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UPDATED ORBIT OF APOPHIS WITH RECENT OBSERVATIONS

D. Bancelin[1], F. Colas[1], W. Thuillot[1], D. Hestroffer[1] and M. Assafin[2]

Abstract. Asteroid Apophis (previously designed 2004 MN4) was first discovered in June 2004. From its first observations, Apophis was revealed to be a special study case in as much as, it reached the level 4 of Torino scale with a high probability of collision in 2029. New observations eliminated all danger for 2029. But, because of a deep close encounter in 2029 (~38000 km), the asteroid will be put on a chaotic-like orbit and some risks of collision in 2036 occur if the asteroid goes through a very small region called keyhole. Now, its orbit is quite well known and thanks to additional observations, the risk for the short term seems to disappear. But what about the long term? As far as the Earth-impact threat study is concerned, the deep 2029-close encounter is an opportunity for space missions towards Apophis. With our technologies, to deflect an asteroid, we can only act from the source. Many deflection missions were studied, from the hardest (nuclear weapons), to the softest (shadow mission). But in order to prepare such missions, we have to be sure that the asteroid is really on an impact trajectory. Moreover, if it is the case, we have to be sure that it won't be put on the trajectory of other keyholes. To this aim, we need a good knowledge of the 2029 region uncertainty and we will analyse the impact of the new observations of March 2011.

Keywords: PHAs, Apophis, b-plane, keyhole, ellipse uncertainty, astrometry

1 Introduction

Near-Earth Asteroids (NEAs) are objects orbiting near the Earth orbit. They are transient bodies that come from the Main Belt Asteroids (MBA). They are generally transported through an interplay of collisions, non-gravitational forces drift and secular resonance, among other sources. NEAs are generally classified into four dynamical families: the Apollos and Atens asteroids that cross twice the orbit of the Earth; the Amors and Atiras which orbiting respectively above and under the Earth's orbit. Among those four categories, some of them can become threatening for the Earth. They are called Potentially Hazardous Asteroids (PHAs) because they can come very close to the Earth. Those objects are characterized by a MOID<0.05 AU (Minimum Orbit Intersection Distance (Gronchi 2005)) which acts as a warning indicator and an absolute magnitude H<22. Objects in this category will be under surveillance and will need special monitoring.
Among the known PHAs, asteroid (99942) Apophis is the more emblematic. It belongs to the Aten family and it is the closest approacher to the Earth in as much as it will pass at about 38000 km from the Earth's center in April 2029. It will pass below the position of geosynchronous orbit and will be visible to naked eye. Apophis became a study case since its discovery in that, it remained dangerous for few days because of a possible impact with the Earth in 2029, with an unprecedented probability estimated to 2.7%. Since, additional observations ruled out every possibility of impact in 2029 but others remain in the future. The most popular one is the 2036-threat, but at the epoch of October 7th 2009, chances of crashing were estimated at 1/250000 by the Sentry/JPL website*.
The last observation of Apophis was done in 2008. After a long period of unfavorable conditions for observations, Apophis has been re-observed in March 2011 at Pic du Midi observatory (French Pyrenean) and Magdalena Ridge Observatory (New Mexico). We report here the new orbit obtained from the adjustment of all data available at MPC† and new sketch of impacts for the next century. We will also discuss on other sources of uncertainty remaining on Apophis's orbit.

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*http://neo.jpl.nasa.gov/risk/
†http://www.minorplanetcenter.net/

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2 2029-close encounter study

During the 2029-close encounter, the gravitational perturbation of the Earth will be so important that the trajectory of Apophis will be very altered. As a matter of fact, the perturbation will be so deep that Apophis will move from the Aten (defined by the semi-major axis a< 1.0 and aphelion Q> 0.983) to the Apollo family (defined by a> 1.0 and perihelion q≤ 1.017) (Fig. 1).

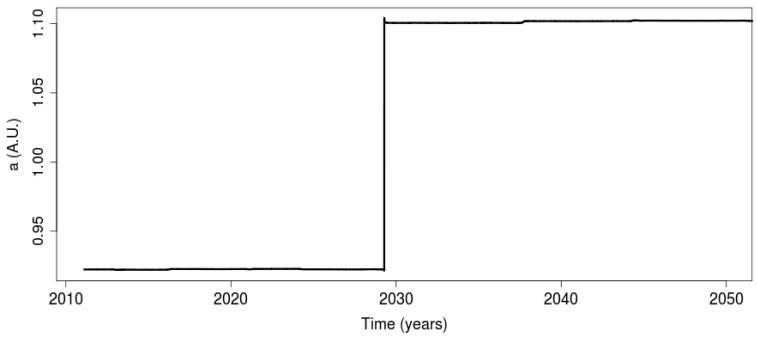

Fig. 1. Time evolution of the semi-major axis of Apophis. The deep close encounter in 2029 will lead to a dynamical change on Apophis's dynamic. It will go from the Aten family (a< 1.0) to the Apollo family (a> 1.0).

Because of this strong deflection, Apophis 2029-post orbit will be chaotic-like. As a matter of fact, a small change on the initial orbital elements or on the dynamical model used will lead to a certain uncertainty on Apophis's location after 2029. We do expect both asteroid and the Earth to meet again in the future after k revolution of Apophis around the Sun and after h years. Those encounters are called *resonant return* (Valsecchi et al. 2003) and are defined by:

$$k \times T_{ap} = h \times T_{\oplus}$$

where T_{ap} is the 2029-post period of Apophis and $T_{\oplus}$ the period of the Earth. Using this relation, we can find the date of resonant return and the 2029-post period range of Apophis associated. Tab. 1 shows some resonant returns some years after the encounter.

Table 1. Resonant returns after the 2029-close approach. The period range correspond to the 2029-post period that Apophis should have in order to meet Earth again.

Year	Resonance	2029-post period range [days]
2034	4:5	[456.2:456.9]
2035	6:5	[437.9:438.6]
2036	7:6	[425.7:426.5]
2037	8:7	[417.1:417.8]
2038	9:8	[410.5:411.3]
2046	17:15	[413.6:414.3]
2048	19:17	[407.9:408.6]
2051	22:19	[422.5:423.3]

As observations contain errors (assumed as gaussian), the orbital elements obtained from the least-squares method will be given with their uncertainties provided by the covariance matrix. This matrix gives the 6-dimensions region of confidence of the orbital elements. When this region is small, this region can be approximate to an ellipsoid. When propagating this covariance matrix, it is possible to estimate the uncertainty related to the distance of closest approach in 2029. To better represent this uncertainty, we can study the geometry of

the close encounter in the b-plane[‡] (Valsecchi et al. 2003). This plane better represents the state of an asteroid approaching the Earth. It passes through the Earth's center and is perpendicular to the geocentric velocity of the asteroid. Thus, the object will have two geocentric coordinate (ξ,ζ) and the projection of the ellipsoid uncertainty in this plane is an ellipse centered on the nominal value of (ξ,ζ). Its semi-major and semi-minor axis are given respectively by the $3\sigma_\zeta$ and $3\sigma_\xi$ standard deviations. Thus, the distance of closest approach is given by $\sqrt{\xi^2+\zeta^2}$. Besides, while some resonant returns lead only to close approaches, others can lead to collision. Using Monte Carlo technique for sampling virtual asteroids (VAs) in the region of confidence, each VAs propagated can become virtual impactors (VIs) if they can reach a distance close or less to the Earth radius. To estimate the risk of collision, it is thus possible to find the region in the sky where all VIs have to pass in order to collide the Earth in the future. Those regions are called *keyholes*. They are narrow regions and the most famous keyhole of Apophis is the 600 meters 2036-keyhole. Keyholes can be primary when they are the consequence of one close encounter, and secondary when they are the consequences of two consecutive close encounters. VIs can also impact at both ascending or descending node. Thus, it is possible to map the uncertainty region and the location of the keyholes' center in the 2029-b-plane. Fig. 2 shows the 3σ ellipse uncertainty which size is $(3\sigma_\xi;3\sigma_\zeta) = (12;73)$ km. The distance of close approach is ~ 38080 km and the position of keyholes are also indicated.

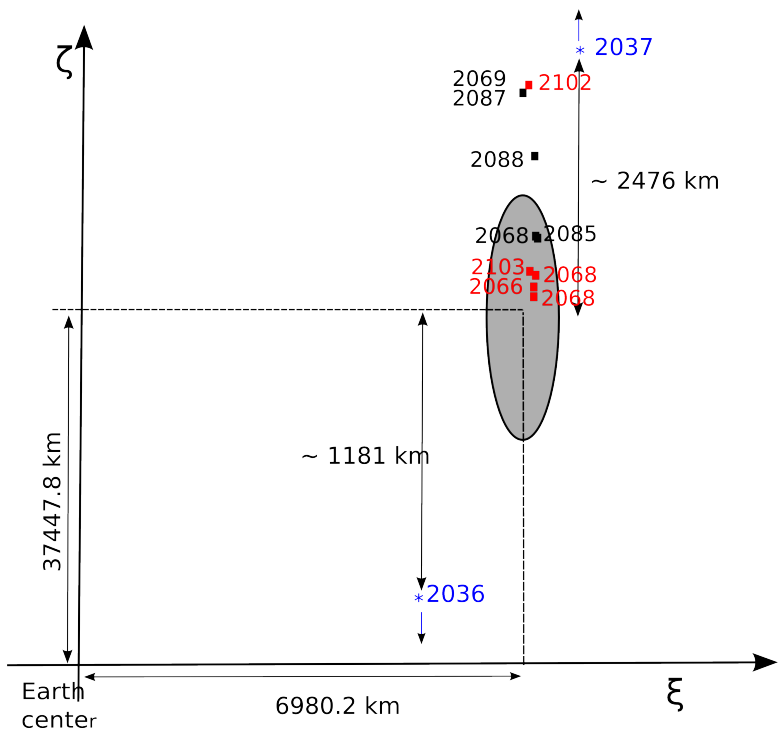

Fig. 2. 2029-b-plane of Apophis. The coordinates of the ellipse's center are indicated as well as the location of the center of primary (★) and secondary keyholes leading to collision at ascending node (■) and descending node(■). The position of the famous 2036-keyhole is also indicated.

The size of the ellipse uncertainty, its position and the location of keyholes depend on the observations available, their accuracy and the data arc length. Of course, keyhole have fixed position and when new observational data are added, the position of the ellipse can shift and thus get closer or go away from some keyholes. The next section will treat this case for the new optical data of March 2011. The dynamical model used for all computations includes all planets, the Moon, relativistic perturbations and the gravitational perturbations of Ceres, Pallas, and Vesta. The numerical integration was performed with a Lie series integrator (Bancelin et al. 2011).

[‡]Also called target plane

3 Observations of March 2011

Apophis was observed at Pic du Midi Observatory located in the French Pyrenean mountain (altitude 2800 m) with a 1meter telescope. The conditions of observation were quite challenging because, the asteroid was visible in the sky with a magnitude of 21 with a high velocity ~ 2.7 arcsec/min and according to the IMCCE website[§], the solar elongation was around 49°. A preliminary astrometry of the CCD images was made using Astrometrica Tool[¶] and the mostly used USNO-B1.0 catalog was chosen for the positions reduction. A new orbital solution and covariance matrix was thus provided using OrbFit package[‖] and thus, the propagation of this new solution and the matrix will give us the new position of the asteroid and the ellipse uncertainty in the 2029-b-plane. On Fig. 3 are represented both ellipses computed without March 2001 data (blurred ellipse) and with March data (solid ellipse). One can see that the new ellipse is upper-shifted and there is no overlap between those ellipses. As a matter of fact, our results show that Apophis seems to pass ≈ 600 km further that the distance previously computed. Besides, those new observations enable to reduce the uncertainty of the ellipse which size is $(3\sigma_\xi;3\sigma_\zeta) = (9;46.5)$ km.

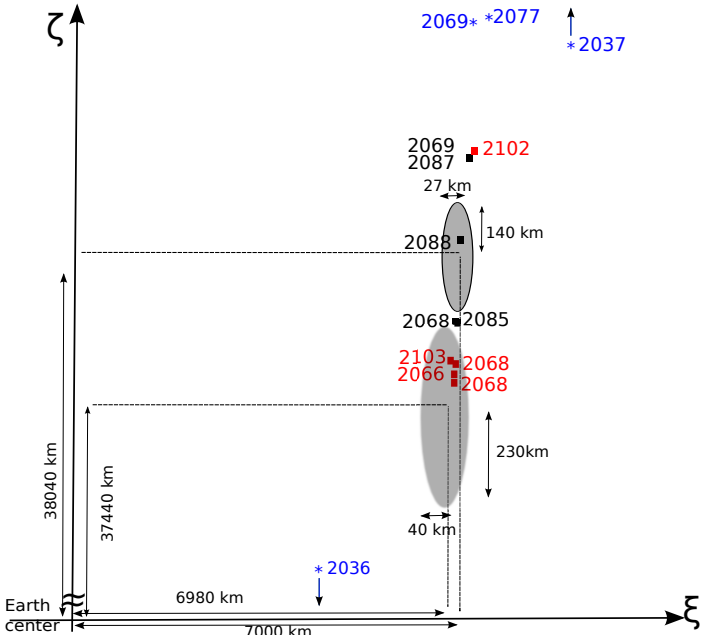

Fig. 3. 2029-b-plane of Apophis. The blurred ellipse was computed using data spanning 2004-2008 and the solid one was computed using 2004-2008 data and March 2011 observations.

Because of this, Apophis seems to move away from 2036-keyhole and to get closer to 2037-keyhole. The new relative positions of those keyholes are indicated in Tab. 2.

Table 2. Relative positions of 2036 and 2037 keyholes from the nominal ellipse center, without and without March 2011 observations.

	Without March data	With March data
2036	1181 km	1781 km
2037	2476 km	1875 km

This new scenario gives a new sketch for impact probabilities because of the vicinity of other keyholes. Tab. 3 gives the relative distance of the center of the closest keyholes from the center of the ellipse as well as there size

[§] http://www.imcce.fr
[¶] http://www.astrometrica.at/
[‖] http://adams.dm.unipi.it/orbfit/

(when it can be determined) and the related impact probability. When the size is set to < 1 it means that only one impact point has been found.

Table 3. Position of the closest keyholes from the center of the ellipse uncertainty. Their size are also indicated as well as their impact probabilities. The color code is the same as on Fig. 1

	Distance from ellipse center (km)	Keyhole size (m)	Impact probability
2068	250	< 1	9.5e-08
2068	500	40	1.1e-06
2069	355	90	1.6e-06
2069	700	110	1.0e-06
2077	730	65	9.5e-08
2085	250	< 1	9.5e-08
2087	355	< 1	9.5e-08
2088	42	< 1	9.5e-08

4 Uncertainties

Those results can raise some questions. Because of the lack of overlap between the two ellipses, we can wonder if strong non-gravitational forces do not act on this asteroid or if other sources of uncertainty remains on its orbit.

4.1 Yarkovsky effect

The main non-gravitational effect acting on small bodies is Yarkovsky effect (Vokrouhlický et al. 2000). Yarkovsky effect leads to a variation of the semi-major axis in a long timescale: Because of the difference of temperature at the surface of the asteroid, the infrared emission, from the surface, of the absorbed solar radiation is anisotropic. This leads to a recoil force affecting the orbital motion of the asteroid. The main effect lies on a secular drift of the semi-major axis (increasing or decreasing depending on the value of the spin obliquity). Objects with diameter ≤20km are sensitive to Yarkovsky effect. Its impact on Apophis's orbit has already been studied in Chesley (2006) and Giorgini et al. (2008). Those authors concluded on a displacement on the position of Apophis in 2029 at about 300 km in distance. But, regarding our results, Yarkovsky alone can not explain the shift of ∼ 600 km in distance in 2029.

4.2 Catalog biases

Chesley et al. (2010) showed that biases exist in stellar catalog, especially in the widely used USNO-B1.0 catalog (used for our astrometric reduction) and proposed a method to remove them from astrometric measurements. This method has been recently implemented in the OrbFit package in order to remove the biaises in (α, δ). An exercise has to be done in order to estimate the impact of such treatment using the new observations.

5 Conclusions

The new observations of March 2011 enable to rule out the possibility of collision with the Earth in 2036. But the important shift found allow us to think that strong non gravitational forces act on this asteroid. Besides, some other uncertainties may participate in this moving. As mentioned in the previous section, a debiaised treatment has to be done on the astrometric data. Other areas may also be exploited. We can consider an other independent software for the astrometric reduction and also an improvement of the dynamical model used (i.e. including J_2 or J_4 of the Earth).

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