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

NEO Impact Consequences and Hazards

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Abstract

A short overview of main characteristics of the impactor population from which major terrestrial impacts originated is given. This population includes the objects that may hit the Earth in the future (potentially hazardous asteroids, PHAs). An impact frequency (a way of measuring the probability of a given collision) versus impact energy (an index of the impact consequences) relationship is described on the basis of this analysis. The current state of actions started planetwide by the most developed countries to face the threat represented by an asteroid collision with the Earth is summarized. The 'Torino scale', which assesses the risks connected with a discovery of a PHA in a simple and clear way is finally described. ***To cite this article: M. Fulchignoni, M.A. Barucci, C. R. Physique 6 (2005).***

Résumé

Conséquences et hasards d'une collision avec la Terre. Les principales caractéristiques de la population des impacteurs qui ont formé les plus importantes structures d'impact terrestres sont brièvement résumées. Dans cette population sont également inclus les objets qui peuvent avoir une collision avec la Terre dans le futur (les astéroïdes potentiellement dangereux, APDs). Sur la base de cette analyse, on présente la relation entre la fréquence des impacts (qui est une mesure de la probabilité d'une collision) et l'énergie qu'ils transportent (à partir de laquelle on peut évaluer les conséquences des collisions). On discute les actions envisagées dans les pays les plus développés pour affronter la menace que représente la collision d'un astéroïde avec la Terre. En conclusion on décrit « l'échelle de Turin », qui permet d'évaluer d'une façon simple et claire les risques associés à la découverte d'un APD. ***Pour citer cet article : M. Fulchignoni, M.A. Barucci, C. R. Physique 6 (2005).***

Keywords: NEO; Impact population; Potentially hazardous asteroids; Torino scale

Mots-clés : NEO ; Population des impacteurs ; Astéroïdes potentiellement dangereux ; l'échelle de Turin

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1. Introduction

All the small bodies located near the Earth, with a perihelion distance <1.3 a.u., are called Near Earth Objects (NEOs). This general denomination includes objects of both asteroidal (star appearance) and cometary (presence of a coma and a tail) origin. The inventory of NEOs when this article was written includes about 3000 objects.

Numerical simulations of their dynamical evolution show that these objects remain members of the NEOs' population for 10^7 years on average before: (i) falling into the Sun; (ii) being ejected from the solar system; or (iii) colliding with a terrestrial planet. Due to this short lifetime, NEOs observed today cannot be the remnants of the primordial planetesimal swarm from which the terrestrial planets formed 4.6 billions years ago: thus, a continuous renewal of the NEOs' population must be hypnotized. One of main goals of NEO research is the understanding of the source(s) and the mechanism(s) of this renewal. The key questions are: (1) what fraction of NEOs came from the asteroid main belt; and (2) how many NEOs, having an asteroid appearance, are in reality dead or dormant comets?

The asteroid members of a family originated from a disruptive collision in the main belt. Perturbations and resonances [1,2] may send a few fragments of the broken asteroid toward the inner regions of the solar system where they become NEOs. The spectra of NEOs are very different indicating different surface properties [3]: quite all the taxonomic classes (considered as representative of the surface composition) found in the main belt are present among the NEOs, including the types P, D which are characteristic of the far external regions of the asteroid belt. This wide variety of taxonomic classes suggests that the processes of dynamical transfer of NEOs are also varied.

Meteorites are NEOs that fall on the Earth; so, in the meteorite collections we have plenty of samples of the NEO population [4]. The comparison of the spectra of meteorites obtained in laboratory with those of asteroids can provide information on the source of meteorites which are also the sources of NEOs.

2. Impacts on the Earth

All terrestrial planet surfaces have undergone continuous bombardment since their formation. On the basis of solid theory [5], the formation of the Earth's moon was initiated by an impact of a Mars-sized object with the proto-Earth which inserted into Earth orbit the material sublimated during the impact, which condensed and accreted to form the Moon.

Recently, Ivanov et al. [6] studied the planetary cratering rate by comparing the size-frequency distributions of impact craters and asteroids. They concluded that, after the era of the heavy bombardment which marked the final stages of planetary accretion, a single projectile population formed the majority of impact craters. Owing to the fact that the projectile size-frequency distribution derived from the lunar craters is similar to the size-frequency distribution of main belt asteroids, these asteroids are supposed to have provided most of the crater forming objects striking the terrestrial planets.

On Earth, larger craters reflect an older population while smaller craters are removed by erosion [7]. The impact structures are characterized by two main morphologies: (1) simple structures, diameter $\leqslant 4$ km, with ejecta forming an overturned rim more elevated than the surrounding terrains, including a bowl-shaped depression, whose bottom is covered by cemented brittle of rocks (breccia); and (2) basins and more complex structures, diameter $\geqslant 4$ km, with a central peak, uplifted ring, concentric fractures, and a rim sculptured by successive land-slide events. Impact melted material can be found at the interior of these craters and/or buried under the slumped impact debris.

The present impactor flux on the Earth is at least 100 times lower than the primordial one which produced an intense bombardment of all the terrestrial planets between 4.6 and approximately 3.9 billion years ago.

To-date, over 170 impact craters have been identified on Earth; their geographical distribution is illustrated in Fig. 1.

The larger terrestrial craters ($D > 50$ km) are listed in Table 1. With the exception of the Vredeford Crater, a 2-billion-year-old crater located in South Africa with a diameter of roughly 300 km, and the Sudbury crater (200 km across), formed on the Canadian shield more than 1.8 billion years ago, all the other terrestrial craters are younger than 1 Gy. The Sudbury Crater, is roughly the size of the much younger Chicxulub Basin (Yucatan, Mexico) caused by an asteroid at the Cretaceous-Tertiary (K-T) boundary. The impactors that created these craters delivered energies exceeding 10^5 Megatons TNT equivalent ($\sim 10^{20}$ J).

The gigantic impacts had different effects on the Earth environment depending on the evolutionary phase of our own planet and the surface biota.

The primordial Earth's atmosphere came from outgassing of volatiles Earth's initial crust generated both by endogenous (volcanic activity) and exogenous (impacts) processes. Moreover, some exotic (prebiotic?) molecules may have been imported by the impacting bodies themselves, even though the largest early impacts, owing to their sterilizing effect on the Earth's surface, could have slowed down the development of proto life forms.

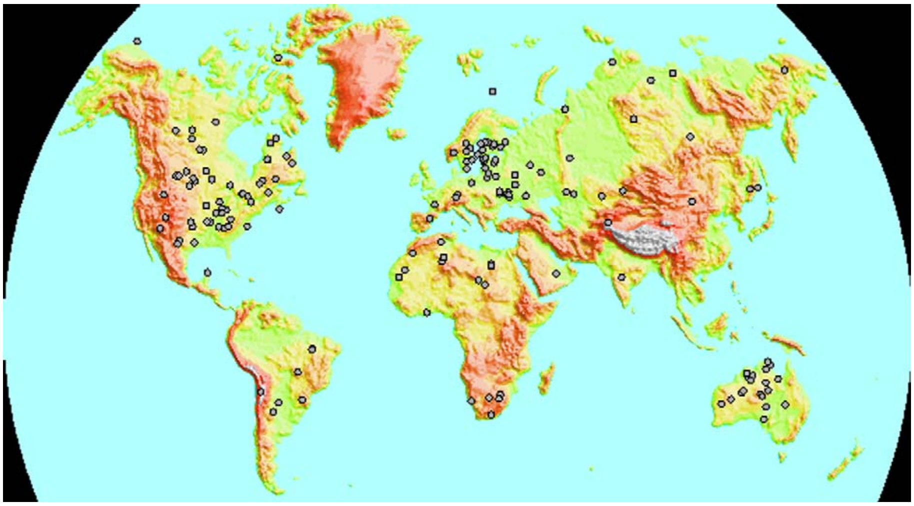

Fig. 1. Geographical distribution of known Earth impact craters.

Table 1
Terrestrial impact craters with $D \geqslant 45$ km [8]

Crater name	Geographical location	latitude	longitude	Diameter (km)	Age (My)
Montagnais	Nova Scotia, Canada	N 42° 53′	W 64° 13′	45	50.50 ± 0.76
Kara-Kul	Tajikistan	N 39° 1′	E 73° 27′	52	<5
Siljan	Sweden	N 61° 2′	E 14° 52′	52	361.0 ± 1.1
Charlevoix	Quebec, Canada	N 47° 32′	W 70° 18′	54	342 ± 15*
Tookoonooka	Queensland, Australia	S 27° 7′	E 142° 50′	55	128 ± 5
Beaverhead	Montana, U.S.A.	N 44° 36′	W 113° 0′	60	∼ 600
Kara	Russia	N 69° 6′	E 64° 9′	65	70.3 ± 2.2
Morokweng	South Africa	S 26° 28′	E 23° 32′	70	145.0 ± 0.8
Puchezh-Katunki	Russia	N 56° 58′	E 43° 43′	80	167 ± 3
Chesapeake Bay	Virginia, U.S.A.	N 37° 17′	W 76° 1′	90	35.5 ± 0.3
Acraman	South Australia, Australia	S 32° 1′	E 135° 27′	90	∼ 590
Manicouagan	Quebec, Canada	N 51° 23′	W 68° 42′	100	214 ± 1
Popigai	Russia	N 71° 39′	E 111° 11′	100	35.7 ± 0.2
Chicxulub	Yucatan, Mexico	N 21° 20′	W 89° 30′	170	64.98 ± 0.05
Sudbury	Ontario, Canada	N 46° 36′	W 81° 11′	250	1850 ± 3
Vredefort	South Africa	S 27° 0′	E 27° 30′	300	2023 ± 4

There is evidence that the mass extinction event occurred at the K/T boundary, 65 million years ago, is linked to a major impact event [9] which led to a planet wide abrupt climate change and affected the global environment so heavily that 50% of marine organism families [10], 20% of the genera [11] and all dinosaurs species disappeared.

Campo Bagatin et al. [12], analyzing a sample of 30 well dated terrestrial craters, studied the impactor energy flux on Earth during the last 150 My, searching particularly for correlation with paleontological extinctions. Owing to the fact that non-decisive arguments can be deduced by comparing the impactor energy flux with the time distribution of the paleontological extinctions, they deduced that there may be a lower impact threshold above which a global environmental catastrophe may occur. Jansa et al. [13] derive a zero extinction threshold limit for an impactor producing a crater with a diameter of 45 km (as the Montagnais crater, which lies entirely beneath the surface of the Atlantic Ocean on the continental shelf of Nova Scotia, Canada) and as 50% genera extinction threshold limit for an impactor producing a giant crater of more than 200 km in diameter (as the Chicxulub crater, in Mexico, Fig. 2).

From the estimates of the terrestrial cratering rate, the frequency of K-T-sized events on Earth is of the order of one every 50–100 million years. Smaller, but still significant impact events, occur on shorter time scales and will affect the terrestrial climate and biosphere to varying degrees. Relatively small impacting bodies, < 0.5 km in diameter that produce impact craters as small as 15–20 km hit the Earth with a frequency of two or three every million years. The most recent known structure in this size range is Zhamanshin in Kazakstthan, with a diameter of 15 km and an age of 1 million years. Impacts on this scale

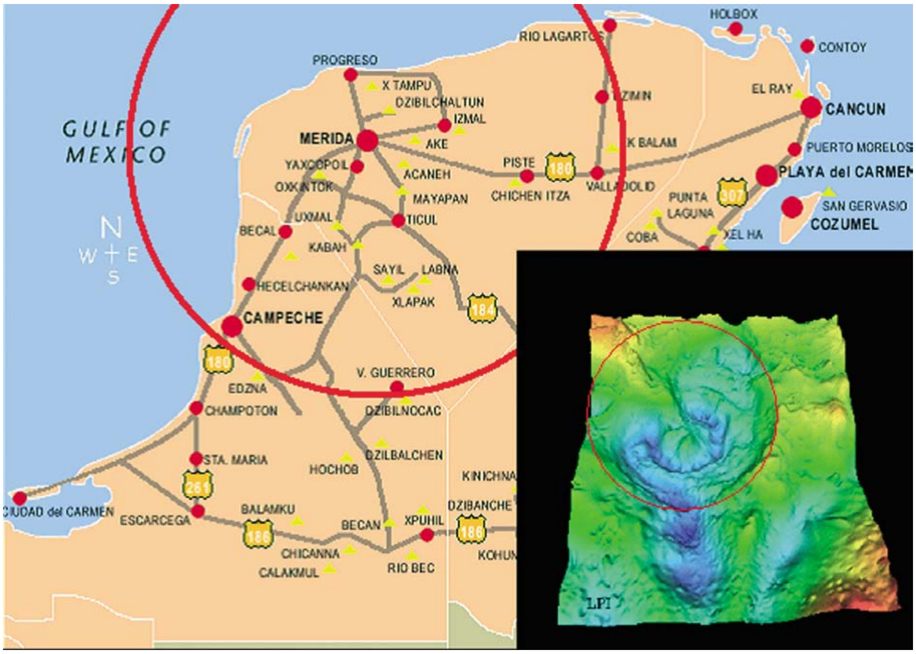

Fig. 2. The Chicxulub crater ($D = 200$ km, marked by a circle), was identified in 1990 by Hildebrand et al. [14] as the source of the iridium rich layer found everywhere on the Earth at the K/T boundary, analyzing the cores drilled in the Yucatan peninsula by Mexican National Petroleum Company.

are likely to have locally a serious effect upon the organized and technologically complex infrastructure on which we rely and they may inject enough poisonous elements from the vaporized impactor to produce a drastic temperature decrease of several degrees and a major climatic shift.

An impact in an ocean by a body 400 m in diameter would generate a tsunami [15] devastating the coasts on both sides of the ocean with wave runups of over 60 m. The December 2004 tsunami in south Asia, generated by a submarine earthquake of 8.9 magnitude on the Richter scale, is thought to have been the largest of the last hundred years. An impact-generated tsunami 10 times more powerful could occur with a typical recurrence time of a few thousand years.

Small impacting bodies (threshold size: up to 20 m if iron–nikel alloys, 200 m if silicate/ice aggregates) release their energy in the atmosphere, as an air burst which are scarcely efficient at delivering their energy to the ground. The Tunguska event (Siberia, 1908) is a typical example of these impacts. The air blast resulted in the devastation of 2000 sq. km of Siberian forest, but there was no loss of human life due to the very sparse population. Events such as Tunguska occur on a time-scale of 100s of years.

The impact frequency during the last 100 million years deduced by the crater records is plotted in Fig. 3 versus the impactor energy obtained from the craters characteristics (diameter, ejecta, underlying melted materials, ...).

3. What we are doing to mitigate the risks represented by a catastrophic collision of a Near Earth object with our planet?

Impacts are random processes both in space and in time.

A list of close approaches to the Earth through the end of the 21st century is available at the site of the Minor Planet Center [16] which contains the predicted encounters by a subset of the NEOs' population, the Potentially Hazardous Asteroids (PHAs), to within 0.05 AU of the Earth from the start of this year through 2178. However, the list does not contains *all* the PHAs. In fact, for example, the asteroid (1989 FC) was discovered by chance a few days after its crossing of the Earth orbit at a distance of 700 000 km from the Earth, which implied that a collision was missed by only a few hours. Its size has been estimated to be of the order of 500 m: enough to form a crater with $D > 40$ km.

On this subset of the Earth crossers it is necessary to focus the attention of scientists, of social and administrative authorities (as Civil Protection, Army, etc.) and of the political institutions at national and international level.

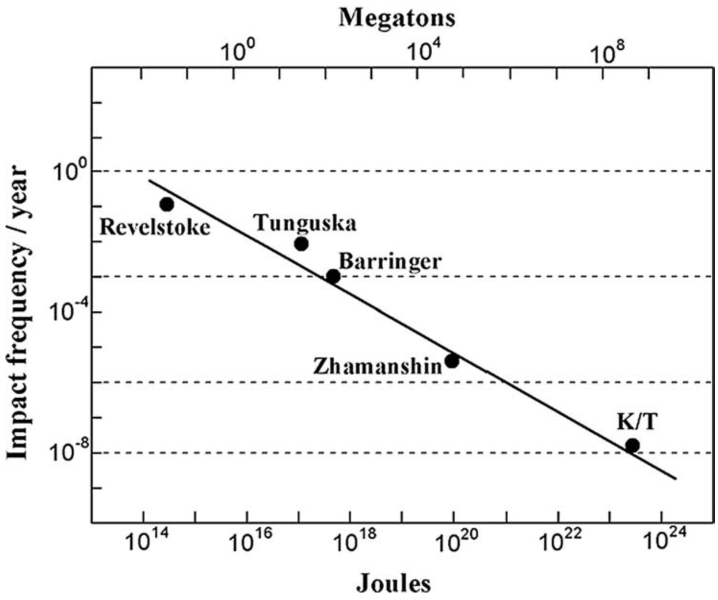

Fig. 3. Frequency of impacts plotted against their energy, either in Joules or Megatons TNT equivalent.

Several international institutions (Europe Council in 1996, UN General Assembly in 1999, British Government in 2000 [17], Global Science Forum of the Organization for Economic Cooperation and Development in 2002, International Council of Scientific Unions in 2003) recognized the threat represented by the PHAs and recommended to the governments of the more developed Nations and to the international research organizations (NASA, ESA, ESO, ...) to support and to finance an international research project on the Earth crossers.

An international professional organization, the Spaceguard Foundation [18] has been set in 1996 with the task of coordinating the research on PHAs, encouraging observers to follow-up the newly discovered objects and to check their actual presence with archived observations, to refine their orbit determination in order to predict a possible collision.

The PHAs' research to date has been organized only in the US: responding to a request of the Congress, in 1998 NASA started the project "Spaceguard Survey" (budget $4 million/year) with the aim of discovery and inventory in ten years of 90% of NEOs with $D > 1$ km, considered as the lower limit of projectile size which can induce a global catastrophe. Midway through program, more than 60% of the targeted objects have been discovered, according to estimates of the NEOs' population.

The Japanese government financed the Bisei Observatory [19], a center devoted to detect space debris and NEOs. The European Space Agency, in the framework of the General Studies, financed the feasibility studies of six space missions toward NEOs; three of these deal with the characterization of the morphology, internal structure and surface composition, while the three others concern the characterization of the populations' bulk characteristics, such as their size frequency distribution, the taxonomy distribution, ...

Moreover, the scientific community has to answer some key questions:

- What should be the next steps of observation programs?
- Where should the next cut-off on the diameter be set for the next Spaceguard Survey? Do we have to search for bodies with sizes down to hundreds of meters, to avoid regional disasters from impactors (such as widespread tsunamis, induced earthquakes and volcanic eruptions, abrupt climatic changes...), or to tens of meters, to prevent local destructions (catastrophic for the heavily urbanized zones)?
- How should space technology be used to mitigate the risk of an impactor collision with the Earth?
- What are the arguments to convince institutional authorities from different countries to join an international effort to react to an impact emergency?
- How should communications toward the public be managed concerning the risks associated whit asteroid impacts to avoid a catastrophe?
- When and by whom should an emergency plan be initiated in case of real threat?

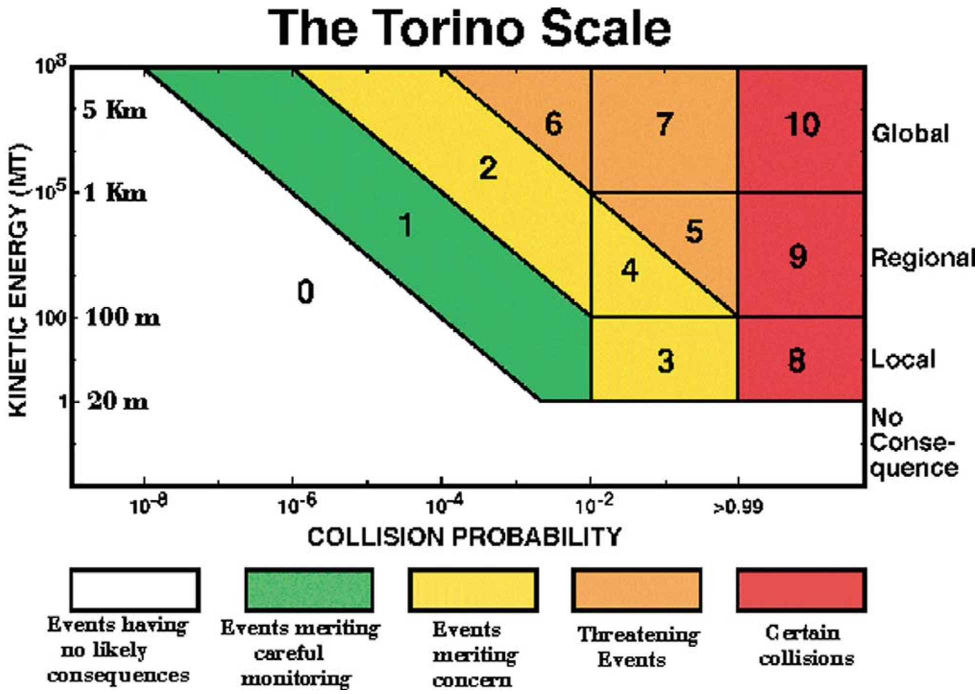

Fig. 4. The ‘hazard space’ where the Torino scale is defined.

4. The Torino scale

If the uncertainties on the orbit of a PHA are such that a collision with the Earth cannot be ruled out, a clear and precise communication to the public is required for reporting these predictions. A 0–10 point hazard scale, has been defined during a dedicated workshop held in Turin (Italy) in 1999 [20]. The Torino scale value, inseparably associated with the date of close encounter, is a simple and efficient tool for assessing ‘a priori’ the risks represented by a PHA.

Collision probability and kinetic energy (collision consequence) are the principal dimensions constituting the ‘hazard space’ where the Torino scale values are defined. They are bounded between 0 (good) and 10 (bad). Close approaches scored with 0 do not represent real danger. Value 1 corresponds to collision probabilities that are comparable to the current annual chance for any given size impactor, whose kinetic energy spans between 10^8 megatons (the value estimated for the K/T impact) and 1 MT (value for which the impactor is destroyed in the atmosphere). At the other extreme of the scale, values 8–10 correspond to certain (probability $> 99\%$) collisions having increasingly high kinetic energies and consequently direr and direr consequences. The definition of the intermediate low values is connected with a low chance ($\sim 1\%$) of a collision having no effects (2), local destruction (3) or regional devastation (4). The intermediate higher values refer to a significant threat of a collision causing regional devastation (5) or global catastrophe (6 and 7). The Torino scale hazard space, the hazard categories (values) and the related definitions are represented in Fig. 4, where a color code progressing from white to green to yellow to orange and to red accounts for the level of concern merited by a close encounter at a specified date.

To face the risks connected with an impact by a NEO with the Earth, it is essential to have a complete inventory of the PHAs, which possibly includes their physical and chemical properties to characterize their nature. The knowledge of the whole NEOs’ population down to a given diameter will provide us with the essential data to assure the survey of the Earth neighborhood. Information on the structure, on the global and local morphology and on the composition of these objects is essential to foresee the mitigation actions in case of a real alert. The Torino scale value will change as soon as new observational data are obtained. As an example, let us take the case of 2004 MN4. This asteroid was observed on 24 and 25 December 2004, and the first calculation of its orbit indicated that it had a chance of 2.7% of hitting the Earth on 13 April 2029. Since the debut of the Torino scale in 1999, no object has risen above a score of 1. But 2004 MN4 rose to level 4 due to the greater than 1% chance of impact and the potential for regional (rather than localized) devastation if the body were to strike Earth. Looking at the archived data, it was possible to find some observations made in June 2004 contained this object but it was not ‘discovered’ at that moment. These data provided a 180-day long orbital arc from which it has been possible to determine the asteroid’s orbit more precisely. The result of this finding is that the asteroid now ranks 0 in the Torino scale: it will miss our home planet. The final value for any close approach will be 0 (the asteroid does not collide with the Earth) or one out of 8, 9, 10 (the asteroid will hit our planet).

Astronomers have the task of obtaining enough data to reach a final conclusion as soon as possible, in order to rule out the threat or to maximize the time available for setting up an effective mitigation strategy [21] and to perform the envisaged actions.

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