Risks to the Earth from impacts of asteroids and comets

Dr Harry Atkinson, chairman of former UK government task force on the subject

Thirty years ago few took seriously the risk to mankind of impacts on the Earth of asteroids and comets, or "near Earth objects" (NEOs) – apart from a handful of dedicated astronomers. There seemed to be little evidence for such a risk: the craters on the Earth and the moon were generally thought to be of volcanic origin, not made by impacts; and while, since prehistoric times, comets must always have aroused interest, or even dread, their true danger was not understood. As for the main risk, asteroids, they were so small and dark that the first (and biggest) was not discovered until 1802. The first systematic survey of asteroids did not begin until 1970.

Two things brought home the potential dangers: first, a suggestion in 1980 by Alvarez (father and son) et al that the dinosaurs had been extinguished as the result of a large object hitting the Earth 65 million years ago; and second, in July 1994, the collisions of a succession of pieces of a large comet, Shoemaker Levy-9, with the giant planet Jupiter, each piece causing an explosion about the size of the Earth (Figure 1). This triggered the production of two films, Armageddon (with Bruce Willis) and Deep Impact, which made the idea of NEO impacts familiar to a much wider public – but may have registered more as science fiction, with a strong dose of "giggle factor". Arthur C Clark had already pointed to the danger of asteroids in his novel Rendezvous with Rama in 1973, and had coined the term "Spaceguard" subsequently used for surveys and by concerned organisations.

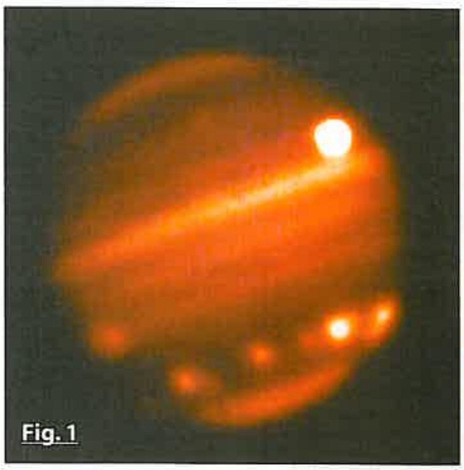
By the early 1990s, however, the US Government had become convinced that NEO impacts were science fact, not science fiction, and Congress initiated expert studies of both the detection and mitigation of NEOs. As a result, NASA was given the task of identifying, over a ten-year period, 90% of all asteroids of diameter greater than 1 kilometre. Observations for this "Spaceguard" survey began in 1998 using dedicated wide-angle US Air Force surveillance telescopes, of aperture 1 metre, each equipped with a large CCD detector array. About 500 of these really big NEOs have already been discovered, about half the estimated total number. The Earth is now seen as orbiting in a sea of near Earth asteroids, as graphically illustrated in Figure 2.

It is remarkable that no other government took the threat seriously – that is until the British minister for research, Lord Sainsbury, set up a task force in January 2000 to advise the government on the nature and risk of NEO impacts and on what the United Kingdom should do in an international context. (This followed the prompting of a British member of parliament, Lembit Öpik, whose grandfather had been an expert on comets and a distinguished director of the Armagh Observatory in Northern Ireland; and campaigning by Duncan Steel and Jay Tate).

The task force, which comprised Sir Crispin Tickell, Professor David Williams and myself (as chairman), reported in September that the risk was indeed real and comparable with other low probability but very high consequence risks taken seriously by governments. The threat from NEOs raises major issues, among them the inadequacy of current knowledge, confirmation of a hazard after initial observation, disaster management, methods of mitigation and deflection, and reliable communication with the public.

The recommendations of the task force covered both science and organisation: for science, that a dedicated international programme of advanced astronomical observations should be set up, particularly to increase knowledge of NEOs of smaller size (down to 300m or less) than those systematically covered by the US survey; these smaller objects can cause great regional or continental damage. For organisation, that steps be taken at government level to set in place appropriate bodies – international, European and in the UK – where all these issues could be discussed and decisions taken. In our view the UK and Europe generally are well placed to make a significant contribution to what should be a global effort.

On 24 February, the British government gave its formal response, welcoming the report and setting out an action-plan



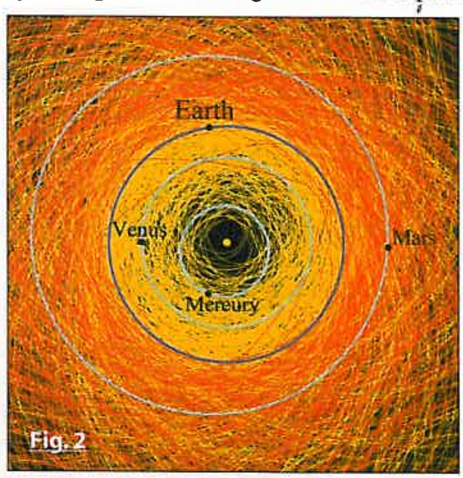


Fig. 1: Impact of comet Shoemaker-Levy 9 on Jupiter, July 1994. Before impact the comet broke into a number of fragments each hitting the planet in a different place, as shown by the belt of bright spots near the bottom of the picture. The impacts created fireballs as big as the Earth. The very bright spot at the top right is the Jovian moon Io. Photographed at infrared wavelengths from Hawaii. [acknowledgement: NASA]

Fig. 2: Orbits of the 800 or so near Earth asteroids of all sizes known at the beginning of the year 2000, with the Sun at the centre. The asteroids which cross the Earth's orbit are in yellow. They are potentially dangerous. The others, coloured red, approach the Earth but cannot strike it. The picture shows that the Earth is hemmed in by a sea of asteroids. [acknowledgements: Scott Manley (Armagh Observatory) and Duncan Steel (University of Salford)]

Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn:2001403

largely based on our recommendations. For international action, the OECD was suggested as a possible coordinating body.

Nature of hazard

Asteroids and comets are primordial material left over from the initial process of forming the solar system. Both types of object, in their millions and billions, normally orbit the Sun far away from the Earth. The asteroids are in a belt between Mars and Jupiter (2 to 4 Astronomical Units from the Sun, one AU being the Earth to Sun distance). The comets are much further away, either in the Edgeworth-Kuiper belt, 30 to 1000 AU from the Sun, or in the Oort cloud, a spherical shell of comets at the cold outer parts of the solar system at 40 to 100 thousand AU, nearly a quarter of the way to the nearest star.

Very occasionally, individual asteroids or comets are deflected by collisions or by gravitational forces into paths coming close to the Earth. The near Earth asteroids usually have orbits rather similar to that of the Earth, with periods of the order of a year; they are often stony (perhaps as groups of rocks held together only by their own weak gravitational forces), but can be carbonaceous or metallic. The near Earth comets, essentially "dirty snowballs", are in highly elliptical orbits with long periods ranging from scores of years (for example Halley's comet at 75 years) to periods so long that they are essentially "one-offs", like Hale-Bopp. These long period comets are totally unpredictable, and can be seen approaching no more than a year before possible collision, making them particularly dangerous. Fortunately, long-period comets are only a fraction of all comets; and comets in general are less numerous than asteroids: but comets travel faster and therefore have much more energy.

The Table shows that while global effects result only from the relatively small numbers of objects of diameter 1 km and above, the smaller ones are also extremely dangerous – and vastly more numerous. Even those of diameter between 30 and 100m, which do not normally reach the Earth's surface, can cause great damage through blast; an example is the 50m Tunguska object, of energy approaching that of the Bikini hydrogen bomb, which would have devastated a major city if differently placed. Two thirds of NEOs hit the sea: the serious effects of the resulting tsunamis cannot be over-emphasised, for example the Eltanin impact shown in Figure 3 (Ward and Asphaug, 2000).

Taking all sizes and impact frequencies into account, the risk of an individual's dying from NEO impacts over his or her lifetime is estimated at about 1 in 20,000. This is roughly the same as the risk of an average American dying in an aircraft accident. (Chapman and Morrison, 1994)

Nevertheless, the chance of impact of a 1 km NEO is seen from the table to be very small, on average only once every 100,000 years or so. It might be thought that this timescale is so long that the risk could in practice be dismissed. However, in other areas, such low probability but high consequence risks are taken very seriously indeed by bodies such as the British Health and Safety Executive. For example, the Sizewell B

Eltanin Asteroid Impact 2.16ma Tsunami Travel Time in Hours

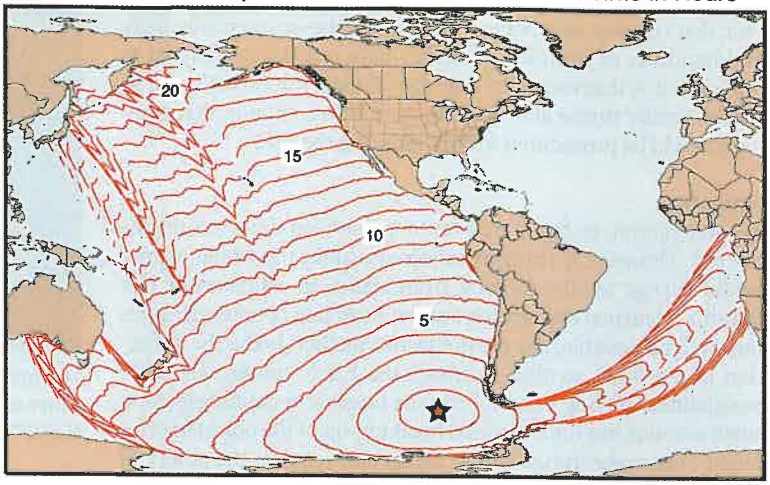


Fig. 3: Calculated progress of tsunami following impact (marked with a star) of a large asteroid, Eltanin, in the SE corner of the Pacific about 2.15 million years ago. Assuming a 4 km asteroid diameter, the initial "crater" in the ocean must have been 60km wide and 5 km deep; after 5 hours the resulting wave would have travelled 3000km and be 70m high. The evidence for the impact comes from the ocean floor which shows damage over hundreds of square kilometres.
[acknowledgement: Steven Ward/Eric Asphaug, Ucal Santa Cruz]

Numbers and effects of impactors of different size (diameter); few of those with sizes in the shaded area survive down to the Earth's surface.

Size	Number	Average interval between impacts	Energy (TNT equivalent Kilo- or Mega-tonnes)	Effect
3m	billions	weeks	2 KT	usually explode harmlessly in upper atmosphere without reaching the Earth's surface. Observed by US defence satellites. However, metallic asteroids can reach the ground; one such object exploded over the Yukon in January 2000, tripping the main electricity network over a wide area.
10m	150 million	decade	65 KT (6 Hiroshima A bombs)	ditto
30m	4 million	<100 yrs	2 MT	explode in upper atmosphere without reaching surface, but blast waves cause serious ground damage (eg Tunguska impact of 50m object in Siberia in 1908, which flattened 2000sq km of forest)
100m	100,000	3,000 yrs	65 MT (5 Bikini Hydrogen devices)	penetrate atmosphere. Serious damage on land; ocean impacts give tsunamis. On average, 5,000 deaths per impact
300m	6,000	40,000 yrs	2,000 MT	major sub-global effects including big tsunamis; half a million deaths probable
1 km	1,000	200,000 yrs	65,000 MT (1,000 Bikini)	global effects similar to "nuclear winter" calculated for all-out nuclear war. Local effects devastating; huge tsunamis if ocean hit. 1.5 billion deaths (quarter of world's population)
10 km	few	100 million yrs	65 million MT (1 million Bikini)	extinction of species (for example of the dinosaurs at the Cretaceous-Tertiary, K/T, boundary 65 million years ago). Most of world's human population would die.

nuclear power station in the UK was originally designed so that the risk of "melt-down" was less than once in 100,000 years. However, that risk was subsequently thought to be unacceptably high, and hundreds of millions of dollars have recently been spent to reduce it. It is interesting to note that if the 1 km object (with its risk of similar timescale) were "owned" by a company, that company would be prosecuted for not reducing the risk.

Mitigation

My assumption, so far, is that nothing has been done to mitigate the risk. However, if mitigation were possible, the whole picture would change totally, moving from statistical estimates of risk towards calculated certainties. Studies show that countermeasures may well be possible, the most effective method being the deflection of the NEO so that it misses the Earth entirely. Of other possibilities, moving people from the target area could help, for a small asteroid, but uncontrolled breaking-up of the object in orbit might only make things worse. Deflection requires the ability to change the object's momentum in orbit. Many ways for doing this have been considered, from solar-sails using the Sun's radiation pressure to high-powered laser beams. At present the only practical approach seems to be to use nuclear explosives. Unfortunately chemical explosives are far too heavy to deliver the punch required. Some tonnes of nuclear explosive would be required to deflect a large asteroid. Current large rockets are capable of launching such a charge in a suitable spacecraft.

Although suitable nuclear charges, designed rather differently from nuclear weapons, have not been made or tested, most of the other technologies required have already been used, for example in the recent Shoemaker-NEAR mission to Eros (Figure 4) in which, for about a year, the spacecraft tracked the asteroid in its orbit around the Sun, much of the time slowly orbiting Eros often only a few tens of kilometres from its surface; finally, early this year, the spacecraft landed safely on the asteroid – after transmitting an unprecedented amount of information about the nature of the object. Going even further, NASA's Deep Impact spacecraft will launch a 1/2 tonne copper projectile at a comet (Figure 5), ejecting material to form a crater more than a hundred metres across and "seven stories deep". The objective is to learn about the inner structure of the comet – but the impact will, incidentally, deflect the comet slightly.

In deflecting an object, it is most important to know its composition and gross structure. As already said, many asteroids are essentially piles of stones: these will simply fly apart unless relatively gentle forces are applied (with accelerations less than 1 metre per second). For this reason the asteroid may need a succession of nudges over a period of time from a succession of nuclear charges. Each charge would be detonated within a radius or two of the object; the x-rays and neutrons from the explosion will eject material from the asteroid's surface, causing it to move in the opposite direction.

While deflection is thus theoretically possible, the use or even testing of nuclear explosives in space would raise serious political problems. Indeed, the use of such means might only be contemplated if a major impact were otherwise inevitable.

It may be worth noting that for no other major natural hazard – for example volcanic action, earthquakes or tsunamis from landslips – may it be possible to act so as to obviate the hazard completely.

Recommendations: more science; international organisation

Essential prerequisites to mitigation are the discovery of the NEO well in advance of possible impact, the accurate determination of its orbit and its composition. That is why the task force gave top priority to a comprehensive survey of objects smaller than those being observed by NASA, going down to diameters of 300m or less; only a tiny proportion of such objects have so far been observed. This needs, on the ground, at least one dedicated wide-angle 3m-class telescope for discovery (preferably through European cooperation), and conventional telescopes for accurate orbit determination and spectroscopic observation of the NEO's composition. Space missions are also most important. We have pointed out the potential value of the ESA missions BeppiColumbo and GAIA for the discovery of NEOs, and have recommended the use of relatively cheap "micro-satellites" to rendezvous with different types of asteroid and comet and gather detailed information at first hand. These would greatly extend the work done by, or planned for, the major rendezvous missions of NASA or ESA. Finally, we recommended multi-disciplinary studies to learn more about the consequences of impacts. The studies would involve astronomers, geophysicists, oceanographers, climatologists, economists and sociologists, and also universities, national research councils and the European Science Foundation.

The above paragraph summarises the task force's first eight recommendations for an enhanced international observational and

Fig. 4: Asteroid Eros, shaped like a potato, is about 33 kilometres long, 13 kilometres wide and 13 kilometres thick. The crater at the top is 5.3 km in diameter. Most known near Earth asteroids are less than 1 kilometre across, much smaller than Eros. Picture taken in February 2000 by NASA's Shoemaker-NEAR spacecraft orbiting Eros at 200 km above its surface. The numerous impact craters show that even asteroids are hit by other asteroids many times in their history. [acknowledgement: NEAR/NASA]

Fig. 5: NASA's Deep Impact mission will project a 500 kg solid mass into a comet (artist's impression) in 2004. A flyby spacecraft will take images and make measurements. The impactor will also take images of the comet's surface prior to impact. The mission aims to increase understanding of the composition and structure of comets. [acknowledgement: Ball Aerospace & Technologies Corp]

scientific programme. Regarding mitigation, we recommended that the UK government, with other governments having the necessary technology, should set in hand studies to look into the practical possibilities of countermeasures, both mitigation of impacts and deflection of incoming objects.

Finally, we made the following recommendations regarding organisation (of which the first two are given in full):

> that the government urgently seek with other governments and international bodies (in particular the International Astronomical Union) to establish a forum for open discussion of the scientific aspects of NEOs, and a forum for international action. Preferably these should be brought together in an international body. It might have some analogy with the intergovernmental Panel on Climate Change, thereby covering science, impacts, and mitigation (including countermeasures). (Recommendation 10)

> that the government discuss with like-minded European governments how Europe could best contribute to international efforts to cope with NEOs, coordinate activities in Europe, and work towards becoming a partner with the United States, with complementary roles in specific areas. We recommend that the European Space Agency and the European Southern Observatory, with the European Union and the European Science Foundation, work out a strategy for this purpose in time for discussion at the ministerial meeting of the European Space Agency in [November] 2001. (Recommendation 11)

Regarding organisation in the UK, the task force recommended that overall responsibility be assigned to a single government department; and, most importantly, that a British national centre be created to provide independent scientific advice to the public, parliament, and the government (Recommendations 10 to 14).

The British government has taken a major step forward in its response to the report of the task force. As said in the response, negotiations with and between international institutions, and analysis of complex scientific proposals, take time. It is welcome news that the government has therefore undertaken to provide a further report later this year on its progress in implementing its plans. There is still much to be done and I await further progress in this vital area.

Further reading

Atkinson HH, Tickell C and Williams DA (2000), Report of Task Force on Potentially Hazardous Near Earth Objects, British National Space Centre, London SW1W 9SS. (An electronic version of the report and of the Government's response, together with links to other useful web sites, are on: www.nearearthobjects.co.uk

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Ward SN. and E. Asphaug E (2000), Asteroid Impact Tsunami: A probabilistic hazard assessment, Icarus, 145, 64-78 (and other papers)