Asteroids threatening Earth

The Key to Apophis

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Academia magazine
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Over 100 metric tons of interplanetary matter enter the Earth's atmosphere every day, mostly consisting of dust and tiny rock fragments. However, around once every few hundred thousand years an object larger than 1 km in diameter collides with our planet, with the impact able to destroy a large country

Fortunately it is now possible to predict the threat of a large asteroid impact long in advance. For the past decade and a half, our skies have been constantly monitored, keeping an eye out for any objects that might pose a threat to our planet. There are various research programs that aim to survey various small celestial bodies present in our solar system, in particular those in the closest proximity to Earth - these programs include Spacewatch, LINEAR (*Lincoln Near-Earth Asteroid Research*) and CATALINA (*Catalina Sky Survey*). The latter has been operating for a few years now and is currently the most effective in the discovery of NEOs (*Near Earth Objects*). Thanks to these intensive efforts to search for asteroids that could come into close Earth proximity, it is estimated that that we are now aware of over 80% of the largest such objects - i.e. those larger than 1 km across.


Don Davis

Comets and asteroids have collided with Earth since its formation, and may have been responsible for bringing in part of Earth's water

Dangerous asteroids

Today the list of PHAs (*Potentially Hazardous Asteroids*), updated daily by NASA at http://neo.jpl.nasa.gov/risk, includes almost 300 objects. One of the highest-ranked objects is asteroid 99942 Apophis, which stirred up considerable concern for several months after its discovery in 2004, as it carried the greatest collision risk of all substantially-sized objects known at the time. However, November 2007 saw the discovery of asteroid 2007 VK_{184}, whose risk of colliding with Earth in 2048 is estimated at 1:3000, currently the highest known chance of collision. Even so, Apophis remains one of the most dangerous objects. The asteroid is almost 300 meters across, and in April 2029 it will pass by the Earth at a distance just several times larger than our planet's radius. Apophis' orbit will be significantly altered by this extremely close flyby. The uncertainty in defining its subsequent orbital parameters will worsen by a few of orders of magnitude. Will this change increase the risk of the object's collision with the Earth in the future? Before making any judgments here, let us first look more closely at this unusual asteroid.

Apophis' recorded history begins on 19 June 2004, when it was discovered by a routine asteroid-searching program. NASA's first predictions, announced on Christmas Eve 2004, estimated the probability of its early collision with the Earth at a quite high 1-in-300 chance. This estimated probability increased over the following days, eventually reaching 1:35. And although current estimates of the likelihood of collision are much lower, the asteroid earned the ominous name given to it on 19 July 2005 with very good reason. In ancient Egyptian mythology, Apophis or Apep was the demon of darkness, nothingness and chaos, occasionally identified with the god Set. He was the complete antithesis of light, i.e. the sun god Ra, and his eternal and sworn enemy.

Apophis' celestial namesake is one of the Aten asteroids, which orbit the Sun in less than a year and spend most of their time closer to the Sun than the Earth. Apophis


ESO

Asteroid sizes vary from ten to several hundred kilometers. Some are binary systems, such as Antiope (pictured here)

takes 323 days to fully orbit the Sun, with its orbit inclined 3 degrees to the ecliptic plane. During each orbit Apophis pierces the ecliptic plane twice (at what are known as *orbital nodes*), while simultaneously intersecting the Earth's orbit. Apophis' most spectacular proximity to the Earth will occur on 13 April 2029, when it will draw very near to our planet while crossing the ecliptic plane. It will flit by a mere 6 Earth radii from the Earth's surface - slightly closer than the distance of geostationary satellites that transmit TV signals. During this flyby the asteroid will be visible to the naked eye as a point of light similar to a somewhat dim star (of apparent magnitude 3).

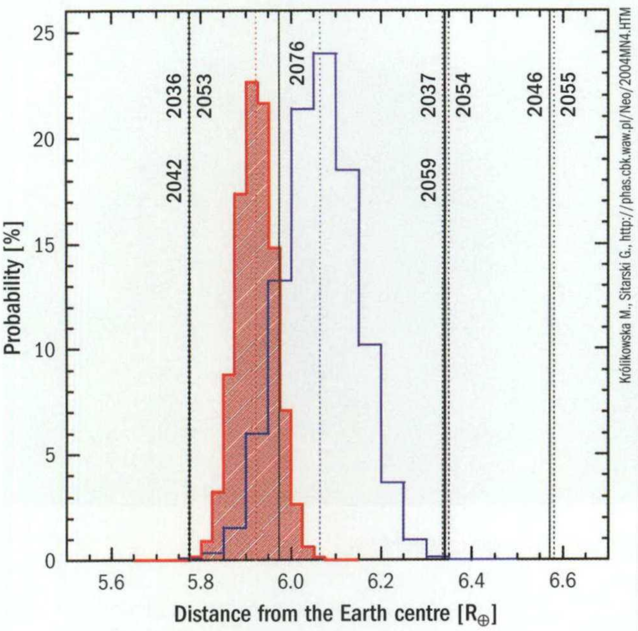
Collision course?

Should we be afraid of such a near miss? Today's estimates suggest that the Earth experiences this kind of close encounter with such a substantial asteroid slightly less often than once every thousand years. Apophis will still stay far enough from the Earth to keep the flyby uneventful. But be that as it may, the precise parameters of the event will have a key bearing on the asteroid's future course, as such close proximity on 13 April 2029 will cause significant changes to Apophis' orbit. It is possible that the flyby could put the asteroid into orbital resonance with the Earth (this occurs when two bodies exert a regular, periodic gravitational influence on each other, usually due to their orbital periods being related by a ratio of two small integers), resulting in an increased likelihood of possible future collisions with our planet starting from 2036. Such a threat may occur if the asteroid passes through what is called a *gravitational keyhole* during its flyby - a small region of space where Earth's gravity could alter the asteroid's course to put it on a collision course with the Earth during a future orbital pass.

Today it appears that there may be several such keyholes for Apophis, although their diameters range between a few hundred meters and a few kilometers, depending on how such keyholes are defined. Are we currently able to predict Apophis' orbit in 2029 with such precision? That task is made more difficult by the fact that the asteroid's current position with respect to the Earth will keep it out of reach for new observations until 2011. We have over 1000 positional and 7 radar observations collected between March 2003-January 2009 (some of them actually having been discovered in data gathered prior to the asteroid's discovery). Research is ongoing to improve the precision of our predictions for the geometry of the greatest proximity in April 2029, and the subsequent trajectory of the asteroid.

Predicting the flyby

Małgorzata Królikowska (one of the present authors), Grzegorz Sitarski, both from the Space Research Centre (Polish Academy of Sciences), and Andrzej M. Sołtan from the Nicholas Copernicus Astronomical Centre (Polish Academy of Sciences) form one of the teams that carries out this type of research. For our calculations, we decided to model the asteroid's motion based on existing observational data. The main purpose of the study was to investigate how different methods of selecting and weighing observational data influence evaluations of the likelihood of Apophis and Earth colliding. We took account of the gravitational influences of planets and the four largest asteroids - Ceres, Pallas, Vesta and Hygeia. Based on simulations of over 15 thousand orbits (known as virtual orbits), varying slightly in parameters (orbital elements), we have been able to establish that the asteroid will most likely pass by at a distance of $6.064 \pm 0.095\ R_e$ (Earth radii) from the center of our planet in April 2029. Unfortunately the uncertainty still inherent in this flyby prediction, although only 1.5%, leaves open the possibility that the asteroid could pass through a gravitational keyhole. A 2029 flyby distance of 5.7736-5.7763 R_e will put the asteroid on a path to either pass extremely close to the Earth or crash into it in 2036, whereas a 2029 flyby



Probability distribution of Apophis' minimum distance from the centre of the Earth at the point of closest proximity on 13 April 2029, calculated using the Monte Carlo method. The blue histogram shows results based on a shorter observational range (2004/03/15-2006/08/16) and the dashed red histogram shows those based on the current range of available data (2004/03/15-2008/01/09). Vertical lines represent gravitational keyholes, marked with dates of possible future collisions. The possible collision in 2076 could only occur if preceded by a flyby at a very precise distance in 2051. Thus the 2029 keyhole for the collision in 2076 is extremely small and the probability of such a collision occurring turns out to be significantly smaller than the probability of one in 2036

distance of 6.3359-6.3488 R_e will put it at risk of such an extremely close orbital pass or crash in 2037. Fortunately the most likely minimum distance of the 2029 flyby lies between those critical values, yet we still cannot rule out the possibility that Apophis might indeed pass through one of these small yet dangerous keyholes. In addition, a 2029 flyby at a distance of 5.97347 R_e could entail a future collision in 2076, although such a collision is far less likely as it moreover relies on the asteroid passing by the Earth at a certain, very specific distance in 2051.

Furthermore, as mentioned earlier, our work has shown that the estimation of collision probabilities in subsequent years does significantly depend on the method of selection and weighing of observational data, although this variation does not exceed 0.0005%. Our calculations were carried out on the basis of unique methods of selecting virtual orbits and obtaining collision orbits devised by Professor Sitarski from the Space Research Centre of the Polish Academy of Sciences. The uncertainty of orbit prediction is further increased by the fact that our knowledge of Apophis' shape and surface is insufficient to be included in simulations of non-gravitational effects of its motion, such as the influence of radiation pressure exerted by the Sun's rays on its motion and the asteroid's own radiation emissions. So, given all these uncertainties, is there really anything to be afraid of?

Dangerous impact

The asteroid's diameter is around 270 m, therefore its impact could release energy equivalent to 510 thousand metric tons of TNT, i.e. tens of times greater than that released during the Tunguska event over Siberia in 1908. Nevertheless the impact would not threaten the entire Earth, but catastrophically affect at most a large fragment of one of its continents. We are still awaiting further observations which will allow us to predict the dangerous asteroid's future course more precisely. The next available opportunity for observation will occur in 2013 when Apophis will pass Earth at a distance of around 14.4 million km. This will allow us to carry out further radar measurements of its distance from Earth at the time of observation. What if these results still prove inconclusive? In such an event, an extraordinary mission may be sent out towards the asteroid.

Heading to the source

In 2007 the Planetary Society announced a contest for the best mission concept that may help us learn more about Apophis. This contest was won by the Foresight mission, envisioning that a probe could be released towards Apophis between 2012-2014, to reach the asteroid around 10 months later. Weighing in at 220 kg, the probe would carry research instruments and a radio transmitter that would allow Apophis' trajectory to be traced more precisely. It should allow for great precision: if in 2017 Apophis' position is known to the nearest tens of meters and its velocity to the nearest thousandth of a millimeter per second, the uncertainty of the distance at which it will pass Earth in 2029 can be reduced to less than 14 meters, which means a 50-fold improvement over current estimates. So far no one has committed to funding the mission, although its development may be taken under consideration during preparation for other planned studies: the NASA Orion Asteroid Mission, the plans for which include manned studies of an asteroid, and an unmanned Don Quijote probe to be sent out by the European Space Agency. Will the results of these or other missions help us predict Apophis' future? Every effort certainly needs to be made to improve our understanding of this dangerous asteroid. ■

Further reading:

Królikowska M., Sitarski G., Sołtan A.M. (2009). How selection and weighting of astrometric observations influence the impact probability. The case of asteroid (99942) Apophis. *Mon. Not. r. Astron. Soc., 399*, 1964-1976.
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