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REVIEW ARTICLE

The near-Earth objects and their potential threat to our planet

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Abstract The near-Earth object (NEO) population includes both asteroids (NEAs) and comet nuclei (NECs) whose orbits have perihelion distances $q < 1.3$ AU and which can approach or cross that of the Earth. A NEA is defined as a "potentially hazardous asteroid" (PHA) for Earth when its minimum orbit intersection distance (MOID) comes inside 0.05 AU and it has an absolute magnitude $H < 22$ mag (i.e. mean diameter > 140 m). These are big enough to cause, in the case of impact with Earth, destructive effects on a regional scale. Smaller objects can still produce major damage on a local scale, while the largest NEOs could endanger the survival of living species. Therefore, several national and international observational efforts have been started (i) to detect undiscovered NEOs and especially PHAs, (ii) to determine and continuously monitor their orbital properties and hence their impact probability, and (iii) to investigate their physical nature. Further ongoing activities concern the analysis of possible techniques to mitigate the risk of a NEO impact, when an object is confirmed to be on an Earth colliding trajectory. Depending on the timeframe available before the collision, as well as on the object's physical properties, various methods to deflect a NEO have been proposed and are currently under study from groups of experts on behalf of international organizations and space agencies. This paper will review our current understanding of the NEO population, the scientific aspects and the ongoing space- and ground-based activities to foresee close encounters and to mitigate the effects of possible impacts.

Keywords Minor planets, asteroids: general · Astrobiology · Meteorites, meteors, meteoroids · Surveys · Sociology of astronomy

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1 Introduction

Asteroids are small rocky bodies ranging in size from a few meters to a few hundred kilometers. Most of these objects are in the so called "main belt," which separates the terrestrial planets from the giant planets, typically between 2.1 and 3.3 AU from the Sun. The size distribution of asteroids suggests that they have undergone many collisions during their existence.

The main belt asteroids are subject to orbital modifications and can be transported into the inner solar system. The small bodies having orbits close to (or crossing) that of the Earth are called near-Earth objects (NEOs). At the moment of this writing, the number of known NEOs is about 10000 (with less than 100 of these being comets), but only the larger ones have been discovered, while a rough estimate of the total population down to 1-m size counts them in millions. Near-Earth objects represent an important subject of study for current planetary research. Their investigation can provide crucial information on the formation and early evolution of the solar system, including topics like the delivery of water and organic-rich material to the early Earth, and the emergence of life. The reserve in water and rare metals held by NEOs is also getting the attention from government agencies and private companies, as asteroid mining could expand the Earth's resource bases in the near future. Furthermore, the impact of NEOs on Earth could also pose a special hazard to our planet. The acronym PHAs ("potentially hazardous asteroids") is reserved for those objects with a diameter greater than about 140 m and trajectories that bring them within 0.05 AU of Earth's orbit. PHAs are large enough to survive passage through the Earth's atmosphere and cause extensive damage on impact.

Even if the statistical risk from impacts is quite low, compared to other natural hazards to mankind, it is not totally negligible. In fact there are evidences of several impacts having occurred in the past, causing at least one major mass extinction (the so called "K–T event" which occurred about 65 million years ago). The recent fall of the Chelyabinsk meteor (February 2013), which caused injuries to more than 1500 people and millions of euros in material damages, showed that even very small objects (less than 20 m) can produce considerable effects due to their explosion in the atmosphere. While the impacts in the past have altered the course of evolution of life on Earth and have paved the way for the dominance of Homo sapiens, it is today rather important not to remain at the mercy of this natural process. To assess the current hazards, surveys were started in the last decades of the 20th century, in order to discover and track NEOs with the aim to foresee how many would collide with Earth. These surveys were able to individuate, at the time of this writing, a number of PHAs that amounts to more than 1400.

Most of the currently available knowledge on small bodies was obtained through observations with telescopes on Earth and the analysis of meteorites found on the surface of our planet. These methods are not powerful enough to characterize the diversity of this population of small bodies. The *in situ* measurements due to space probes provide much more information, even if limited to a small number of asteroids.

Only three space missions have been specifically devoted to study a NEO. The NASA NEAR-Shoemaker spacecraft (Cheng 2002) remained in orbit for a year (2000–2001) around (433) Eros, S-type, the larger NEO (23 km in diameter). A large number of measurements have been taken at different wavelengths (X and Gamma rays, near-infrared, radio). The images have revealed unexpected surface characteristics, such as the absence of small craters, which could be explained by seismic activity induced by large collisions, which redistributes regolith on the surface. The Hayabusa mission (Fujiwara et al. 2006) of the Japanese Space Agency (JAXA) was even more ambitious. The probe was put into a heliocentric hovering orbit flying in parallel to the asteroid (25143) Itokawa, and realized two "touch-and-go" descents, to collect samples of regolith. In June 2010, the probe has sent back to Earth a capsule containing the few micrograms of soil samples collected at the surface of the asteroid. The very low density of the asteroid measured by the probe (1.3 g/cm^3) suggests a non-monolithic nature of Itokawa, but rather a conglomerate of different fragments (rubber pile). The analysis of the grains brought back to Earth confirms that Itokawa has a surface whose composition is similar to that of ordinary chondrites. The Chinese Space Agency Chang'e 2 probe, repurposed for an extended mission after surveying the Moon, flew by asteroid Toutatis in December 2012, and returned close-up photos of this PHA.[1]

Space missions to collect and transport to Earth samples of more primitive asteroids and to obtain their characterization, will mark the next decade. NASA is developing the mission OSIRIS-Rex (Drake and Lauretta 2011) that has as objective the sampling of the surface of the PHA asteroid (101955) Bennu, of type B. JAXA will launch (within one year) the Hayabusa2 mission (Yoshikawa et al. 2012) to explore and sample the NEO C type asteroid 1999 JU3, and the MarcoPolo-R mission (Barucci et al. 2012) is a candidate for the third medium-class (M3) mission of ESA's Cosmic Vision programme. The objective of the latter mission is the PHA asteroid 2008 EV5, which seems to have extremely primitive characteristics. These missions can also be considered as demonstration/precursor missions of those necessary to avoid/reduce impact risk.

NASA and ESA have initiated programmes to assess the threat posed by NEOs. The European Commission has launched the research programme NEOShield (Harris et al. 2013) in order to establish the procedures to be put in place to deflect any NEO in collision course with the Earth, or at least to minimize the effects of the impact. The aim of NEOShield, who brings together most of the competences present in Europe on the threat associated with an impact of an Earth-crosser asteroid, is to provide a concrete scientific base to national and international authorities which will have to define, to programme, and finance the actions intended to minimize the risks associated with such an impact.

The remainder of this paper is devoted to the description of the various aspects of the threat represented by an asteroid impact with the Earth. Section 2 contains an outline of the NEO population, and of the PHA subgroup, with some discussion on their origin from the main belt asteroids and their physical properties. The physical characterization of potential impactors is critical to be ready to react to any threat. Section 3 deals with the risks associated with asteroid hazards and the uncertainties in current knowledge of those risks, including the evidence obtained by the studies of the impact craters found on the Earth's surface. Section 4 describes quite extensively the

[1] http://www.planetary.org/multimedia/space-images/small-bodies/change-2-images-of-toutatis.html.

observational efforts in completing the inventory of NEOs and PHAs. The major dedicated surveys are described, together with their principal achievements or expected results. Section 5 is focused on the necessary efforts to improve our knowledge of the orbits of possibly threatening objects, reducing the error ellipse that describes the uncertainty in the prediction of the impacts and defining the actual collision probability. Section 6 addresses the mitigation techniques envisaged at present to deflect an asteroid in route of collision with the Earth. The three most promising techniques, the kinetic impactor, blast deflection, and the gravity tractor, as well as their applicability, are discussed in detail. The fact that the collision hazard posed by NEOs is global and has to be analyzed in its international context, even if national institutions have to be involved, is discussed in Sect. 7, together with the aspects of organization, coordinated activities, and responsibilities necessary for a mitigation effort.

2 The NEO population

The near-Earth objects have perihelion distances $q < 1.3$ AU, and orbits that periodically bring them in the proximity of the Earth.

The NEOs are an evolving population with a lifetime limited to a few million years after which most of them end in a Sun-grazing state or are ejected from the solar system, while a small fraction of them collide with a terrestrial planet. Due to the short dynamical lifetimes of their orbits, NEOs must be continuously replenished from major small bodies reservoirs, identified mainly in the main belt region corresponding to given mean motion and secular resonances with Jupiter and Saturn (Morbidelli et al. 2002). About 10000 NEOs have been detected at the time of this writing, but the known population is continuously growing thanks to dedicated surveys (see Sect. 4).

A small fraction of the discovered NEOs (<1 %) consists of cometary bodies that are called near-Earth comets (NECs), though observational biases are present due to the smaller mean size of comets, combined with their more eccentric and inclined orbits. Furthermore, extinct cometary nuclei whose near-surfaces have lost their volatiles are observationally indistinguishable from low-albedo asteroids, and could be identified only based on their dynamical properties, like the Tisserand parameter or the minimum orbit intersection distance (MOID) with respect to Jupiter. Using such an approach, DeMeo and Binzel (2008) found that the expected fraction of "extinct" comets in the NEO population is 8 ± 5 %, while a higher value (~ 15 %) has been suggested by Mommert et al. (2012).

Based on their orbital elements, the near-Earth asteroids (NEAs) are classified into four groups: Atiras and Amors have orbits entirely inside and outside Earth's orbit, respectively, while Atens and Apollos lie on Earth-crossing orbits (Atens have semi-major axes $a < 1$ AU and aphelion distances $Q > 0.983$ AU, while Apollos have a >1 AU and $q < 1.017$ AU, where 0.983 AU and 1.017 AU are the Earth's perihelion and aphelion distances, respectively).

2.1 The "potentially hazardous asteroids"

Among NEOs, the "potentially hazardous asteroids" are those objects *large enough* and coming *close enough* to Earth to be considered particularly dangerous, as their

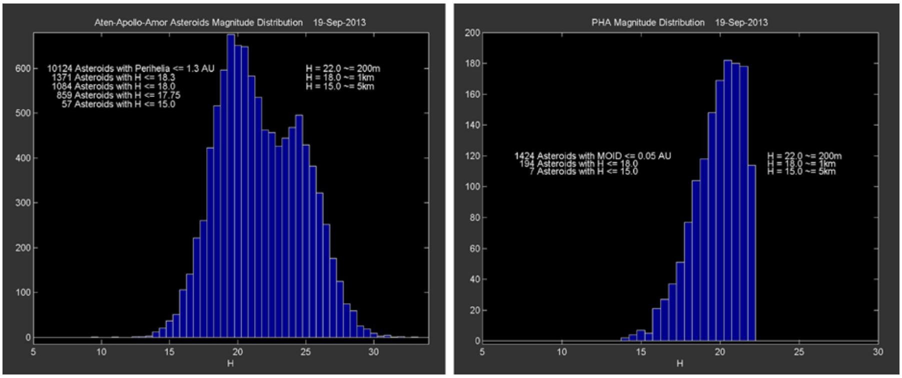

Fig. 1 Absolute magnitude distributions for all NEAs (*left*) and PHAs (*right*), as of 2013, September 19th. From the Near-Earth Asteroid Database (http://earn.dlr.de/nea/)

impacting our planet would represent devastation at least on a regional scale. They are defined as NEOs with a MOID smaller than 0.05 AU (7.5 million km) and absolute magnitude $H < 22$, corresponding[2] to a diameter $D \sim 140$ m, assuming the mean albedo of 0.14 for the NEA population (Mainzer et al. 2011).

To date, more than 1400 PHAs are known. While their mean physical properties do not significantly differ from those of the rest of the NEO population, it is notable that their distribution in terms of H is shifted towards fainter magnitudes with respect to all NEAs (Fig. 1). This can be explained by an observational bias due to their proximity to Earth, which allows for fainter objects to be detected.

2.2 NEO physical properties

A remarkable characteristic of the NEO population is its high degree of diversity in terms of physical properties (e.g., Dotto et al. 2005). As evidenced mainly by radar observations and lightcurve inversion (Fig. 2), some objects have very elongated shapes, others have complex, non-principal axis rotation states. On some occasions, very long and very short rotational periods are measured, and even multiple systems are observed. Binary systems seem indeed quite common within NEOs, the estimated fraction being ∼15 % of the total population (Pravec et al. 2006; Fang and Margot 2012). NEO diversity is also emphasized by the different spectral types found within the population, providing also some hints about the NEO origin. The asteroid taxonomic classifications are not directly based on composition or mineralogy; nevertheless, the members of the same taxon have similar spectra and hence would present a limited suite of constituents.

The most recent classification is the taxonomy by DeMeo et al. (2009), based on visible and near-infrared spectra. In agreement with previous classifications, three

[2]We recall that the absolute magnitude can serve as a proxy for the diameter D of an asteroid, as $D = 1329 \times 10^{-0.2H}/\sqrt{p_V}$, where p_V is the asteroid albedo and D is expressed in km (e.g., Pravec and Harris 2007).

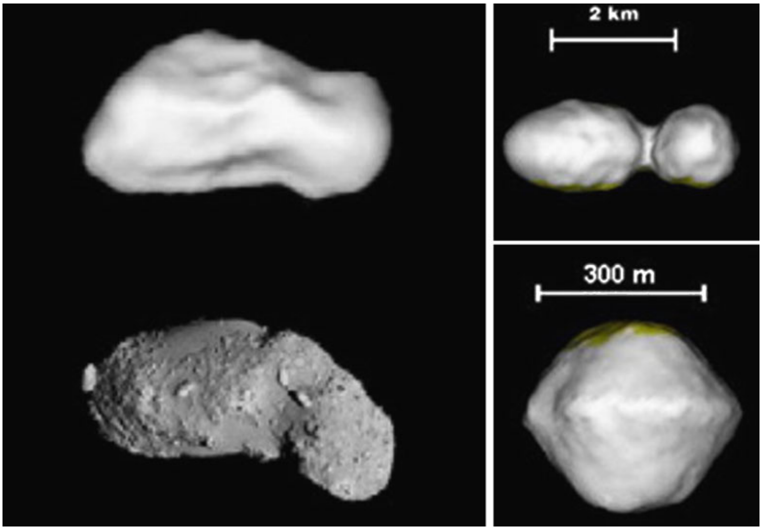

Fig. 2 (*left*) Asteroid (25143) Itokawa as modeled from radar observations (Ostro et al. 2005) and as imaged by the Hayabusa mission (Credit: JAXA). (*right*) Radar shape models of asteroids (8567) 1996 HW1 (*upper image*; Magri et al. 2011) and 2008 EV5 (*lower image*; Busch et al. 2011)

major groupings (the S-, C-, and X-complexes) are defined, plus a number of end members. Asteroids with intermediate spectral characteristics are assigned multi-letter designations. Though the low-albedo, carbonaceous C-types represent the majority of the asteroids in the main belt, the silicaceous, volatile-poor S- and Q-types dominate among NEOs representing together about 70 % of the population (while C-types account for only about 20 % of NEOs). This is explained by the fact that the main "feeding zones" for the NEO population are located at the 3:1 resonance (three orbits of the asteroid for each orbit of Jupiter) and ν_6 resonance (precession frequency of the asteroid's longitude of perihelion equal to that of Saturn) in the inner main belt, where stony asteroids are more abundant (see, e.g., Morbidelli et al. 2002; Masiero et al. 2011). Several studies are devoted to the search for the relationships between the meteorite types and the taxonomy, mineralogy, and source regions of NEOs. For example, Dunn et al. (2013) found that the Flora dynamical family, which lies near the ν_6 resonance, is the likely source of the LL ordinary chondrites, while Walsh et al. (2013) suggest that several C-type NEOs could have originated from the so-called Nysa-Polana complex in the inner main belt. However, this kind of investigations is greatly complicated by the fact that the taxonomic classification of a NEO more likely indicates the formation region of its parent body rather than its immediate origin in the main belt. Indeed, roughly speaking, a compositional gradient was present in the nebula, and solar system material has undergone different degrees of thermal processing, as a function of its heliocentric distance. Subsequently, a strong planetesimal mixing occurred, as a consequence of the planetary migrations that considerably changed the semi-major axes of interacting planetesimals (e.g., Walsh et al. 2011). Moreover, the latest scenarios of protostellar chemistry indicate that complex chemical processes took place already in the solar nebula, with the subsequent transport and mixing of the products (e.g., Nuth and Johnson 2012).

Tentative associations have been, however, established (on the basis of their spectra and albedos) between different asteroid taxonomic classes and petrologic types of meteorites. Different thermal histories are supposed to have produced the different petrologic types: ordinary chondrites (similar to S- and Q-type asteroids) have undergone moderate thermal evolution over the age of the solar system, while carbonaceous chondrites (similar to C-types) are inferred to be more primitive. A direct demonstration that the ordinary chondrites come from S-type asteroids has been found in the laboratory analyses carried out on the samples recovered by the JAXA Hayabusa spacecraft from the surface of the S-type NEO (25143) Itokawa: the mineralogy and mineral chemistry of the Itokawa dust particles are identical to those of thermally metamorphosed metal-poor ordinary chondrites (Nakamura et al. 2011). This result also confirms the Earth-based spectroscopic observations as an important tool to derive information on asteroid surface compositions and grain densities, which can be estimated from laboratory measurements on the analogue meteorite types. Indeed, Binzel et al. (2001) had already suggested a link between Itokawa and LL chondrites, based on the analysis of high-quality spectra obtained from the ground. The information on the taxonomic classification is important also because this can give some hints about the internal structure of asteroids, inaccessible to direct remote investigation. Indeed it is well known that asteroids belonging to the S-complex are less porous on average than those in the C-complex (Carry 2012).

Further assumptions on the internal structures of NEOs can be derived from their rotational properties. From Fig. 3 it is evident that for NEOs (and asteroids in general) larger than about 200 m in diameter, a "spin barrier" is present at a rotational period of about 2.2 hours. This is the limiting spin rate for a cohesionless structure, above which it begins to break up. Hence most objects spinning slower than this limit likely have a "rubble pile" structure, i.e. they are loose aggregates held together by mutual gravitation. On the other hand, "fast rotators" with periods shorter than about 2.2 hours must be monolithic objects, or at least rubble piles with some amount of cohesive strength, otherwise they would fly apart (e.g., Pravec et al. 2007; Holsap-

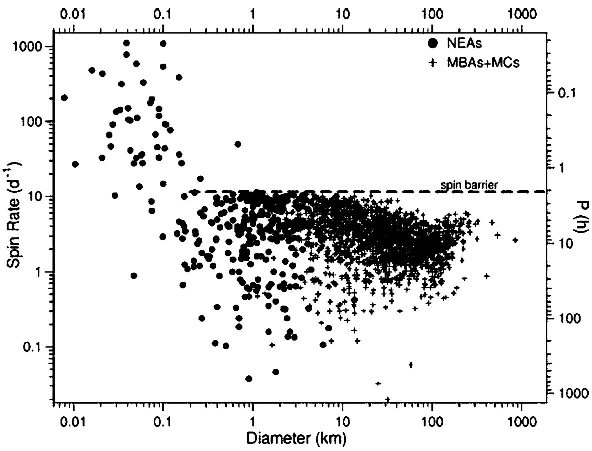

Fig. 3 The spin barrier in the spin rates for asteroids larger than about 200 m in diameter. NEAs are represented as *dots*, main belt asteroids and Mars crosser asteroids as *crosses*. From Pravec et al. (2007)

ple 2007). A recent study suggests that the population of rapidly rotating asteroids can include rubble piles with cohesion due to van der Waals forces between regolith grains (Sánchez and Scheeres 2013).

As we will outline in the remainder of this paper, the knowledge of physical properties like the shape, the rotation, the surface and subsurface properties, the internal structure, of a threatening NEO, is essential to define a successful *mitigation* strategy. By the term mitigation is usually intended any means to foresee and minimize the impact hazard from an asteroid and to protect the Earth from the destructive effects of such a potential collision.

3 Impacts on the Earth

Most solid bodies of the Solar System display surfaces with a record of accumulated impact cratering. The sizes of these craters can reach thousands of kilometers in diameter, as measured on the Moon, Mercury and Mars. Planetary solid bodies have been resurfaced in particular during a period of intense impact cratering by a flux of planetesimals that occurred sometime between 4.5 and 3.8 Ga. Although the interpretation of the data is still a subject of debate (e.g. Haskin et al. 1998), there is a growing consensus that an intense bombardment occurred in the inner solar system at about 3.9 Ga. This period is well known as the Late Heavy Bombardment (LHB) (Gomes et al. 2005). Since the LHB period, the rate of crater production on Earth has been considerably lower, but it is appreciable nonetheless on astronomical time scales: Earth experiences impacts large enough to produce a 20 km diameter crater about once every million years on average.

Though still debated, it has been proposed that impacting asteroids delivered organic matter and water to the early Earth (Alexander et al. 2012). Indeed, current exobiological scenarios of the origin of life invoke an exogeneous delivery of organic matter and prebiotic molecules, and these organic compounds (capable of triggering the prebiotic synthesis of biochemical compounds) have been detected in meteorites (e.g., Cooper et al. 2001; Martins et al. 2008).

There have also been major impact events throughout the Earth's history which possibly disrupted the environment and caused the extinction of life forms. The mass extinction event occurred at the Cretaceous-Tertiary (K/T) boundary, 65 million years ago, has been linked to a major asteroid impact (Alvarez et al. 1980) which led to a strong planet climate change affecting heavily the global environment and to the disappearance of all dinosaur species (Raup and Sepkoski 1986). Further data analysis carried out during the last decades in the fields of palaeontology, geochemistry, climate modeling, geophysics and sedimentology, confirmed the association of the K/T event with the collision of an asteroid. The Chicxulub crater around the Yucatán Peninsula of Mexico (see Fig. 4) is strongly believed to be linked with the K/T event (Schulte et al. 2010).

On Earth, the dynamic atmosphere and the plate tectonics erase the impact record. Hence larger craters reflect an older population, while smaller craters are removed by erosion (Grieve 1993). Despite the geological processes obliterating the impact struc-

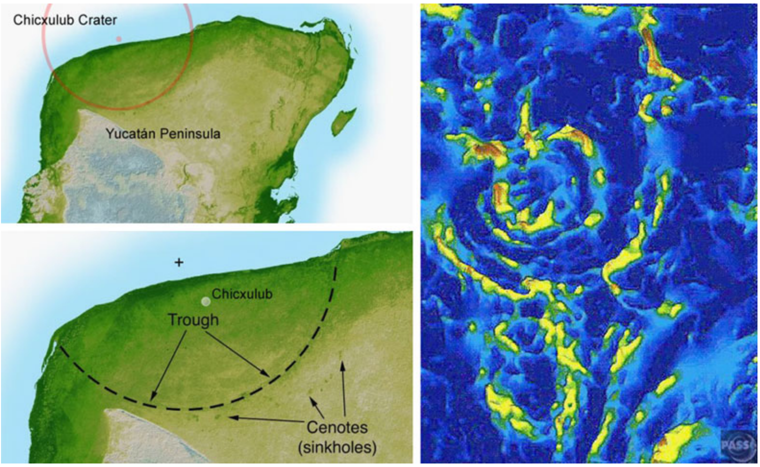

Fig. 4 The Chicxulub crater, Yucatán Peninsula, Mexico. On the *left*, shaded relief image from NASA's Shuttle Radar Topography Mission STS-99. The surrounding sinkholes suggest a prehistoric oceanic basin in the depression left by the impact. On the *right*, gradient map of the gravity anomaly over the Chicxulub crater (image from the Earth Impact Database)

Fig. 5 Map of all confirmed impact craters as of June 2013. Impact craters shown on the map are clearly not uniformly distributed. Older surfaces, such as Scandinavia, North America, Australia have collected craters longer and thus there are more of them, while areas that are young or have high sediment deposition rates have few craters (ocean floors, Amazon, Greenland and Antarctica). Image from the Earth Impact Database

tures, evidence of about 185 collision craters has been discovered and confirmed[3] on our planet (Fig. 5), with many more impact craters suspected and with new craters

[3]From the "Earth Impact Database", maintained by the Planetary and Space Science Centre at the University of New Brunswick, Canada. http://www.passc.net/EarthImpactDatabase/index.html.

Table 1 Terrestrial impact craters with $D > 50$ km, in order of size. Data from the Earth Impact Database (see references therein). The cited diameter is the best estimate for the collapsed transient crater diameter (rim-to-rim dimension). Taking into account the outermost ring diameter, the order of size would be affected

Crater name	Geographical location	Diameter (km)	Age (Ma)	Coordinates
Vredefort	Free State, South Africa	160	2023 ± 4	27°0′S 27°30′E
Chicxulub	Yucatán, Mexico	150	64.98 ± 0.05	21°20′N 89°30′W
Sudbury	Ontario, Canada	130	1850 ± 3	46°36′N 81°11′W
Popigai	Siberia, Russia	90	35.7 ± 0.2	71°39′N 111°11′E
Acraman	South Australia, Australia	90	∼590	32°1′S 135°27′E
Manicouagan	Quebec, Canada	85	214 ± 1	51°23′N 68°42′W
Morokweng	Kalahari Desert, South Africa	70	145.0 ± 0.8	26°28′S 23°32′E
Kara	Nenetsia, Russia	65	70.3 ± 2.2	69°6′N 64°9′E
Beaverhead	Idaho and Montana, USA	60	∼600	44°36′N 113°0′W
Tookoonooka	Queensland, Australia	55	128 ± 5	7′S 142°50′E
Charlevoix	Quebec, Canada	54	342 ± 15	47°32′N 70°18′W
Siljan	Dalarna, Sweden	52	376.8± 1.7	61°2′N 14°52′E
Kara-Kul	Pamir Mountains, Tajikistan	52	<5	39°1′N 73°27′E

added continuously. The largest terrestrial craters with $D > 50$ km are listed in Table 1. With the exception of the Vredeford Crater (160 km), formed in South Africa about 2 Ga, and the Sudbury crater (130 km), formed in Canada more than 1.8 Ga, all the other large terrestrial craters are younger than 1 Gy.

3.1 Population of impactors

The cratering rate on a planet is related to the population of projectiles, and a good understanding of the cratering process requires to establish the relationships between the diameter of the produced craters and the properties of the impacting bodies (mass, velocity, impact angle, etc.). Most of the craters on terrestrial planets produced after the LHB are connected to the NEO population, and this has been characterized in terms of its orbital and size distribution (e.g., Bottke et al. 2002; Marchi et al. 2009; Greenstreet et al. 2012). Determining such information requires the combination of observational, numerical, and theoretical efforts in order to produce reasonable models of debiased orbital and absolute magnitude distributions. A good knowledge of the population of potential impactors could allow to determine their impact frequencies on planets. The cratering record of the Moon is the most valuable to assess collision rates, as our satellite presents very old surfaces, which have been studied in detail for decades (e.g., Marchi et al. 2012, and references therein). The lunar cratering record shows that the frequency of impacts decreases approximately as the cube of the resulting crater's diameter, which is on average proportional to the diameter of the impactor.

The most recent estimation of the NEA population has been performed by Harris (2013a) (Fig. 6). The number of NEAs of $H < 17.75$ (corresponding to those with a diameter > 1 km, assuming an albedo of 0.14) has been estimated to be $N(H <$

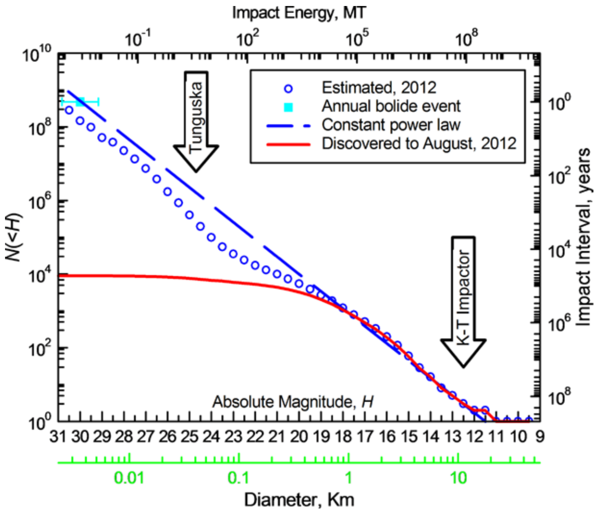

Fig. 6 The cumulative NEA populations, estimated and discovered up to August 2012, vs. absolute magnitude H. The number $N(<H)$ is the total number of NEAs larger than the specified size. The diameter scale is computed from H, assuming that $H = 17.75$ is equivalent to $D = 1$ km (mean albedo of 0.14). The current observed rate of atmospheric impacts is plotted at the upper left, and the energies of the Tunguska and K/T impacts are also indicated. See text for more details on the scale equivalences (image courtesy of Harris 2013a)

17.75) = 976 ± 30. This latest estimate for the population of "large" NEAs is in excellent agreement with the result of $N(D > 1\text{ km}) = 981 \pm 19$ obtained by the NEOWISE survey (Mainzer et al. 2011). NEOWISE is the term used to describe the NEO observing capability of the Wide-field Infrared Survey Explorer (WISE) telescope, active from December 2009 to February 2011. A total of 129 NEAs were discovered by NEOWISE, but its infrared-sensing was particularly useful especially to better evaluate the observational bias against dark asteroids existing in current ground-based optical searches.

In Fig. 6, the discovered and estimated NEA populations are associated with the impact energy scale derived from the diameter scale, assuming a mean impact velocity of 20 km/s and an average bulk density of impactors of 2.5 g/cm^3 (typical for stony S-type asteroids). The mean time between impacts (inverse impact frequency) is scaled from $N(<H)$ taking an estimated single-object impact frequency of 5×10^{-8} yr^{-1}. Stony asteroids of about a 1-km diameter (equivalent to an impact energy of about 46 Gt of TNT) strike Earth every 400000 years on average. The exact energy released by an impactor obviously depends on a number of parameters, like its diameter, density, velocity, and impact angle. Stony asteroids with a diameter of 4 meters impact Earth approximately once per year. Asteroids with a diameter of 7 meters enter Earth's atmosphere about every 6 years with as much kinetic energy of the atomic bomb dropped on Hiroshima (approximately 16 kt of TNT), but the airburst only generates a reduced release of 5 kt of TNT. These explode in the upper atmosphere, and most or all of the solids are vaporized.

3.2 Impact hazard

It is well established that large NEOs represent a threat for survival of living species, and that even small ones can be the source of local or regional damages. Throughout recorded history, several minor impact events (and exploding bolides) have been reported, causing injuries, land damage or other significant localized consequences.

One of the best-known recorded impacts in modern times was the Tunguska event, which occurred in Siberia, Russia, in 1908 (e.g., Longo 2007). The Tunguska explosion knocked down about 80 million trees over an area covering 2150 square kilometers. It is estimated that the shock wave from the blast would have produced an earthquake of 5.0 on the Richter Scale. An explosion of this magnitude is capable of destroying a large metropolitan area.

The Chelyabinsk meteor event (e.g., Yeomans and Chodas 2013), which exploded in the atmosphere on February 2013, is the largest recorded object to have encountered the Earth since the Tunguska event. The object, estimated to be about 17-20 m in diameter, exploded in an airburst over Chelyabinsk Oblast (Russia) at an altitude of about 23 km. The released energy is estimated to be about 440 kt of TNT explosives (equivalent to about 30 Hiroshima bombs). The shock wave caused injuries to more than 1500 people. Several thousands of buildings were reported to have been damaged by the explosion in the surrounding areas.

The effects of the entry in the atmosphere of a small NEO depend highly on its physical (mass and mechanical), compositional properties, and the speed and geometry of the entry. In particular, meteors rich in iron are more likely to survive entry than highly porous or fragile materials. For instance, when the asteroid 2008 TC3 impacted the Nubian desert of northern Sudan on October 2008, it is estimated that the asteroid lost 99.9 % of its mass in the atmosphere, as it was too fragile to survive the stresses involved in atmospheric entry (Jenniskens et al. 2009). The fraction of mass reaching the ground was similarly quite small for the Chelyabinsk event (Ivanova et al. 2013).

For impacts in an ocean, the generation of a tsunami needs to be also considered. Asteroids larger than a few hundred meters can produce tsunamis of tens of meters height and moving at tens of km/hr. Still, Chesley and Ward (2003) analyzed the risk from impact-generated tsunamis as a function of impactor size, considering a number of uncertainties in their model, and they found that most tsunami damage comes from small, more frequent events, with waves of only a few meters height and penetrating only a km or less inland.

3.2.1 Risk quantization

A peculiarity of asteroid impacts, with respect to other natural disasters, is that they present a huge spread of possible consequences, from the localized small property damages to catastrophic global extinction events. Hence a huge effort is necessary to make the "statistical" risk from asteroid impacts clear to the general public and political institutions.

In this sense, the early discovery of NEOs and the definition of their impact probabilities is extremely important, as well as giving a clear and precise communication to the public for reporting these predictions. For this purposes, "The Torino Scale" (Binzel 2000, last update by Morrison et al. 2004) has been established as a tool for public communication of risk for impact hazard using a 10-point integer scale, based on the collision probability and the released energy (depending by the asteroid size) of the possible collision. Close approaches scored with 0 do not represent real danger, while the extreme value 10 is when a collision is certain, and capable of causing a global climatic catastrophe that may threaten the future of civilization. A more technical impact hazard scale, the "Palermo scale" (Chesley et al. 2002), has been developed in order to categorize and prioritize potential impact risks spanning a wide range of impact dates, energies and probabilities. This scale is intended for specialists and assesses the degree to which objects should receive additional attention (i.e., observations and analysis).

A fundamental issue concerning the impact risk and its communication to the public is the available warning time. Indeed, it could take years of observations until the trajectory of a NEO is accurate enough to assess with certainty if an impact would occur or not; considering that an optimal mitigation strategy would probably require years to decades to be successful, this means that attaining this accuracy level on a possible collision with the Earth might come too late. Taking into account all of the above, in the next sections we will discuss several aspects of the detection, characterization, and impact risk mitigation of NEOs.

4 Surveys of near-Earth objects

Starting from the 1980s, the awareness of the possible risks associated with asteroid impacts has progressively increased. In 1990, the US Congress mandated NASA to "define a programme for dramatically increasing the detection rate of Earth-orbit-crossing asteroids", and in 1998 NASA officials adopted the so-called "Spaceguard Goal" to detect 90 % of NEOs larger than 1 km within 10 years. In the 1990s, the availability of CCDs and the birth of a number of surveys dedicated to the discovery and follow-up of NEOs, led to a dramatic increase in the discover rate (Fig. 7). Such increase concerned the PHA population too, rose from 166 known objects at the beginning of 1999 to more than 1400 at the time of the present writing.

The Spacewatch Project[4] (Gehrels 1991), founded in 1980 at the University of Arizona, was the first to use CCDs (1989) to survey the sky for comets and asteroids, including NEOs. A further major step was made with the start of the operations of the Lincoln Near Earth Asteroid Research Program (LINEAR)[5] (Stokes et al. 2000) at the Massachusetts Institute of Technology, using wide field telescopes originally designed for the US Air Force to observe Earth-orbital spacecrafts. LINEAR was the most prolific NEO survey from 1997 until it was overtaken by the Catalina Sky Survey (CSS)[6] (Larson et al. 2006) in 2005, a role that CSS still maintains. CSS is a system of three telescopes funded by NASA, two of them being located in Arizona, while a third one is in Australia. Furthermore, in 2010 the first (PS1) of the original intended array of four telescopes (PS4) of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS)[7] (Kaiser et al. 2010) began science observations and contributed significantly to NEO discoveries since then.

[4] http://spacewatch.lpl.arizona.edu/.

[5] http://www.ll.mit.edu/mission/space/linear/.

[6] http://www.lpl.arizona.edu/css/.

[7] pan-starrs.ifa.hawaii.edu/.

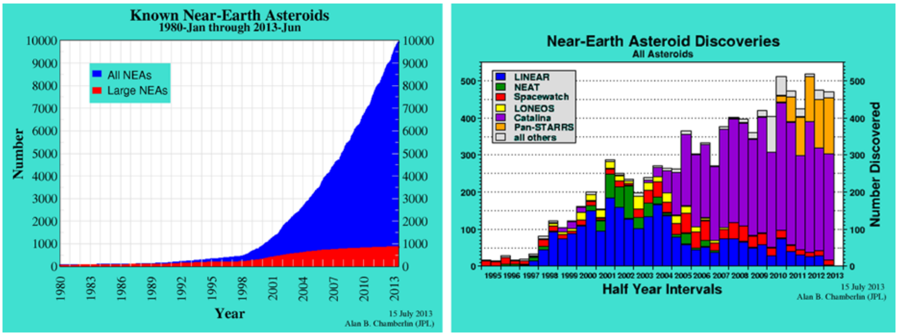

Fig. 7 (*left*) Cumulative discoveries of NEAs between 1980 and June 2013. "Large" NEAs are defined as those with absolute magnitude $H < 17.75$, corresponding to one kilometer spherical NEAs assuming a mean value of 14 % for albedo. One can note the significant increase in the discovery rate after the definition of the "Spaceguard Goal" and the start of the operations of dedicated surveys. The near completion of the 1-km requirement is also evident. (*right*) NEA discoveries between 1995 and mid-2013, showing the contribution of the different surveys. From http://neo.jpl.nasa.gov/stats/

Figures 6 and 7 show that the original "Spaceguard Goal" has basically been reached and that our knowledge of NEOs larger than 1 km is near completion. Yet, as discussed in Sect. 3, even much smaller bodies can pose severe threats at local and regional scales. In 2005 the US Congress mandated NASA to extend the current survey programmes in order to reach a 90 % completion of the NEA population greater than 140-m in diameter within 2020. Figure 6 shows that a 140-meter object impacts on Earth on average every about 30000 years, causing major damages on regional scales. It is to be noted, however, that even after achieving the original "Spaceguard Goal", about 3/4 of the estimated residual risk in terms of estimated fatalities per year still lies in the few remaining undiscovered large objects, while the risk from small regional impacts is only about 1/4 the total. And even after completing the next level goal of 90 % completeness down to 140-m size of the objects, about half of the residual risk will lie in the fractional probability that even one large object remains undiscovered (Harris 2013b).

Due to their magnitude limitations, the current surveys like CSS, LINEAR, or Pan-STARRS (nor their planned developments), cannot reach a 90 % completion of the NEA population larger than 140 m (corresponding to a limiting magnitude for the survey of $V = 24$), and new generation surveys are necessary. Figure 8, for example, shows the total coverage of the sky in 5 months (February-June 2013) by all the existing surveys down to the magnitude $V = 21$. Apart from the limits in the achieved magnitudes that makes it difficult to locate small/dark NEOs, Fig. 8 also shows that the southern hemisphere remains largely unscanned, and that searches for asteroids at low solar elongations are still rather difficult. Unknown objects with a radiant close to the Sun can impact the Earth undetected, like for the Chelyabinsk event discussed in Sect. 3.

In order to meet the goal of the 90 % completion of the NEA population at a 140-meter scale, new systems are required: larger telescopes (or multiple small telescopes simultaneously observing the same stellar field) to catch fainter (smaller) objects, larger fields of view to increase the sky coverage, optimized observing strategies for

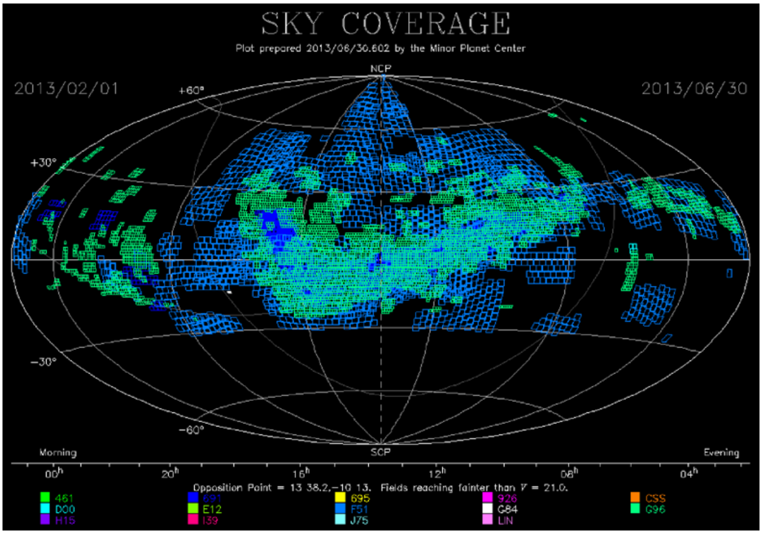

Fig. 8 Sky coverage obtained by all of the surveys searching for NEOs, between February and June 2013. Only scanned fields reaching magnitudes fainter than $V = 21$ are shown. Contribution from the different surveys (listed with the corresponding code given by the Minor Planet Center) are indicated by different colors. Plot generated through the Sky Coverage service offered by the Minor Planet Center (http://www.minorplanetcenter.net/iau/SkyCoverage.html)

low solar elongations. Future programmes that could help to increase our capability to detect objects as small as ∼140 meters include the 8.4-meter wide-field Large Synoptic Survey Telescope (LSST)[8] (Jones et al. 2009), planned to start its full operations in 2022 and capable of imaging the entire visible sky every few days. The LSST will reach a limit magnitude of $V \sim 25$ for detecting NEOs and finding 90 % of the PHAs over 140 meters in diameter is listed within its main purposes. The 4.3-meter Discovery Channel Telescope (DCT)[9] (Bowell et al. 2007) at the Lowell Observatory (Arizona) started its early scientific observations in 2013. It will not be able to detect 90 % of asteroids larger than 140 meters as a stand-alone facility, but will contribute greatly in the coming years with its 2.3-square-degree field of view and limiting magnitude fainter than $V = 23$. A mention is also due to the Asteroid Terrestrial-impact Last Alert System (ATLAS)[10] (Jedicke et al. 2012), being developed at the University of Hawaii with funding from NASA. The system, expected to be fully operational by the end of 2015, will be composed by up to eight small telescopes housed at one or two locations in the Hawaiian Islands. ATLAS will not contribute significantly to the cataloging goal for PHAs, but it is intended to patrol the visible sky twice a night looking for early detection of dangerous asteroids. A one-week warning is predicted for a 45-m asteroid and three weeks for a 140-m one.

[8] http://www.lsst.org/lsst/.

[9] http://www.lowell.edu/dct.php.

[10] http://www.ifa.hawaii.edu/info/press-releases/ATLAS/.

Within the future NEO discovery programmes, different space-based infrared telescopes have been also proposed. These include the Sentinel[11] telescope of the non-profit B612 Foundation, with a scheduled launch in 2017-2018 into a Venus-like orbit, and the NEOCam[12] (Mainzer 2006; McMurtry et al. 2013) mission that the JPL plans to propose to NASA's call for Discovery proposals in 2015, to be placed at the Sun-Earth L1 Lagrangian point. The main advantages of such dedicated space-based infrared survey telescopes would be the possibility to search for NEOs with orbits largely inside Earth's orbit (i.e. difficult to be discovered from ground-based surveys because of the Sun interference) and the immunity to the above mentioned observational bias of ground-based surveys against low-albedo NEOs. A first step in this direction has been made in February 2013 with the launch of the Canadian Near Earth Object Surveillance Satellite (NEOSSat)[13] (Hildebrand et al. 2004), a microsatellite in a Sun-synchronous orbit using a 15-cm telescope to search for NEOs in regions extending from 45° to 55° solar elongation and ±40° ecliptic latitude, at optical wavelengths. Despite a limiting magnitude of only $V = 20$, NEOSSat is expected to enhance our knowledge of the Aten and especially Atira populations.

5 Orbit refinement and collision probability

The Minor Planet Center (MPC)[14] operating at the Smithsonian Astrophysical Observatory is the official organization that takes charge of collecting positional data from worldwide observatories, then processing and publishing the calculated orbits of NEOs and PHAs. The Near-Earth Object Program[15] of the NASA/JPL, and the Near Earth Objects Dynamic Site (NEODyS)[16] operated at the University of Pisa (Italy) and sponsored by ESA, are the two main services that currently maintain Web-accessible information about the orbits and risk assessment of NEOs. Both of these services continually update a "risk list" of the potential future Earth impact events. Until now, no asteroid has been found to pose a serious danger to the Earth, but how to proceed if a potential impactor is detected and what to do in the case that an actual impact threat should arise?

The first step to be considered is a careful evaluation of the impact probability through the object orbit refinement, to be accomplished making use mainly of optical astrometry and radar ranging when new observational windows open. Extended data mining in astronomical image archives should also be performed, as pre-discovery records could help to improve and secure the preliminary orbit (e.g., Vaduvescu et al. 2013). Non-gravitational forces have also to be taken into account for a precise orbit determination (e.g., Brož et al. 2006). Indeed, despite the fact that non-gravitational

[11] http://b612foundation.org/sentinelmission/.

[12] http://neocam.ipac.caltech.edu/.

[13] http://neossat.ca/.

[14] http://www.minorplanetcenter.net/.

[15] http://neo.jpl.nasa.gov/.

[16] http://newton.dm.unipi.it/neodys/.

perturbations are many orders of magnitude weaker than gravity, their effect accrues in the long-term and can influence the planning and implementation of "slow push" mitigation attempts that could require decades (see Sect. 6). For NEOs, the main non-gravitational force to be considered is the Yarkovsky effect that arises from the anisotropic thermal re-emission of the absorbed solar radiation (e.g. Farnocchia et al. 2013). Thermal re-emission of sunlight from irregularly shaped NEOs can also perturb their rotational rate and obliquity. This effect is named YORP (Rubincam 2000) and can also produce quasi-secular changes in an asteroid's orbital elements, due to the photon thrust from the irregular shape (Rubincam 2007). Another perturbation acting on very small NEOs is produced by the solar radiation pressure, which has recently been detected for the first time by Micheli et al. (2012) on 2009 BD, one of the smallest multi-opposition NEOs currently known ($H = 28.1$). General relativistic corrections are of the same order as the non-gravitational forces. The main relativistic terms to be considered in the computations (Farnocchia et al. 2013) are those of the Sun, of the Earth (important during close approaches), and of Jupiter (for asteroids with a large aphelion distance).

An important issue to be raised in the context of the orbit prediction after a close approach, is the presence of the so-called *keyholes* (e.g., Valsecchi et al. 2003) in the target b-plane (the plane comoving with the Earth and perpendicular to the incoming velocity of the NEO). Indeed, the perturbation from a close encounter can change the semi-major axis of the orbit of the small body, and it is seen that the subsequent encounters of the NEO with the Earth are not independent of the occurrence of the previous ones (resonant returns[17]). Keyholes are small regions (compared to the usually much larger uncertainty of the NEO trajectory) of the b-plane of a specific close approach, such that an orbit through it (among the different possible orbits within the uncertainties) would collide with our planet on a subsequent encounter. The case of the PHA (99942) Apophis is emblematic: discovered in December 2004, it became instantly notorious because of a possible impact with the Earth in 2029, and was the first object to reach the level 2 in the Torino Scale. Further observations excluded a collision in 2029, but the passage through a keyhole could lead to an impact on one of its resonant returns during the next decades (Bancelin et al. 2012). Hence dedicated observation campaigns to improve our knowledge of Apophis' orbit will be periodically necessary in the future.

It has to be stressed that keyholes could be tiny on astronomical scales, with a width of e.g. only ∼600 meters for the keyhole that Apophis will have in 2029. Such a precision in the orbit prediction is not achievable from Earth-based observations (e.g. Giorgini et al. 2008), and the launch of a dedicated rendez-vous space mission could be the only possibility to assess in advance if an object will pass into a keyhole and impact the Earth on a subsequent resonant return. A rendez-vous mission will give highly accurate positioning data thanks to the continuous improvements in navigation measurements that currently allow to reach uncertainties in the spacecraft position of about 4 kilometers per astronomical unit of distance between Earth and

[17] If as a consequence of an encounter with Earth, the NEO is perturbed into an orbit of period $P \approx k/h$ years, with h and k integers, then after h periods of the asteroid k periods of the Earth have elapsed, and a "resonant return" will take place.

spacecraft (James et al. 2009). For example, a space mission visiting Apophis during its close approach with the Earth in 2021 (when it will be at a minimum distance of about 0.113 AU) would allow to achieve the necessary improvement in the asteroid positioning to determine if it will pass into its keyhole in 2029.

Such pre-mitigation "reconnaissance missions" would be extremely important also for the physical characterization of NEOs (e.g., Michel 2013). Indeed, not only the knowledge of the asteroid's physical properties will allow a precise determination of the non-gravitational forces acting on the NEO (e.g. the Yarkovsky/YORP effects would depend upon its shape and thermal properties) but would be essential to define successful mitigation strategies, as we will discuss in the next section.

6 Mitigation strategies

If an impact threat is confirmed (or if the collision probability is judged too high), the prevention of the collision of a NEO on course for the Earth would require either the destruction of the object, ensuring that the produced fragments would not be hazardous themselves, or, more realistically, deflecting it slightly from its catastrophic orbit, ensuring that the deflection operation does not simply move the object to another hazardous trajectory. We note that in general the fragmentation of an hazardous body should be considered with caution, as it could be extremely difficult to predict the right amount of energy required for the complete disruption of the asteroid, and also to foresee the fate of the (possibly large) produced fragments, which could hit the Earth anyway. Obviously, in the case of impact of a small asteroid (i.e. tens of meters in size), a mitigation space mission could be not necessary, and "classical" hazard protocols like sheltering and evacuation could be organized.

Several techniques have been proposed to deflect an asteroid on the route of collision with the Earth. They can be divided in two main categories: "slow-push" or "impulsive" methods, depending on the fact that the velocity change is imparted to the asteroid applying a small but continuous steady force, or in one impulse, respectively. The mean change in velocity required to deflect an asteroid from an Earth impact trajectory is about $3.5 \times 10^{-2}/t$ m/s, where t is the lead time in years (Chesley and Spahr 2004).

The two main impulsive methods are the *kinetic impactor*, which uses an impactor vehicle launched onto an interplanetary intercept trajectory, imparting a velocity change to the asteroid by hitting it at high velocity, and the *nuclear blast deflection*, where the asteroid's path is changed by using a stand-off or on/beneath surface explosion. The kinetic impactor is a relatively simple and mature technique that could be effective for asteroids smaller than about 1 km, with a warning time of at least a few years. The nuclear option is the most efficient method in terms of energy transport and, despite its intrinsic risks, could be our only available possibility for the mitigation of the hazard from the larger asteroids (i.e. more than several hundred meters in size) or when the warning time is limited to less than a few years.

Slow-push techniques can be used instead for an accurate control of the orbit changing imparted to small asteroids (up to a few hundred meters in diameter), with decades of advance warning before of their impact with the Earth, or to prevent the

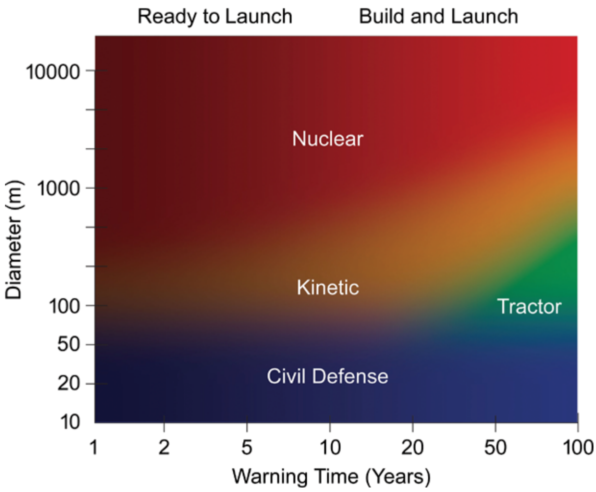

Fig. 9 Approximate regimes of applicability of the four main types of mitigation, including civil defense (i.e. sheltering and evacuation measures). Image from the report "Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies", by the US National Research Council (NRC). Image by Tim Warchocki, Copyright ©National Academy of Sciences

passage of an asteroid through a keyhole that would result in a subsequent collision trajectory. Proposed slow-push mission concepts include: the installation on the asteroid surface of solar sails, chemical or electrical or nuclear engines, or of "mass drivers" to excavate the surface and throw material away; the vaporization of surface material through high energy laser beams or orbiting mirrors that would focus the solar radiation on the asteroid surface; the application of a contact force through a "space tug", i.e. a spacecraft physically connected with the asteroid; and several more. However, most of these methods present severe limits in terms of their overall performance, cost, or technology readiness. The *gravity tractor* technique—consisting of a spacecraft hovering above the asteroid's surface, towing it with no physical attachment using gravity as a towline—is at present the slow-push method with the highest technology readiness level, and it also presents the advantage to be the most independent from the physical properties of the target asteroid.

The kinetic impactor, the nuclear deflection, and the gravity tractor hence seem the most readily implementable techniques that we can use if an actual impact threat should arise. Their applicability obviously depends on the size of the potential impactor diameter and on the available warning time before the collision, as schematically suggested in Fig. 9. In the next sections we discuss these three mitigation approaches in more detail.

We stress that, whatever the technique to be used, an accurate knowledge of the target orbit and mass are obvious prerequisites for the planning and execution of the mitigation mission. Other physical properties can be crucial as regards the mitigation approach. Such information can be given by a space mission with an orders of magnitude improvement over what possible from the Earth, hence a "reconnaissance" mission should always be planned well ahead of the actual mitigation mission, in order to investigate the crucial physical and dynamical properties of the target asteroid.

6.1 Kinetic impactor

The kinetic impactor mitigation technique (e.g., Rathke and Izzo 2007) is based on a momentum transfer imparted via an impactor spacecraft that crashes onto the asteroid at high velocity (∼10 km/s), slightly changing its orbit. A second observer spacecraft (e.g. that used for precursor reconnaissance) is also required to measure the resulting change in the asteroid's orbit, by means of a Radio Science Experiment (RSE) carried out before and after the impact.

This method is well within our current technical capabilities, and has already been studied to a phase A level within the ESA Don Quijote mission study. Moreover, the technology of impacting a small body at high velocities (10.3 km/s) has been already demonstrated by the NASA Deep Impact mission (A'Hearn et al. 2005), though no deflection could be measured in that case because of the size of the impactor (370 kg only) and of the target comet Tempel 1 (∼6 km of mean diameter).

The imparted change in velocity scales with the impactor mass and relative velocity at the moment of the collision, and ejecta from the impact might enhance the efficiency. The impulse enhancement factor due to ejecta recoil is usually defined as the ratio of the momentum imparted to the asteroid to the momentum of the impactor, and is commonly given the symbol β. Holsapple and Housen (2012) have recently investigated how β depends on the impactor properties, on the asteroid size and composition, and they found that generally $1 \leq \beta \leq 2$.

The way in which the stress-waves produced by an impact are propagated and attenuated inside an asteroid strongly depends by its porosity: in a porous body, as the shock propagates, energy is expended to collapse the pore spaces, with also a consequent heating of the object. Stress-waves are also attenuated through the scattering by (large) voids. The dissipative effect of porous materials has been investigated by laboratory experiments of collisional fragmentation, numerical simulations, and scaling theories. E.g., Housen and Holsapple (2012) have demonstrated that large craters can be formed in porous bodies without the production of ejecta, as an effect of shock compaction. Suppression of ejecta starts to occur for porosities greater than ∼40 %. For porosities below ∼40 %, excavation, as opposed to compaction, is the dominant mechanism in crater formation.

In the conservative hypothesis of a very porous NEO ($\beta \sim 1$), the instantaneous change in velocity given by a kinetic impact is of the order of $m \times v_{\mathrm{rel}}/M$, where m and M are the masses of the impactor and the NEO, and v_{rel} is their relative velocity. As an example, using a 10-ton spacecraft impacting at 10 km/s, a 500-meter NEO of density 2.5 g/cm^3 could be deflected by 10^{-3} m/s. In the case of a 200-meter object, the obtained deflection would be of 10^{-2} m/s.

To obtain a three-dimensional model of the asteroid interior, a radar tomographer onboard the reconnaissance precursor mission could be used to detect subsurface discontinuities like voids and fractures. As the penetration depth and spatial resolution would depend on the radar frequency and bandwidth, a range of frequencies should be foreseen, obtaining a finer sampling near the surface (i.e. where the shock waves attenuate) and a coarser resolution deeper into the surface. The accuracy of the radar tomography can be increased through a transponder to be released on the surface, like in the CONSERT experiment onboard the ESA Rosetta mission (Kofman et al.

2007). Several seismometers could also be deployed around the surface to perform seismic imaging. Seismometry would yield a spatial resolution comparable to radar tomography, but the two techniques could be considered complementary. In fact, seismic imaging would be challenging if dealing with highly attenuating porous bodies, while certain materials like rocks flecked with metal may be opaque to radar sounding (Asphaug et al. 2002). The seismometers should be coupled with a small-scale impact experiment to produce the necessary signal, or alternatively with an explosive charge to be released on the surface. The Apophis 2029 mission under phase 0 study at CNES (French space agency) envisages to obtain information about the porosity and internal density distribution of the PHA Apophis during its close approach with the Earth in 2029, using both radar tomography and a seismic experiment (Prado et al. 2012).

The efficiency of momentum transfer from the impactor to the hazardous asteroid crucially depends also on the impact accuracy. Knowledge of the size, shape, and rotation of the target are hence fundamental prerequisites. Moreover, the asteroid albedo and phase curve behavior, besides of giving constraints on its composition, would be also important to determine the illumination conditions during the spacecraft approach and optimize the impact trajectory.

It is clear that performing a kinetic impactor against a low-albedo, highly porous C-type asteroid could be more challenging than using this mitigation technique against the silicaceous S-type objects.

6.2 Nuclear blast deflection

With this mitigation scenario (e.g., Plesko et al. 2011), the NEO is deflected by using an explosion above (or on, or beneath) the surface. Obviously, the most powerful (yet with associated political and ethical issues) explosive technology at mankind's disposal is nuclear. Assuming the use of the W87 thermonuclear warhead (which has a yield of 300 kt of TNT) for a stand-off nuclear detonation, Schaffer et al. (2007) have estimated that NEOs of about 200 m in diameter can be deflected by about 10 cm/s.

A stand-off nuclear explosion will generate X-rays radiating spherically outwards, carrying the total energy of the nuclear charge and striking the surface of the asteroid. The radiation is absorbed by a thin surface layer, which heats up to equilibrium temperature and vaporizes. The rapid expansion of the vaporized material forms a mechanical shock wave in the surrounding material. The magnitude of the blast effect could be increased if the blast occurs on or below the surface of the asteroid, because a greater fraction of the nuclear explosion energy is directed at the asteroid, and because a buried explosion may result in ejecta through fragmentation. Obviously, landing on the asteroid and digging its surface would greatly complicate the mitigation mission.

As for the kinetic impact scenario, the estimation of nuclear explosion effects depends on a number of physical properties related to the composition and internal structure of the asteroid. The mechanical impulse generated by the evaporation of the surface layer of the asteroid depends on the mass thickness of this layer. The absorption coefficients largely depend on the atomic numbers of the elements making up this layer, and its depth is mostly determined by the abundance of iron and heavier elements. Knowledge of atomic abundances and of the chemical composition of the surface layer is therefore crucial. The porosity and the material cohesion of the asteroid are also determining factors in estimating the effect of the nuclear explosion. A lander performing in situ analysis of the surface—yielding detailed knowledge of the elemental composition, as well as of the mechanical and thermal properties—could be mandatory to reach the precise determination of these quantities required for the design of a blast deflection mission.

As for the kinetic impact technique, extreme attention should be paid to the dynamical fate of the produced fragments and ejecta, in order to avoid to direct them towards the Earth. This implies the necessity to accurately model the spin and the shape of the body.

6.3 Gravity tractor

The gravity tractor technique (Fig. 10) has been firstly proposed by Lu and Love (2005). To alter the trajectory of a threatening body, a hovering spacecraft will tow the asteroid with no physical attachment, using gravity as a towline. Hence this method is largely insensitive to the asteroid's surface properties and internal structure. Also, this approach avoids the destruction of the asteroid in smaller fragments that could be hazardous themselves. Furthermore, this mitigation technique has the advantage to not require a separate reconnaissance spacecraft, as the gravity tractor itself could carry the scientific payload for target characterization and be able to monitor in almost real-time (through an onboard transponder to provide accurate tracking of the asteroid) the induced deflection. In the case of a binary target, the deflection induced by a gravity tractor hovering over the pole of the system could cause the secondary to be dragged along with the primary, even if it was not known to exist prior to the mission (Schweickart et al. 2006). However, it should be noted that if impulses are needed in the orbit plane of the satellite, the gravity tractor operations would be greatly complicated.

Lu and Love (2005) calculated that a 20-tonne gravity tractor, hovering at an altitude of 50 m over the surface, with an exhaust-plume halfwidth of 20°, and a total thrust of about 1 newton (see Fig. 10), could effectively deflect an asteroid of 200 m diameter and density of 2 g/cm^3. The velocity change imparted to the asteroid in a single year of hovering would be of 1.9×10^{-3} m/s, enough to miss the Earth with 20 years of lead time (with a fuel requirement of about 400 kg for the thrust, using existing technology). The change in velocity needed to prevent an impact would be much smaller if applied before a previous close approach of the asteroid. Indeed, assuming a deflection manoeuvre conducted in 2027, Schweickart et al. (2006) calculated that a 1-tonne gravity tractor could shift the PHA Apophis (with an impact date in 2036) of one Earth radius with a mission duration of 20 days only, and a total fuel mass of about 10 kg for the deflection. Still, very accurate knowledge of the shape and rotational properties of the target asteroid are required, as the equilibrium hover point is unstable, and in order to keep the spacecraft position control and a correct thrust, a high accuracy on the measure of the distance from the asteroid's surface will be demanded. Moreover, a critical point for this deflection concept could be represented

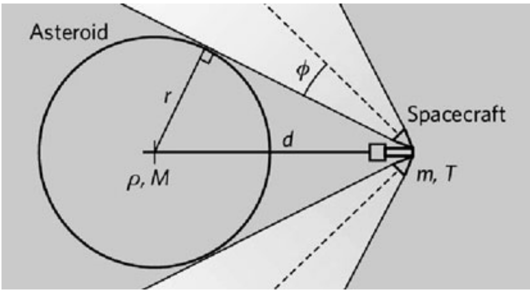

Fig. 10 Gravitational tractor. The asteroid (assumed to be spherical) has radius r, density ρ and mass M. The spacecraft has mass m, total thrust T and an exhaust-plume halfwidth Φ. It hovers at distance d from the asteroid's centre. The thrusters are tilted outwards to prevent exhaust impinging on the asteroid surface. The thrust required to balance the gravitational attraction is given by $T \cos[\sin^{-1}(r/d) + \Phi] = GMm/d^2$. From Lu and Love (2005)

by the almost continuous thrust that should be applied by the spacecraft engines in order to achieve such position control.

The space missions to NEOs planned or in study for the next decade, like NASA OSIRIS-REx, JAXA Hayabusa2 and ESA MarcoPolo-R could represent the occasion to demonstrate the actual feasibility of the gravity tractor technique.

A further aspect to mention, as regards gravity tractor and other slow-push techniques, is the following. For an object on impact course with the Earth, its impact location is known. Whether it impacts on land or near a coastline will most directly affect a particular nation and perhaps its neighbors. The process of altering the asteroid trajectory through a slow-push approach will first change the impact location, perhaps causing the impact point to cross the border of a neighboring nation. Thus a new risk will be created to other citizens who might not have had any initial danger, implying a very complex political situation. This illustrates the necessity for internationally agreed mitigation plans and strategies, which are missing so far.

7 Conclusions and future perspectives

During the last decades, near-Earth objects emerged as one of the main topics in planetary research (e.g., Yeomans 2012). Investigation of these can provide important information on the early phases of the solar system, and on the emergence of life on Earth. Moreover, their mining exploitation has been envisaged. But the importance of their study also lies in the potential threat that they pose to our planet. The presence of remnants of very old and more recent craters on Earth surface, as well as the paleontological evidence of mass extinction episodes of most of the terrestrial fauna and flora (e.g., Jablonski 1994; Nichols and Johnson 2008) testify to the past catastrophic effects of asteroid collisions with our planet. It would be imprudent to neglect the danger represented by a possible future impact.

The near-Earth objects represents a population on which it is necessary to concentrate the attention of the scientists, of the social and administrative authorities (for example, civil protection, the military authorities, etc.), and of the political institutions at the national and international level. In the 1990s, various international authorities (e.g., Council of Europe, UN General Assembly, Organisation for Economic Cooperation and Development) have recognized the importance of the threat of NEO impacts and recommended the governments of most developed nations and international organizations (ESA, NASA) to support and finance an international study on the threat represented by asteroid collisions.

Several international efforts to discover and characterize hazardous objects threatening the Earth have been made, as well as some theoretical studies on the more reliable techniques to be developed to mitigate the effect of an asteroid impact with our planet. These studies have generally been driven by scientific curiosity and there is a lack of coordination. The Scientific and Technical Subcommittee of the UN Committee on the Peaceful Uses of Outer Space (COPUOS) presents each year to the UN General Assembly its activity in reviewing the international cooperation in peaceful uses of outer space, including the programmes dealing with the NEO threat carried out in its 74 member Nations.

The research on NEOs was until very recently really organized only in the United States, where NASA, requested by the U.S. Congress, has funded since 1998 up to $ 4 million per year the project called “Spaceguard Survey”. The current goal of the programme is to discover and catalogue at least 90 % of NEOs having a diameter larger than 140 m (i.e. the size considered in the Torino Scale as the bottom to generate a regional catastrophe). The Minor Planet Center at the Harvard-Smithsonian Center for Astrophysics collects, archives, makes available on the web all the observations of asteroids and comets as soon as they are transmitted to the center. Moreover (and practically in real time) it computes orbits for all individual, identified objects. At the Jet Propulsion Laboratory long-term predictions of asteroid orbits and possible threat estimations are carried out.

At a European level, the Near-Earth Object Dynamic Site (NEODys) system in Pisa, Italy (with a mirror site in Spain), monitors and publicizes all potentially hazardous objects. The European Space Agency started in 2009 the programme “Space Situational Awareness” (SSA), which is focused on three main areas: space weather, space surveillance and tracking, and near-Earth objects. The SSA NEO Coordination Centre (NEOCC),[18] located at ESA/ESRIN (Frascati, Italy), started in May 2013 its activities which include prediction of NEOs orbits, production of impact warnings when necessary, and involvement in potential mitigation measures.

Starting in 2012, the European Commission, within its Seventh Framework Programme, provides co-financing for the NEOShield project,[19] which has been set up to provide solutions to the critical scientific and technical issues that currently stand in the way of demonstrating the feasibility of the promising mitigation options with a test mission. NEOShield aims to provide detailed test-mission designs, so that it will be possible to quickly develop an actual test mission at a later stage. An aim is also to formulate a global response campaign roadmap that may be implemented when a

[18] www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/Near-Earth_Objects_-_NEO_Segment.

[19] http://www.neoshield.net.

serious impact threat arises, that will consider the necessary international decision-making milestones, the required reconnaissance observations, and a campaign of the necessary mitigation acts.

We stress that, on a theoretical basis, humanity already has the necessary technology and expertise to deflect asteroids on route of collision with the Earth and protect our planet against the most probable (smaller) future collisions. Yet, the applicability and effectiveness of the different mitigation techniques that have been proposed still have to be demonstrated in space. In order to maximize our chances of success in a state of necessity, because an actual impact threat arose, it is crucial to test these mitigation techniques and the related technologies beforehand.

Furthermore, detailed hazard protocols have to be defined and tested, as for other natural disasters. Civil defense (warning, sheltering, evacuation) is the most plausible mitigation act against hazardous objects of a few tens of meters in size, which constitute the most frequent impacting asteroids on Earth. Civil defense is obviously also part of the mitigation efforts for more destructive events, especially after that the impact point of the threatening asteroid has been identified on the Earth surface, in locations possibly densely populated. Needless to say, civil defense could be the only possible mitigation in the case of a very short warning time prior to the collision, whatever the size of the threat.

Time is therefore the dominant factor in the mitigation of the NEO impact risk, as regards both the available warning time to organize a mitigation strategy and the risk perception by political institutions and the general public. As concerns the first point, it would be wise to have ready or quickly operational the necessary spacecrafts and instrumentation to be launched, for example making use of duplicates from previous space missions. As for the low frequency of NEO impacts, though there are no deaths in recorded history due to such collisions, it must be remembered that a single event could cause more deaths and destruction than any war or epidemic that ever has occurred on our planet. We need to be ready and prepared.

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