National Aeronautics and Space Administration

(99942) Apophis: Complex Rotation and Hazard Assessment

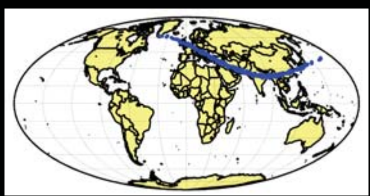
D. Farnocchia[1], D. Vokrouhlický[2], D. Čapek[3], S.R. Chesley[1], P. Pravec[3], P. Scheirich[3], T.G. Müller[4]

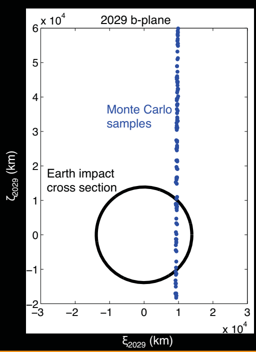
[1]Jet Propulsion Laboratory, California Institute of Technology; [2]Institute of Astronomy, Charles University; [3]Astronomical Institute, Czech Academy of Sciences; [4]Max-Planck-Institut fü extraterestrische Physik

Apophis is one of the most remarkable near-Earth asteroids in terms of impact hazard. In 2004 the probability of an impact in 2029 reached a peak of 2.7%. With the data available today we know that Apophis will pass Earth safely in 2029 at about 38,000 km. However, despite the availability of a well observed arc and three radar apparitions, the 2029 Earth encounter has such a strong scattering effect on the trajectory of Apophis that post-2029 predictions are only possible in a statistical sense and impacts in the following decades are hard to rule out.
To predict the future ephemerides of Apophis the dominant source of uncertainty is the Yarkovsky effect, a small nongravitational perturbation that arises from the anisotropic re-emission at thermal wavelengths of absorbed solar radiation. Modeling the Yarkovsky effect acting on an asteroid is generally challenging, as we need a good knowledge of the asteroid's physical model or observable deviations from a purely gravitational trajectory. A further complication comes from the complex rotation state of Apophis. We use the available information on the physical properties of Apophis, e.g., shape, size, thermal inertia, and rotation state, to estimate the Yarkovsky effect by solving the nonlinear heat transfer equation on a finite-element mesh of facets model of the shape of Apophis.
We find that the Yarkovsky perturbation significantly affects the trajectory of Apophis, thus contradicting the idea that a complex rotation state implies an insignificant contribution of the Yarkovsky effect. We analyze the implications on the hazard assessment by mapping the orbital uncertainty to the 2029 close approach and computing the keyholes, i.e., the locations at the 2029 Earth encounter leading to a resonant impact at a future close approach. Whereas collisions with Earth before 2060 are ruled out, impacts are still possible after 2060 with probabilities up to few in a million.

The December 2004 hazard assessment

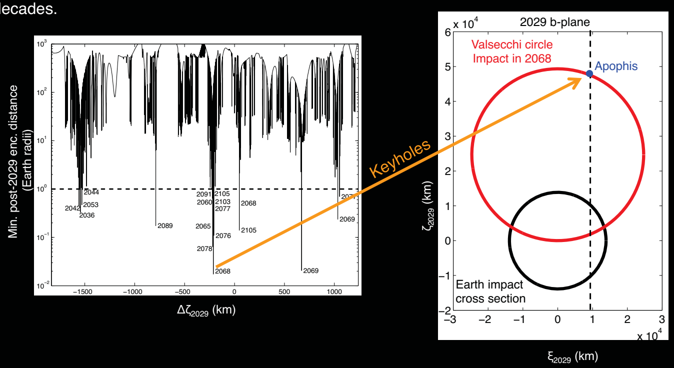
Asteroid (99942) Apophis was discovered on 2004 June 19 by Tucker, Tholen, and Bernardi, but quickly became lost until it was rediscovered on 2004 December 18 by Garradd. At that point it was immediately clear that Apophis would make a close Earth encounter in April 2029 with significant chances of an impact. For several days, additional observations increased the impact probability up to a peak of 2.7%.





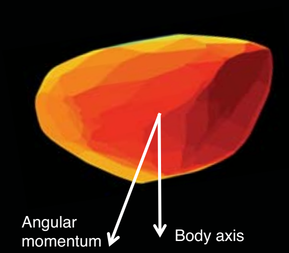
Possibility of post-2029 impacts

Precovery observations from March 2004 obtained by the Spacewatch survey ruled out the 2029 impact. Thanks to radar observations from 2005, 2006, 2012, and 2013 as well as optical data through 2014, we know that Apophis will pass Earth safely at about 38000 km in 2029. However, this close encounter has such a strong scattering effect on nearby orbits that the post-2029 trajectory can only be known in a statistical sense and impacts are possible in the following decades.



For Apophis the ephemeris uncertainty is dominated by the Yarkovsky effect, a subtle nongravitational perturbation that mainly acts as a semimajor axis drift da/dt. While the gravity-only positional uncertainty in 2029 is only 7 km, the Yarkovsky effect can produce orbital deviations of hundreds of kilometers.

Apophis' physical model



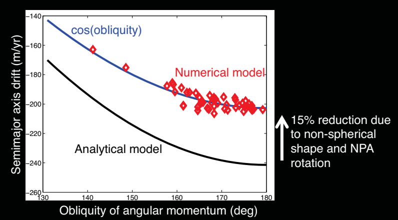
Mueller et al. 2014, infrared observations
- Diameter 375 ± 15 m
- Thermal inertia 250—800 SI

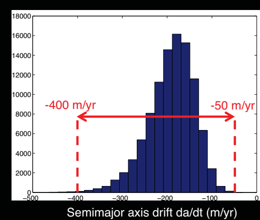
Binzel et al. 2009, spectral observations
- Sq taxonomy
- Density 1.3—3.5 g/cm^3

Pravec et al. 2014, photometry
- Absolute magnitude 19.1 ± 0.2
- Shape model
- Non-principal axis rotation
- Obliquity of angular momentum 157°—172°

Yarkovsky effect modeling

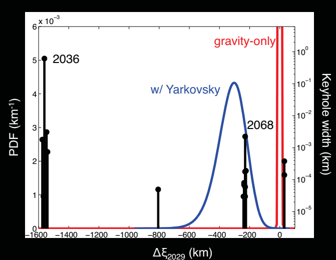
To fully capture the physical properties of Apophis and its non-principal axis (NPA) rotation state, we numerically solve the heat transfer problem on the facets of Apophis' shape model. The solution is computed in an iterative way starting from a uniform temperature on the surface. Upon convergence, we compute the overall thermal recoil acceleration and derive the average da/dt.





Hazard assessment

We apply a Monte Carlo method where we randomly sample the semimajor axis drift according to Yarkovsky modeling and the orbit from the least squares fit. Each sample is propagated to 2029 to obtain a distribution for ζ_{2029}.
The integration of the ζ_{2029} distribution over the keyholes gives the impact probability (IP) for future encounters.



Year	IP × 10^6
2060	0.1
2065	0.3
2068	6.7
2076	0.5
2077	0.2
2078	0.2
2091	0.2
2103	0.5

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
www.nasa.gov