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Asteroid and comet hazards: the role of physical sciences in solving the problem

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1. Introduction

Starting in the 1990s, the problem of hazardous impacts of sufficiently large celestial objects (asteroids and comets) with Earth (the asteroid–comet hazard, or ACH) attracted marked attention from scientists, technicians, politicians, the military and the general public, both globally and in Russia. Over the last decade and a half, hundreds of scientific papers and seven monographs have been published on this topic in the Russian language alone. A fairly comprehensive and up-to-date review can be found in a recent monograph [1] which, for the first time in the Russian literature, provides a thorough and detailed discussion of all aspects of the ACH problem.

An impact of a Tunguska type object (say, 50 m in size with a speed of 20 km s^{-1}) would release an energy of about 10 megatons of TNT, resulting in what can be defined as a local catastrophe. Based on the total damage area of about 2000 km^2 in the Tunguska event, an impact of Earth with a 300-m asteroid (for example, Apophis) would have a more damaging effect than would the entire global arsenal of explosives. With many tens of thousands of square kilometers of total damage area (a regional catastrophe), this impact will have severe continental-scale consequences. Space objects larger than a kilometer will produce in falling on Earth consequences of global significance.

Impacts of Earth with minor solar system bodies (dust particles, meteoroids, asteroids, and comets) are rarely dangerous. Average rate estimates for such impacts and their qualitative consequences are listed in Table 1.

Very small size objects enter Earth's atmosphere in a virtually continuous flow without noticeably affecting our lives. Nor do larger, meter-sized objects, so spectacular as they enter and break up in the atmosphere and fall on the ground, cause any serious trouble. Denoting by D the size of a body, the following scalings can be used for back-of-an-envelope purposes: the body energy $E \propto D^3$, and the collision frequency $f \propto D^{-2}$ (see Ref. [2]). The average (destruction) energy e released per unit time on the ground due to an impact with a body of size D is, to a first approximation, proportional to D. This means that over larger time intervals larger bodies carry more energy e than their smaller counterparts and hence represent a higher average degree of threat than smaller ones (see Section 3 for a discussion on average versus specific risk). On the other hand, impacts with objects more than a kilometer in size are so rare on the time scale of *homo sapiens* existence that, in spite of their deadly consequences, they are primarily a subject for experts in the geophysical and biological histories of Earth. From a practical point of view, this means that impacts with celestial objects measuring from about 30–50 m to about 0.5–1.0 km should be given the most attention.

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The following points characterize the threat from an ACH:

• there is virtually no upper limit to how hazardous the ACH can be;

• although estimates show that the average level of threat is low (for example, the probability for an Earth dweller being killed by an asteroid or comet impact is comparable to that of being killed in an air crash [3]), a specific event (impact) may have capital-C consequences, not only for an individual country, but for humankind as a whole;

• the threat is global in scope;

• unlike all other natural space-related threats, the global ACH threat can be predicted with a fairly high degree of certainty (provided the problems to be considered in Sections 2 and 3 are solved).

As a structurally complex problem (which it is), there are three basic aspects to be recognized in the ACH problem:

(1) Detecting, determining the properties of, and assessing the risk from hazardous celestial objects.

(2) Protection and damage reduction.

(3) Having a cooperative approach.

Problem number one for science — that of identifying all hazardous objects and determining their properties — is considered in Section 2. Section 3 discusses how to assess the impact consequences and general risk. Protection and damage reduction problems and work organization as a whole can hardly be ignored, even in a brief review like this, and they are accordingly addressed in Section 4, albeit in very general terms. Section 5 concludes and summarizes by pointing to the physical sciences — primarily astronomy and geophysics — as a key to solving the ACH problem.

2. How to detect and to obtain detailed knowledge of hazardous celestial objects

Before proceeding, some definitions are in order. By *near Earth objects* (NEOs) we refer to asteroids and comets with perihelion distance $q < 1.3$ AU. Among these, we distinguish *potentially hazardous objects* (PHOs) whose orbits can bring them within 7.5 million kilometers from Earth's orbit. The reason why an orbit away from the Earth's orbit in less than twenty Moon orbit radii makes an object a threat is that this distance is the scale of uncertainty which is involved in predicting the motion of a small celestial object 100 years or so in advance and which arises from the currently uncertain parameters and imperfect model describing the motion of the object.

The detection and detailed characterization of hazardous objects are at the top of the agenda for the ACH research community.

Detection, the way it is currently understood, means that a hazardous object (50 m or larger in size) needs to be detected promptly (no later than a month before a potential impact according to current requirements) and adequately (with a completeness greater than a certain threshold value, usually 90%). The subsequent regular *monitoring* of hazardous objects, both already known and those newly discovered by survey programs, should provide improved knowledge of their orbits and allow the full (as far as possible) study of their physical properties — potentially resulting in more

Table 1. Impacts of small celestial objects with Earth: average rate and consequences.

Object	Size D	Characteristic intercollision interval	Crater size, km	Consequences of an impact with Earth
A small dust particle	$D < 0.1$ cm	Practically continuously		Burns up in the atmosphere or falls on the ground
Meteoroid	0.1 cm $< D < 1$ m			Burns up in the atmosphere
	1 m $< D < 20-30$ m	A few months		Reaches the ground at a low speed or completely disintegrates and burns up
	$D > 30$ m	About 300 years	None	Tunguska type mid-air explosion
			> 0.5	Ground explosion (for example, Arizona crater)
				Local catastrophe
Asteroid or comet	$D > 100$ m	Several thousand years	> 2	Ground or underwater explosion
				Regional catastrophe
	$D > 1$ km	More than 500 thousand years	> 2	Global catastrophe
	$D \approx 10$ km	100 million years	200	End of civilization

reliable evaluation of the probability and consequences of an impact and providing necessary information for humankind to take preventive measures in advance.

While until the mid-1990s hazardous objects were detected either by chance or within individual asteroid/comet research programs, the launch in 1998 of the Spaceguard Survey program supported (including financially) by the U.S. Congress, enabled detection at a much higher rate. In an important development, NASA committed itself to discovering, within ten years, no fewer than 90% of all near-Earth asteroids greater than 1 km in diameter — a task which is considered to have been completed by the end of 2009.

According to data from the NASA-funded Minor Planet Center operating under the auspices of the International Astronomical Union (http://cfa-www.harvard.edu/cfa/ps/mpc.html), about 8,000 NEOs had been discovered as of mid-April 2011 (overwhelmingly by US observation facilities and the US-coordinated network). Most of this number are asteroids; a few comets are a class of minor bodies which are very difficult to observe. According to data as of late June 2011, the number of PHOs is 1,237, including 70 comets.

The most important question is perhaps that of NEO detection completeness. Table 2 lists estimates of the number of 'unrecognized' potentially hazardous objects. There are an estimated few tens of thousands of PHOs more than 100 m in size and a few hundreds of thousands of PHOs more than 50 m in size. Quite uncertain as these estimates may be, the number of unrecognized objects is a hundred times that of known PHOs. What threatens us most is what we know of least!

Although there are quite a few large astronomical telescopes in the world, detecting PHOs on a mass scale is unfortunately not a task they are up to. A modern detection system requires developing special-purpose instruments. It is currently well known that, for a telescope to detect 50–100 m NEOs, the following parameters and operating conditions are optimum:

• a field of view of several (preferably ten) degrees squared;

• a penetrating power of 22nd stellar magnitude or more for exposures of no longer than a few dozen seconds, which implies a telescope aperture of no less than 1–2 m. Infrared (IR) space telescopes may have a smaller aperture, though, because it is mostly in the IR range (5–15 μm) that asteroids reradiate most of their absorbed solar energy;

Table 2. The number of unrecognized potentially hazardous objects.

Size of the object, km	Estimated number of unrecognized PHOs	Proportion of unrecognized PHOs, %
> 1	< 40	< 20
> 0.140	$> 2 \times 10^4$	$\gtrsim 90$
> 0.05	$> 2 \times 10^5$	$\gtrsim 99$

• (for ground-based telescopes) a large number of clear nights and a high quality of images;

• very high-capacity computer equipment and mathematical software for obtaining operational information on new objects in one night and completely processing it before the next begins.

There are a number of projects currently underway in the USA to develop instruments specialized to detect hazardous celestial objects. One of these, Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) is primarily intended to solve the U.S. Air Force's space control problems.

The Pan-STARRS telescope, a system of four 1.8-m-aperture, 3-degree-field-of-view telescopes, has a charge coupled device (CCD) camera with a huge number (1.4 billion) of pixels and reaches a 24th stellar magnitude in 60 seconds. When in a search and survey mode, the entire available sky area is covered three times a month by these telescopes. As yet, only the first (prototype) telescope, PS1, has been built and is already in operation [4]. The still larger, 8-m LSST (Large Synoptic Survey Telescope) project is part of a unique civilian-purpose sky survey system [5] to be used for astronomical and cosmological purposes and for detecting dangerous objects. The system will be able to cover every 15 s a sky area 50 times that of the full Moon, and to detect objects as faint as 24.5th stellar magnitude. The telescope will have a 3-billion pixel digital camera and collect an equivalent of 7,000 DVDs of information nightly. The projected launch date of the facility is after 2015.

Radar observations of asteroids are of a great value not only in providing very accurate information on the orbital motion of an asteroid but also in providing data on its physical properties, such as size, shape, and the composition of surface layers. The radar observation of individual asteroids is primarily conducted at the Goldstone and Arecibo radio astronomy observatories, at a rate of 10–15 objects per year [6] and with the radar range limited to 70 million km.

Russia, too, while lacking state-of-the-art equipment for the mass-scale detection of hazardous celestial objects, is making efforts to jump on the bandwagon. The wide-angle AZT 33VM telescope, a project of the Institute of Solar and Terrestrial Physics, Siberian Branch of the RAS (Irkutsk), with parameters only marginally worse than Pan-STARRS, appears to be the most promising. With a field of view of about 3 degrees and a primary mirror diameter of 1.6 m, AZT 33VM will be able to detect 24th stellar magnitude objects with an exposure time of 2 min.

Both in Russia and elsewhere, space-based NEO detection systems are being developed. These present major advantages over their Earth-based cousins and will already appear in space sometime within this current decade (for a more detailed discussion, see Ref. [1]).

The use of currently available astronomical instruments (or their networks) to monitor hazardous celestial objects is not so much a problem of technology as it is of organization. Thus far, no organizational 'interface' has been developed, which would allow these instruments (networks) to be used in the service mode, and it is precisely this mode — that is, a regular and standardized operation of observational systems involved — which is needed to solve ACH-related detection and monitoring problems.

The processing of information on the observed positions of NEOs is currently being carried out by the Minor Planet Center operating at the Smithsonian Astrophysical Observatory in Cambridge, MA, USA, which also identifies and assigns preliminary names to them, provides first preliminary and then more refined calculated results on their orbits, and publishes information on those objects for which additional observations are needed to confirm their discovery and to refine their orbits and other characteristics. The prediction of motion of potentially hazardous objects, the search for their close approaches to Earth, and the estimation of impact probabilities within the next few decades will be (and indeed are being) made at the Jet Propulsion Laboratory, Pasadena, CA, USA, and the University of Pisa, Italy.

In Russia, while a number of research institutes are concerned with exploring NEO motions, no measures have yet been taken on a systematic basis to achieve the country-wide integration of available information sources. The creation of a national information and analysis center for collecting and processing ACH-related information is at the top of the agenda.

3. Assessing risk

Assessing the degree of threat (or risk) is a crucial component of the ACH problem, because the underassessment or overassessment of risk leads to devastating consequences or huge material and social losses, respectively.

Two notions can be usefully introduced at this point: average impact risk, and a specific impact risk. The average degree of threat is calculated over a large time interval and, as we saw above, this background threat is moderate.

The degree of threat (risk) can be defined, to a first approximation, as the product of the impact probability and the severity of possible impact consequences. Although both are determined with a very large relative error, the risk must be evaluated opportunely and reliably. The reliable assessment of risk for a specific event (impact) and the timely delivery of an 'alarm signal' is what ACH science primarily is expected to provide — a task which requires a weighted and careful approach and which is another illustration of the high responsibility science has to society.

Put somewhat simplistically, the reliable assessment of risk factors is the responsibility of fundamental sciences: astronomy, in particular celestial mechanics, is expected to estimate the likelihood of a specific event (impact), whereas geophysics and physics of explosions, along with economic and social sciences, are responsible for assessing the impact consequences.

For risk assessment purposes, as far as PR is concerned, the so-called Torino scale is applied, which is similar to the white–red scale some countries use to categorize national threats. The Palermo scale, a more professional option introduced in Ref. [8], is the common logarithm of the relative risk R defined as $R = P_i(f_B \times DT)$, where P_i is the probability of a specific impact, DT is the time in years until the potential event, and f_B is the number of impact events per year with energy E (in TNT megatons) defined as $f_B = 0.03 \times E^{-4/5}$. That thus far no objects have been discovered to pose an alarmingly high level of risk is only due to our lack of knowledge. Whether applying the Torino or Palermo scale, the risk can be assessed only approximately. The calculation of a degree of threat for a specific impact is always individual in character.

Impact probabilities cannot currently be calculated without large errors. A review by the present author of some work on estimating the 2036 Apophis event risk revealed a spread in the calculated impact probabilities of as much as five (!) orders of magnitude. Clearly, to create a more reliable (certified) methodology, a critical overhaul is required, both of the mathematical methods used (in terms of their coordination) and in the description of the physical processes included in the models of motion.

Although time-proven approaches of classical celestial mechanics are of course being used to their full extent, even today there is still room for significant innovation in the field. A relatively recent example is the astronomical boom due to the widely recognized importance of the Yarkovsky effect and of its modification, the YORP (Yarkovsky–O'Keefe–Radzievskii–Paddack) effect for the evolution of asteroid orbits [10]. Some progress has also been made in calculating comet orbits, a very complex issue due to the large number of additional difficult-to-treat nongravitational factors (as exemplified by the fact that it is unrealistic, for a vaporizing comet, to calculate with high accuracy how the motion of its core is affected by the gas flow emerging from the core). This reasoning relates to the orbits of both the short-period and long-period comets. The appearance of the latters is currently unpredictable altogether.

Long-period comets are discovered at best a few months or a year before they appear in the vicinity of the Sun. As a typical example [11], for the comet C/1983 H1 (IRAS–Araki–Alcock), with an orbital period of 963.22 years, there was a mere two week gap between its discovery (27 April 1983) and its Earth flyby at a distance of 0.0312 AU (11 May 1983). Moreover, such comets have a large velocity relative to Earth, and their cores can disintegrate into large fragments. All this greatly complicates the problem of preventing comets from hitting Earth.

Along with the astronomical aspects, some of which have been considered above, of no less importance for developing adequate risk assessment methods is the accurate assessment of the consequences of a possible impact event. In doing such an assessment, a large number of specific factors should be considered, including the properties of the object, atmospheric entry conditions, the probable impact site, the date and time of the event, and ocean floor and beach profiles (an asteroid falling on sea can produce a tsunami!), plus adding a number of other important factors of an economic and social nature. Various aspects of the possible catastrophic consequences of an asteroid or comet hitting Earth are discussed in detail in monograph [12]. Note, however, that commonly accepted standards and procedures for reliably calculating risk are as yet unavailable, so efforts in this realm are clearly necessary. In this context, specialists from the Emergency Control Ministry of Russia (EMERCOM) and experts in natural disaster risk assessment have a crucial role to play (see, for example, Ref. [13]).

4. More aspects of the asteroid-comet hazard problem

The choice of measures to counter a space object impact threat should consider the size of the hazardous object and the warning time, i.e., the time available until the impact. There are two major methods to choose between destroying (disintegrating) the threatening object and deflecting (diverting) it from its orbit. If the warning time is large, say a few years or more, the current understanding favors the diversion scenario, whose implementation can be done in more than ten specific ways, according to experts.

In the short-warning low-mass case, breaking the object into smaller, nonthreatening pieces (using, for example, inertial mechanical dissectors) can be an option. For large masses, the only possible countermeasure is to disperse the object with nuclear (thermonuclear) explosions. An asteroid measuring more than 0.5 km across is a threat against which there is at present no defense. Importantly, the above methods need to be seriously worked out before being used. The consequences of an impact are still a matter of very large uncertainty. For more on that, see Ref. [1].

What is primarily needed to effectively address the ACH problem is cooperative efforts, both in Russia and internationally. In this context, the Expert Working Group on the Asteroid and Comet Hazard Problem was set up in 2007 at the Russian Academy of Sciences Council on Outer Space to coordinate research in this field in the country, which was transformed into the Expert Working Group on Space Threats early in 2011. The group comprised representatives from RAS research institutes, higher education institutions, the Russian Federal Space Agency (Roskosmos), EMERCOM, the Russian State Atomic Energy Corporation (Rosatom), the Russian Federation Ministry of Defense, and other interested agencies and organizations. Materials of the Expert Working Group are available at http://www.inasan.ru/rus/asteroid_hazard/.

The primary goal of the group was to conceptually develop an organizing program for a federal level ACH countermeasure system — somewhat analogous to the European Space Situational Awareness (SSA) program [14], under deployment since 2009.

The detection and monitoring of all hazardous objects, as well as their deflection (destruction) and the mitigation of damage they cause, are a challenge no country — even the most powerful one — can manage alone. The obvious areas where coordination is of particular importance are establishing a global network for detecting and monitoring hazardous objects and coordinating prevention and damage mitigation measures.

To prevent a threatening impact, an international decision-making procedure should be agreed upon and started under the aegis of the UN. In 2001, Action team 14 was established within the UN Committee on the Peaceful Uses of Outer Space for coordinating international efforts to address the ACH problem. The main task of the team is to prepare a document on interaction principles between states to be followed in organizing work on the ACH. A detailed discussion of the cooperation issue is given in Ref. [15].

5. Conclusion

This paper can obviously be summarized as follows:

(1) The ACH is quite a real problem and a serious global concern, and Russia cannot afford to sit on the sidelines.

(2) What science concerned with ACH has to provide first and foremost is reliable risk assessment for a specific event (impact) and a timely alarm signal. This requires a solid scientific approach and implies a very large responsibility to society.

(3) The physical sciences, particularly astronomy and geophysics, should play a dominant role in solving the ACH problem.

(4) The way things are in Russia, coordination on the part of the state is a sine qua non. For the project to be effective, a federal level program is needed.

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