100 Myr. They estimated that chaotic diffusion drives about 2 asteroids larger than 5 km into the Mars-crossing region every million year. The escape rate is particularly high in the region adjacent to the ν_6 resonance, where this resonance becomes effective, and also due to the dense presence of mean motion resonances with Mars. The high rate of diffusion of asteroids from the inner belt can explain the existence of the population of numerous Mars-crossers. Following [19], we define the latter as the population of bodies with $q > 1.3$ AU that intersect the orbit of Mars within a secular cycle of their eccentricity oscillation (in practice within the next 300 000 yr). Based on the statistics on bodies with absolute magnitude $H < 15$, which constitute an almost complete sample in both populations, the Mars-crossers are about 4 times more numerous than the NEOs of equal H. It was believed in the past that most $q > 1.3$ AU Mars-crossers were bodies extracted from the main transportation resonances (i.e., 3:1 and ν_6 resonances) by close encounters with Mars. However, the eccentricity of bodies in these resonances increases so rapidly to Earth-crossing values that actually only a few bodies can be extracted by Mars from these resonances and emplaced in the Mars-crossing region with $q > 1.3$ AU. This low probability is only partially compensated by the fact that, once bodies enter this Mars-crossing region, their dynamical lifetime becomes about 10 times longer. Indeed, numerical integrations indicate that if the 3:1 and the ν_6 resonances sustained both the Mars-crossing population with $q > 1.3$ AU and the NEO population, the ratio between these populations would be only 0.25 (i.e. 16 times smaller than observed).

The population of Mars-crossers extends up to $a \approx 2.8$ AU, suggesting that the phenomenon of chaotic diffusion from the main belt extends at least up to this threshold. In addition to the main component of this population (called IMC hereafter), there are two specific groups of Mars-crossers with orbital elements that mimic those of the so-called Hungaria ($1.77 < a < 2.06$ AU and $i > 15°$) and Phocaea ($2.1 < a < 2.5$ AU and $i > 18°$) populations, arguing for the effectiveness of chaotic diffusion also in these high inclination regions. To reach Earth-crossing orbits, the Mars-crossers random walk in semi-major axis under the effect of Martian encounters until they enter a resonance that is strong enough to further decrease their perihelion distance below 1.3 AU. For the IMC group, the median time required to become Earth-crosser is ≈ 60 Myr; about 2 bodies larger than 5 km become NEOs every million year [20], consistent with the supply rate from the main belt estimated by [17]. The mean time spent in the NEO region is 3.75 Myr [12]. The median time to reach Earth-crossing orbits from the two groups of high inclined Mars-crossers exceeds 100 Myr [20]. The paucity of Mars-crossers with $a > 2.8$ AU is not due to the inefficiency of chaotic diffusion in the outer asteroid belt. It is simply the consequence of the fact that the dynamical lifetime of bodies in the Mars-crossing region drops with increasing semi-major axis towards the Jupiter-crossing limit. In addition, the observational biases for km-sized asteroids in this region are more severe than in the region $a < 2.8$ AU. In fact, the outer belt is densely crossed by high-order mean motion resonances with Jupiter and three body resonances with Jupiter and Saturn so that an important escape rate into the NEO region should be expected. Nearly 2000 observed main belt asteroids with $2.8 < a < 3.5$ AU and $i < 15°$ and $q < 2.6$ AU have been numerically integrated for 100 Myr [12]; almost 20% of them entered the NEO region. About 30 000 bodies with $H < 18$ can be estimated to exist in the region covered by the initial conditions of [12]. According to these integrations, in a steady-state scenario this population could provide ≈ 600 new $H < 18$ NEOs per million year, but the mean time that these bodies spend in the NEO region is only ≈ 0.15 Myr.

Although the NEO population with small semi-major axes is dominated by objects of asteroid origin, comets are also expected to be important contributors to the overall NEO population. Cometary bodies can be subdivided into two groups: those coming from the Kuiper belt (or, more likely, the scattered disk) and those coming from the Oort cloud situated outside the Solar System. The first group includes the Jupiter-family comets (JFCs) whose orbital distribution has been well-characterized with numerical integrations by [21]. These integrations did not include the terrestrial planet perturbations and non-gravitational forces, which may explain why the authors found that their cometary test bodies remained confined to $a > 2.5$ AU orbits.

The population of comets of Oort cloud origin includes the Long Periodic and the Halley type groups. To explain the orbital distribution of the observed population, several researchers have postulated that the comets from the Oort cloud rapidly 'fade' away, either becoming inactive or splitting into small components [22,23], but this conclusion is badly constrained. Hence, calculating the population on NEO orbits is problematic although best-guess estimates suggest that impacts from Oort cloud comets may be responsible for 10–30% of the craters on Earth (see [24]). If true, the comets of Oort cloud origin should be considered among the primary sources of NEOs.

3. Evolution in the near-Earth space

Planetary close encounters strongly influence the dynamics of the bodies in the NEO space. Each encounter gives an impulse velocity to the body's trajectory, causing the semi-major axis to 'jump' by a quantity depending on the geometry of the encounter and on the mass of the planet. The change in semi-major axis is correlated with that in eccentricity (and inclination), by the quasi-conservation of the so-called Tisserand parameter relative to the encountered planet with semi-major axis a_p and expressed as $T = (a_p/a) + 2[(a(1-e^2)/a_p)\cos i]^{1/2}$ [25]. An encounter with Jupiter can easily eject the body from the Solar System ($a = \infty$ or negative), while this is virtually impossible in encounters with the terrestrial planets.

If close encounters with a unique planet provided the only perturbations, and neglecting the effects on the inclination, a body would random-walk on a curve of the (a, e)-plane defined by $T =$ constant. These curves are transverse to all mean motion resonances and to most secular resonances, so that the body can be extracted from a resonance and be transported into another one. On the other hand, resonances change the eccentricity and/or the inclination of the bodies, whereas the semi-major axis remains unchanged. The real dynamics in the NEO region is therefore the result of a complicated interplay between resonant dynamics and close encounters (see [26]). Moreover, since encounters with several planets can occur at the same time, the Tisserand parameter approximation is not valid anymore even in absence of resonant effects.

As anticipated in the previous section, most bodies that become NEOs with $a > 2.5$ AU are preferentially transported to the outer Solar System or are ejected on hyperbolic orbit. If the eccentricity is sufficiently large, the NEOs in this region approach the Jupiter-crossing limit where the giant planet can scatter them outwards. At that point, their dynamics becomes similar to that of Jupiter-Family Comets. A typical example is represented by the top evolution in Fig. 1(A). The body penetrates the NEO region due to the increase of its orbital eccentricity inside the 5:2 resonance until $e = 0.7$; then, encounters with Jupiter extract it from the resonance and transport it to larger semi-major axes. Only bodies extracted from the resonance by Mars or the Earth and rapidly transported on a low eccentricity path to smaller semi-major axes can escape the scattering action of Jupiter. However, such evolution is increasingly unlikely as the initial semi-major axis is set to larger and larger values.

Conversely, the bodies on orbits with $a \approx 2.5$ AU or smaller do not approach Jupiter even at $e \approx 1$, so that they end their evolution most typically by colliding into the Sun. Most of the bodies originally in the 3:1 resonance are transported to $e \approx 1$ without having a chance of being extracted from the resonance. For the bodies originally in the ν_6 resonance, a temporary extraction from the resonance in the Earth-crossing space is more likely (Fig. 1(A)). Most IMCs with $2 < a < 2.5$ AU eventually enter the 3:1 or the ν_6 resonance and subsequently behave as resonant particles.

Figs. 1 (B) and (C) show evolutionary paths from ν_6 and 3:1, which are unlikely (they occur in 10% of the cases), but which are also crucial to understand the observed NEO orbital distribution. In these cases, encounters with Earth or Venus extract the body from its original resonance and transport it into the region with $a < 2$ AU (called the 'evolved region' hereafter). Once in

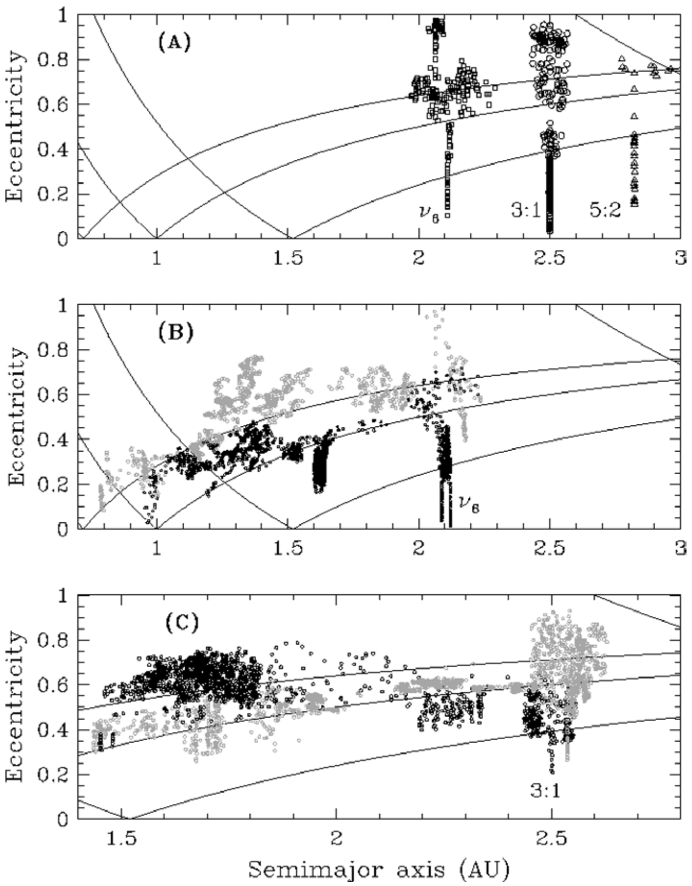

Fig. 1. The plots, adapted from [11] show examples of the orbital evolutions of objects leaving the main NEO source regions in the asteroid belt. The curves indicate the sets of orbits having aphelion or perihelion at the semi-major axis of one of the planets Venus, Earth, Mars or Jupiter. (A) Typical evolution paths from the ν_6, 3:1 and 5:2 resonances. (B) A long-living particle from the ν_6 resonance. The evolution before 20 Myr is shown in black, and the subsequent one is illustrated in grey. (C) A long-lived particle from 3:1; black dots show the evolution during the first 15 Myr.

the evolved region, the dynamical lifetime grows longer ($\approx$ 10 Myr [27]) because there are no statistically significant dynamical mechanisms that pump the eccentricity up to Sun-grazing values. To be dynamically eliminated, the bodies in the evolved region must either collide with a terrestrial planet (rare event), or be driven back to $a > 2$ AU, where powerful resonances can push them into the Sun. The enhanced lifetime partially compensates for the difficulty these objects have in reaching this evolved region. Thus, the latter should host 38% and 70% of all NEOs coming from the 3:1 and ν_6, respectively [12].

The dynamical evolution in the evolved region can be very tortuous, and does not follow any clear curve of constant Tisserand parameter. The main reason is that first-order secular resonances are present and effective in this region, and continuously change the perihelion distance of the body (see [28–30]). In some cases the perihelion distance can be temporarily raised above 1 AU, where, in absence of encounters with the Earth, the body can reside for several million years (notice the density of points at $a \approx 1.62$ AU, $e \approx 0.3$ in Fig. 1(B)). The Kozai resonance [31,32] and the mean motion resonances with the terrestrial planets [33] can also provide a protection mechanism against close approaches, thus stabilizing the motion of the bodies temporarily locked into them. Among mean motion resonance trappings, the temporary capture in a co-orbital state has an important role, where the body follows horseshoe and/or tadpole librations about a planet. This phenomenon has been observed in the numerical simulations by [28,34,35], and a detailed theory has been developed [36]. Several NEOs have been recently identified to evolve on such orbits and the analysis of their orbital behaviour has shown for some of them frequent transitions from a horseshoe phase to a quasi-satellite one [37].

A few additional features in the evolution of Fig. 1(B) are remarkable. For instance, the evolution penetrates in the region inside the Earth's orbit (aphelion distance smaller than 0.983 AU). It is then plausible to conjecture the existence of a population of Interior to the Earth Objects (IEOs [1]). Note that only two IEOs have been observed at present; the first one has been discovered by the LINEAR telescope in February 2003 and the second one at LONEOS in Arizona in May 2004.

4. Quantitative modelling of the NEO population

Since strong biases exist against the discovery of objects on some types of orbits, the observed orbital distribution of NEOs is not representative of the real distribution. There are two possible methods to estimate the real NEO population from the observed one. One relies entirely on the data from observational surveys and tries to apply a correction for observational bias. The other uses theoretical orbital dynamical constraints in combination with the detections from observational programs with known biases.

Given the pointing history of a NEO survey, the observational bias for a body with a given orbit and absolute magnitude can be computed as the probability of being in the field of view of the survey, with an apparent magnitude brighter than the limit of detection (see e.g. [38]). Assuming random angular orbital elements of NEOs, the bias is a function $B(a,e,i,H)$, depending on semi-major axis, eccentricity, inclination and on the absolute magnitude H. Each NEO survey has its own bias function. Once it is known, in principle the real number of objects N can be estimated as $N(a,e,i,H)=n(a,e,i,H)/B(a,e,i,H)$, where n is the number of objects detected by the survey. The problem, however, is the given resolution; even a coarse binning in the 4-dimensional orbital-magnitude space of the bias function and of the observed distribution requires the use of about 10 000 cells. Since the total number of NEOs detected by the most efficient surveys is a few hundreds, n is equal to zero in the vast majority of the cells, and it is equal to 1 in most other cells; cells with $n>1$ are very rare. The de-biasing process of the NEO population is therefore severely affected by small number statistics.

This approach has been applied using the largest detection sample size obtained by the LINEAR project [39]. It led to a model of the NEO population distribution, in the form of 1-D functions of absolute magnitude, semi-major axis, eccentricity and inclination. It predicts a very slow decay of the NEO population with increasing inclination, which is difficult to believe. In fact, the study of the dynamics shows that the inclination distribution is strongly dependent on semi-major axis and eccentricity: dynamically young NEOs with large semi-major axis, which constitute the majority of the population, roughly preserve their main belt-like inclination. Only dynamically old NEOs in the evolved region have a much broader inclination distribution, due to the action of the multitude of resonances that they crossed during their lifetime. This difference between the inclination distributions at low and large semi-major axes is not captured by the direct de-biasing method, because of the use of 1-D projections required to beat down the small number statistics problem. This illustrates the limitations of the method.

An alternative way to construct a model of the real distribution of NEOs heavily relies on the dynamics. From the results of numerical integrations, it is actually possible to estimate the steady state orbital distribution of the NEOs coming from each of the main source regions defined in Section 2 (see below for the method). In this approach, the key assumption is that the NEO population is currently in steady-state. To compute the steady state orbital distribution of the NEOs coming from a given source, the following method is employed: first, the dynamical evolutions of a statistically significant number of particles, initially placed in the NEO source region(s), are numerically integrated. The particles that enter the NEO region are followed through a network of cells in the (a,e,i)-space during their entire dynamical lifetime. The mean time spent in each cell (called residence time hereafter) is computed. The resultant residence time distribution shows where the bodies from the source statistically spend their time in the NEO region. As it is well known in statistical mechanics, in a steady state scenario, the residence time distribution is equivalent to the relative orbital distribution of the NEOs that originated from the source.

This dynamical approach was first introduced by [40] and was later imitated by [41]. Unfortunately, these works used Monte Carlo simulations and not direct numerical integrations, so that they only provided a very approximate knowledge of the statistical properties of the dynamics. The approach has then been improved using modern numerical integrations [42,12]. This allowed the computation of the steady-state orbital distributions of the NEOs coming from three sources: the ν_6 resonance, the 3:1 resonance, and the IMC population. The latter was considered to be representative of the outcome of all diffusive resonances in the main belt up to semi-major axes $a=2.8$ AU. The overall NEO orbital distribution was then constructed as a linear combination of these three distributions, thus obtaining a two-parameter model. The NEO magnitude distribution, assumed to be source-independent, was constructed so its shape could be manipulated using an additional parameter. The resulting NEO orbital-magnitude distribution was then ‘virtually’ observed by applying on it the observational biases associated with the Spacewatch survey [43]. This allowed us to determine a good combination of the three distributions which resulted in a model distribution fitting appropriately the orbits and magnitudes of the NEOs discovered or accidentally re-discovered by Spacewatch. To have a better match with the observed population at large semi-major axes, the model has been extended by considering also the steady-state orbital distributions of the NEOs coming from the outer asteroid belt ($a>2.8$ AU) and from the Transneptunian region [12]. The resulting best-fit model nicely matches the distribution of the NEOs observed by Spacewatch, without restriction on the semi-major axis (see Fig. 10 in [12]).

An important aspect of this model is that once the values of the parameters of the model are determined by best-fitting observations of a defined survey, the steady-state orbital-magnitude distribution of the *entire* NEO population is determined. This distribution is valid also in those regions of the orbital space which have never been sampled by any survey because of extreme observational biases. For instance, the model predicts the total number of IEOs, despite the fact that none of these objects had ever been detected when this model was elaborated [12]. This underlines the power of the dynamical approach for debiasing the NEO population.

5. The debiased NEO population and impact hazard with the Earth

The total NEO population is estimated to contain about 1200 objects with absolute magnitude $H < 18$ and $a < 7.4$ AU. In 2004, approximately 55% of these objects have been observed. The NEO absolute magnitude distribution is of type $N(< H) = C \times 10^{0.35\pm0.02H}$ in the range $13 < H < 22$, implying $29\,400 \pm 3600$ NEOs with $H < 22$. Assuming that the albedo distribution is not dependent on H, this magnitude distribution implies a power law cumulative size distribution with exponent -1.75 ± 0.1. This distribution is in perfect agreement with that obtained in [61], who directly debiased the magnitude distribution observed by the NEAT survey, and with the crater size distribution on the Moon (-2 exponent) on which scaling laws have been applied to derive the projectiles' size distribution.

The debiased orbital-magnitude distribution of the NEOs with $H < 18$ is shown in Fig. 2. For comparison, the figure also reports the distribution of discovered objects, combining the results of all NEO surveys. Most of the undiscovered NEOs have H larger than 16, and semi-major axis a in the range 1.5–2.5 AU. Overall, 32% $\pm$ 1% of the NEOs are Amors, 62% $\pm$ 1% are Apollos, and 6% $\pm$ 1% are Atens. 49% $\pm$ 4% of the NEOs should be in the evolved region ($a < 2$ AU), where the dynamical lifetime is strongly enhanced. The ratio between the IEO and the NEO populations is about 2%.

With this orbital distribution, and assuming random values for the argument of perihelion and the longitude of node, about 21% of the NEOs turn out to have a Minimal Orbital Intersection Distance (MOID) with the Earth smaller than 0.05. The MOID is defined as the minimal distance between the osculating orbits of two objects. By definition, NEOs with MOID < 0.05 AU are classified as Potentially Hazardous Objects (PHOs), and the accurate orbital determination of these bodies is considered a top priority.

When a small body collides with the Earth, the corresponding impact energy depends not only on the impact velocity, but also on the bulk density and size of the object. Therefore, to estimate the collision probability with the Earth as a function of the impact energy, the absolute magnitude distribution of NEOs must be converted into a size distribution of this population. Since H is related to the diameter by the albedo, it is first necessary to estimate the albedo distribution. The albedo is also used to estimate the body's bulk density.

Two independent approaches have been used to estimate the NEO albedo distribution. In [44], the albedo distribution of the bodies in and/or near each of the NEO sources has been computed from available observations. Then, knowing from [12] the contribution of each source to the NEO population, the albedo distribution of the NEO population as a function of orbital elements has been derived. In [62] it is considered that the taxonomic type distribution of NEOs is different in the regions with $T < 3$ and $T > 3$, where T is the Tisserand parameter relative to Jupiter. Inside each of these two regions, the taxonomic type

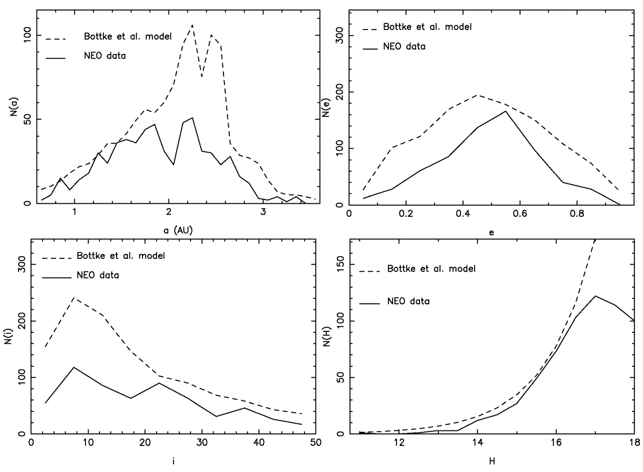

Fig. 2. The steady state orbital and absolute magnitude distribution of NEOs with $H < 18$, from [12]. The predicted NEO distribution (dashed curve) is normalized to 1200 objects. It is compared with the 626 multi-opposition NEOs known on 7/14/2004 (solid curve).

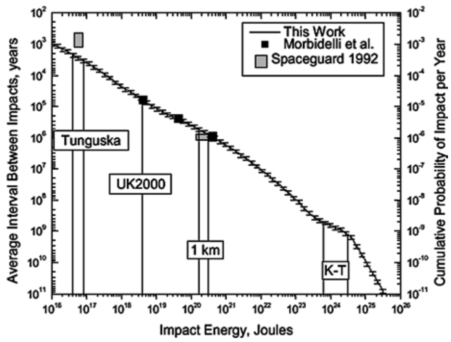

Fig. 3. Collision probability as a function of impact energy, according to [44]. Taken from [62]. Courtesy of S. Stuart.

distribution is independent of the orbital parameters, and is the one determined directly from the observations reported in [63]. The taxonomic type is then correlated to an albedo, using the results reported in [64]. This gives an albedo distribution for NEOs, in the $T < 3$ and $T > 3$ regions.

The results obtained through these two methods are in very good agreement. Both imply that on average, the usually assumed conversion $H = 18 \Leftrightarrow D = 1$ km slightly overestimates the number of kilometre-size objects. There should be ∼1000 NEOs with $D > 1$ km, against ∼1200 NEOs with $H < 18$.

Once the albedo distribution is determined, to estimate the NEO collision probability with the Earth as a function of collision energy [44,62], then proceed in the same way. It is assumed that the density of bright and dark bodies is 2.7 and 1.3 g/cm^3, respectively. These values are taken from spacecraft or radar measurements of a few S-type and C-type asteroids. The collision probability model described by [45] was then used. This model, which is an updated version of similar models described by [46–48], is based on the assumption that the values of the mean anomalies of the Earth and the NEOs are random. The gravitational attraction exerted by the Earth is also included. There is a remarkable agreement between the final results of [44] and [62], as shown in Fig. 3. In particular, it is found that the Earth should undergo a 1000 Megaton collision every 50 400 ± 6400 years. Such impact energy is on average produced by bodies with $H < 20.6$. The NEOs discovered so far carry only 18% ± 2% of this collision probability.

The original goal of the Spaceguard survey, a NEO survey program proposed in the early 1990s, was to discover 90% of the NEOs with $H < 18$ [49]. However, it would be more appropriate to state the goal in terms of discovering the NEOs carrying 90% of the total collision probability. However, *the two goals are not equivalent.* For instance, the Atens, which represent only 6% of the total NEO population, carry about 20% of the total collision probability; thus, their discovery – of secondary importance in the context of the original Spaceguard goal – becomes a top priority when collisional hazards are taken into account.

6. Injection mechanisms into the NEO source regions

We finally come to discuss the mechanisms that are at the origin of the injection of small bodies into the main NEO source regions. The model of [12] implies that 37% ± 8% of the NEOs with $13 < H < 22$ come from the ν_6 resonance, 25% ± 3% from the IMC population, 23% ± 9% from the 3:1 resonance, 8% ± 1% from the outer belt population and 6% ± 4% from the Transneptunian region. Thus, the long-debated cometary contribution to the NEO population probably does not exceed 10%. Note, however, that, as already explained in Section 2, this model does not account for the contribution of comets of Oort cloud origin, which is still largely unconstrained. These comets should be relegated to orbits with $a > 2.6$ AU and/or orbits with large eccentricities and inclinations.

By themselves, these fluxes do not constrain the mechanism (or mechanisms) that resupply the transporting (powerful and diffusing) resonances with new bodies. The shallow size distribution of NEOs, however, suggests that direct collisional injection probably does not play a dominant role in the delivery of asteroidal material to resonances. Indeed, fresh fragments from catastrophic break-ups are expected to have a much steeper size distribution, at least similar to that of the observed asteroid families [50,51]. Moreover the mean lifetime in the NEO region is only a few Myr, too short for collisional erosion to significantly reduce the slope of a size distribution dominated by fresh debris (bodies with a diameter of about 170 meters have a collisional lifetime greater than 100 Myr [45]). It is also unclear how collisional injection could explain the relative abundance of multi-kilometre objects in the NEO population. According to standard collisional models, only the largest (and most infrequent) catastrophic disruption events are capable of throwing multi-kilometre objects into the transporting major resonances [52,53]. The NEO size distribution shows some interesting similarities with the main belt size distribution. At present, a direct estimate of the latter is available only for $D > 2$ km asteroids [54], but its shape has been extrapolated to smaller sizes using a collisional model [55]. They estimate that the main belt's size distribution for $0.2 < D < 5$ km asteroids is NEO-like or possibly shallower, in agreement with the results of recent surveys [56,57].

So, how can we explain the shallow size distribution of NEOs with respect to the steeper one expected from direct collisional injection? This problem can actually be solved by considering the Yarkovsky thermal effect. The latter causes km-sized bodies to drift in semi-major axis by approximately 10^{-4} AU per Myr [58] (see also [59]), enough to bring into resonance a large – possibly sufficient – number of bodies. The Yarkovsky drift rate is also slow enough that the size distribution of fresh collisional debris would have the time to collisionally evolve to a shallower, main belt-like, slope before entering into a region source. To demonstrate the validity of this scenario, an original simulation scheme has been designed [60] that allowed the computation of the 'current steady-state' flux of $H < 18$ asteroids in the main NEO source regions, assuming that the main belt has its current properties (and not accounting for stochastic events like an asteroid family formation). The simulation depends on poorly constrained parameters, such as the collisional disruption and spin-axis reorientation time scales, their size dependence, and the average magnitude of the Yarkovsky and YORP effects. The latter is a variant of the Yarkovsky effect, which acts on the spin axis obliquity and rotation frequency of the bodies. The Yarkovsky-driven fluxes are then obtained, assuming that there are 1 300 000 bodies with $H < 18$ in the entire belt (among which 563 000 have $a < 2.8$ AU). The estimated fluxes indicate that about 100–160 bodies with $H < 18$ should enter the 3:1 resonance every million years while 40–60 should enter the ν_6 secular resonance. These rates are similar to those independently derived on the pure basis of the NEO population model [12], although the ratio between the fluxes into the 3:1 and ν_6 is in the range 2.5 to 3.0, whereas in [12] it is 1.8 ± 0.75. However, from the NEO model, it is difficult to discriminate between NEOs coming via the ν_6 resonance from those coming from the Mars-crossing population, so that the former contribution might well have been overestimated.

Having checked that the Yarkovsky effect is able to inject asteroids to the NEO source regions at appropriate rates, one must then check whether the H distribution of the bodies captured into the region sources is consistant with this distribution for the NEOs. Assuming that the cumulative magnitude distribution of main belt asteroids is $N(< H) \propto 10^{\beta' H}$ with $\beta' = 0.25$ in the $15.5 < H < 18$ range (consistent with the SDSS survey [56]), it was found [60] that the bodies captured into the resonances have a similar magnitude distribution, although the exponent coefficient would be $\alpha = 0.33$–0.4. The lowest value is obtained taking into account the YORP effect, whereas higher values correspond to weaker or no YORP. These values of α are all compatible with three debiased magnitude distributions of the NEOs obtained independently [61,42,39]. This result definitely confirmed that the Yarkovsky and YORP effects are at the origin of the moderately steep magnitude distribution of NEOs compared to that of the main belt population. These effects thus play the major role in the continuous supply of asteroids to resonances, maintaining the NEO population in a steady state. No other mechanism studied so far, including the catastrophic disruption of parent bodies in the resonance vicinities, is nearly as efficient.

7. Conclusions and perspectives

Long-term numerical integrations, semi-analytical methods, and statistical techniques have led to a major breakthrough in our understanding of the origin, evolution and steady-state orbital distribution of NEOs. The 'powerful resonances' of the main belt have been shown to transport the asteroids into the NEO region on a time scale of only a few hundreds thousands of years and eventually eliminate most of these bodies by forcing them to collide with the Sun. The 'diffusive resonances' have been shown to be additional important sources of NEOs. The steady-state orbital distributions of the NEO sub-populations related to the various sources have then been computed and a quantitative model of the debiased orbital and magnitude distributions of the NEO population, calibrated on available observations, has finally be elaborated.

Despite this steady progress, the NEO population is still lacking some understanding in several areas. As more and more NEOs are continuously found, the NEO model presented here will certainly need to be refined. Moreover, although it is now clear that the vast majority of NEOs with semi-major axes inside Jupiter's orbit are of asteroidal origin, the contribution of inactive comets coming from the Oort cloud needs a better quantification even if as they evolve inward, the majority of them must physically disrupt [23].

We also need to better understand the changes that occurred over the last 3.8∼Gy (after the so-called Late Heavy Bombardment), in terms of the total number of NEOs and their size or orbital distribution. For this purpose, we need for instance to definitely clarify whether the members of asteroid families have sometimes dominated the rest of the main belt asteroid population and if they still do so. If not, the break up of asteroid families can be considered a noise in the history of the NEO population.

The Yarkovsky effect has been found to be at the origin of the shallow slope of the magnitude distribution of NEOs. However, the study performed to show this assumed that all NEOs come from either the 3:1 or the ν_6 resonances, whereas the NEO population is also partially sustained by the network of diffusive resonances. The bodies transported by this last route might have a main-belt-like distribution, unlike those coming from the powerful resonances, whose magnitude distribution is somewhat steepened by the Yarkovsky effect. As a consequence, the NEO population should actually be a weighted average of the two slopes, which is even more compatible with observations. The encouraging results of the studies on this topic motivate the development of more sophisticated simulations of the Yarkovsky-driven evolutions of small bodies. For instance, it would be interesting to start from more detailed models of the orbital and magnitude distributions of main belt asteroids, accounting for fully consistent collisional cascade processes and taking advantages of improved estimates of the strength of the YORP effect.

We believe that a detailed knowledge of the physical properties of asteroids close to the transporting resonances would eventually allow us to indirectly but accurately deduce the compositional distribution of the NEO population. In turn, this would enable an accurate conversion of NEO absolute magnitudes into diameters, and better quantify the collisional hazard (frequency of collisions as a function of the impact energy) for the Earth. This is a good motivation to design space missions dedicated to in-situ measurements on main belt asteroids.

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