The potentially hazardous asteroid 2009 FD

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Abstract.

Third of the most interesting potentially dangerous asteroids, after (99942) Apophis and (101955) Bennu, is 2009 FD. We computed impact solutions of the asteroid 2009 FD based on its 296 optical observations from 2009 February 24.36493 UTC to 2014 April 02.15110 UTC, and 1 radar observation from 2014 April 07 20:21:00 UTC. We used the freely available OrbFit Software Package and studied the orbit of 2009 FD forward in the future searching for close approaches with the Earth and for possible impacts up to 2201.

Possible impact solutions were computed using the JPL DE405 planetary and lunar ephemerides taking into account the different A2 non-gravitational parameter in the motion of the asteroid 2009 FD.

We computed possible impacts in 2185, 2186, 2191, 2192, 2194, 2196 and 2198. They are possible only with the non-gravitational parameter, A2 in the range (-46.0, 0)$\times 10^{-15} au/d^2$, with the gap between (-25.0, -11.0)$\times 10^{-15} au/d^2$.

It denotes that if A2 is greater than $+0.0\times 10^{-15} au/d^2$, or smaller than $-46.0\times 10^{-15} au/d^2$ than impacts with the Earth, are excluded.

They are possible with the non-gravitational parameter, A2<=0. It implies that impacts are possible if 2009 FD rotates in retrograde direction.

Key words: astrometry-minor planets, asteroids: individual: 2009 FD

Introduction

The asteroid 2009 FD was discovered on 2009 March 16 at the (IAU J75) OAM Observatory, La Sagra. Asteroid 2009 FD belongs to the Apollo group, comprising 5500 members as of 2014 June 12, and is one of 11045 known Near-Earth Asteroids at this time (http://www.minorplanetcenter.net/iau/lists/Unusual.html). Apollos have perihelion distances less than 1.0 au and semimajor axes greater than 1.0 au (http://www.minorplanetcenter.net/iau/lists/Unusual.html).

We computed directly from the OrbFit software an absolute magnitude H of 24.14. When H is computed from astrometric observations only, it is generally assumed that the real value is somewhere in the interval [H-0.5, H+0.5] mag. The NEODyS Team gives a priori typical RMS=0.44 mag in brightness uncertainty for 2009 FD for weighing all observations. The same value of RMS we also computed using the OrbFit software.

We calculate the diameter D of the asteroid from its H and albedo p_v using the formula of Fowler and Chilemni (1992):

$$D = 1329 \times 10^{-H/5} p_v^{-1/2} [km] \quad (1)$$

Hence, for H = 24.14±0.44 and a geometric albedo of 0.01 (Mainzer, A. et al. 2014), we found the diameter of 2009 FD to be between D=405 m and 607 m, with the mean value of 496 m for H=24.14.

The JPL NASA and the NEODyS lists H=24.1 and D=470 m. 2009 FD has a rotation period of about 4.00 h (Behrend, R. 2009, revised)

In Table 2 of Carry (2012) the average bulk density of meteorites are given. They are mostly between 1600 kg/m^3 and 3400 kg/m^3 for chondrites, through 3250 kg/m^3 for achondrites to 4700 kg/m^3 for stony-iron meteorites. Hence, a mass of asteroid 2009 FD is between 1.02×10^{11} kg for density of 1600 kg/m^3 to 3.00×10^{11} kg for 4700 kg/m^3.

The JPL NASA Sentry Risk Table (http://neo.jpl.nasa.gov/risk/) lists, as of June 12, 2014, 472 Near Earth Asteroids which have potential future Earth impact events. 2009 FD has over 5 years observational arc and is still in this Table since year 2009.

Recently, based on 292 optical observations of the asteroid 2009 FD from 2009 February 24.366 UTC to 2014 April 07.849 UTC the NEODyS Team presents new Impactor Table computed with the new, experimental software OrbFit version 4.3
(http://newton.dm.unipi.it/neodys/index.php?pc=1.1.2&n=2009FD).
It handles the Yarkovsky non-gravitational effect as a model uncertainty, and solves for 7 parameters instead of 6. This new parameter is the transverse component of the Yarkovsky effect.

Their results are compatible with those obtained by the JPL/SENTRY group by using Yarkovsky MonteCarlo models:
http://neo.jpl.nasa.gov/risk/2009fd.html.

Our results are based additionally on 1 radar observation by (251) Arecibo made in 2014 April 07 20:21:00 UTC and using all 296 optical observations up to 2014 May 02.15110 UTC.

1. Orbit

The JPL NASA's Sentry Risk Table (http://neo.jpl.nasa.gov/risk/) and the Risk Page of the NEODyS
(http://newton.dm.unipi.it/neodys/index.php?pc=4.1) present possible impact solutions of potentially dangerous asteroids. They list the name of each hazardous asteroid, the dates of its potential impacts, the probability of possible impact at each date, the impact energy and so called Palermo and Torino scales. The Sentry Risk Page contains two tables with dangerous asteroids: table with recently observed object, i.e. within past 60 days, and table with objects not recently observed. To compute impact solutions of potentially dangerous asteroids we used the OrbFit software v.4.2 (http://adams.dm.unipi.it/ orbmaint/orbfit/).

To propagate the orbit, the OrbFit software used internal control of propagation methods (multistep, Runge-Kutta-Gauss and Everhart). Usually we set automatic control (multistep for main belt, Everhart for high eccentricity and/or planet crossing).

Generally, the OrbFit software searches for possible impacts and give standard solutions as are presented by the JPL NASA and the NEODyS Teams, i.e. date of possible impact, σ LOV - the coordinate along the Line of Variations (LOV), impact probability, impact energy, and Torino or Palermo scale (special hazard ratings).

First, we computed orbit of the asteroid 2009 FD based on all observations using the OrbFit software. Table1 lists keplerian orbital elements of 2009 FD with their uncertainties computed by the author.

Table 1. Asteroid 2009 FD. Keplerian orbital elements with their uncertainties for the epoch JD2456800.5=2014-May-23

a	e	i	*Ω*	*ω*	M
au		deg	deg	deg	deg
1.16308722546	0.493058866849	3.1363642146	9.4862732817	281.2925392212	353.2292482747
1.75×10^{-9}	4.86×10^{-8}	6.33×10^{-6}	1.69×10^{-5}	1.66×10^{-5}	4.21×10^{-6}

Fig.1 presents the orbit of 2009 FD in the ecliptic plane. Positions of the asteroid and planets are presented for the epoch 2014-May-23. The dashed line denotes the part of the orbit below the ecliptic plane.

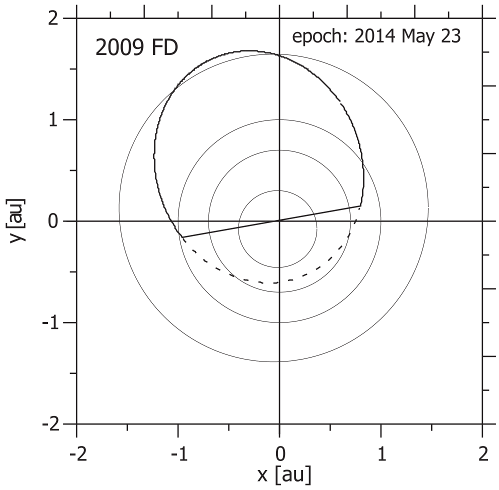

Fig. 1. The orbit of 2009 FD in the ecliptic plane. Positions of the asteroid and planets are presented for the epoch 2014-May-23. The dashed line denotes the part of the orbit of 2009 FD below the ecliptic plane.

2. Search for impact solutions

We computed possible impact solutions and impact orbits according to our method (Wlodarczyk, 2007) which is based on the method of Milani included in the OrbFit software where the covariance cloning is based on the Line of Variations (LOV) with the largest eigenvalue, where σ LOV denotes the position of an asteroid on the orbit along the line of variations in σ space (Milani et al. 2005). We used covariance matrix by the NEODyS.

We searched for potential impacts out to σ LOV $= 3$ similarly to the NEODyS's CLOMMON2 System. Moreover, we computed 600 virtual asteroids (VAs) on both sides of the LOV which gives 1201 VAs and propagated their orbits to JD 2524958.5 TDT=2201-January-1. We take into account the JPL DE405 ephemerides, perturbations of 25 additional massive asteroids from the main belt of asteroids (Farnocchia et al. 2013), the error model based on Chesley et al. (2010) and the Yarkovsky effects.

Moreover, in all our computations we follow the same method of the weighting and selection of observations as the NEODyS site. For each measured right ascension and declination the a priori RMS was used. They are computed based on the statistical performance of the given observatory. The NEODyS site gives a summary of these statistics for each observatory. For example, the J75-OAM Observatory, La Sagra (discoverer of the asteroid 2009 FD) statistics are also available from the NEODyS site list:
http://newton.dm.unipi.it/neodys/index.php?pc=2.1.2&o=J75&ab=0.

If insufficient observations are available for statistical analysis, then the NEODyS site uses an a priori RMS of 3 arcsec for observations obtained before 1890, 2 arcsec for those acquired prior to 1950 and 1 arcsec for others. For automatic rejection of bad observations, the value of χ from the usual χ^2 test is computed. In the case of the asteroid 2009 FD χ^2 threshold is equals to 1.111 arcsec.

Parameter χ gives a characterization of the relative quality of the observation for a given asteroid. Next automatic outlier rejection routine discards observations at $\chi = \sqrt{10}$ and recovers at $\chi = \sqrt{9.21}$. It should correspond to 1% of rejections if the errors are close to Gaussian.

For all observations, the residuals, both in right ascension and declination, and the parameter χ are computed by the NEODyS site or by us using the OrbFit software.

The NEODyS Team published impact solutions of the asteroid 2009 FD using 292 optical observations and the new, experimental software OrbFit version 4.3
(http://newton.dm.unipi.it/neodys/index.php?pc=1.1.2&n=2009FD).
Their date of computation is May 20, 2014. As the NEODyS states, it handles the Yarkovsky non-gravitational effect as a model uncertainty. It is worth noting that it is difficult to constrain the value of parameters of Yarkovsky effect because of the poor knowledge of the physical properties of asteroid. Hence, the NEODyS used an apriori constraint for the transverse acceleration given by A2=$\pm 30.0 \times 10^{-15} au/d^2$. The results are similar to the JPL/SENTRY group by using Yarkovsky MonteCarlo models. A2<0 denotes negative orbital drift, i.e. value of semimajor drift, da/dt < 0, and A2>0 is for positive orbital drift, i.e. value of semimajor drift, da/dt > 0. For another potentially dangerous asteroid (99942) Apophis (Farnocchia et al. 2013) computed distribution of non-gravitational parameter A2 from the assumed physical modeling in the range of about [-50, +50] $\times 10^{-15} au/d^2$. In the case of asteroid 2009 FD we searched for potential impact solution using value of non-gravitational parameters from A2=$-200 \times 10^{-15} au/d^2$ to A2=$+200 \times 10^{-15} au/d^2$ with the step of 20 $\times 10^{-15} au/d^2$. Hence, we found that there are some main impact solutions around A2=$-40 \times 10^{-15} au/d^2$.

Therefore, we searched for potential impact solution using value of non-gravitational parameters from A2=$-60 \times 10^{-15} au/d^2$ to A2=$-20 \times 10^{-15} au/d^2$ with the step of 2 $\times 10^{-15} au/d^2$. And finally, we searched for impact solution between $-40 \times 10^{-15} au/d^2$ to A2=$-30 \times 10^{-15} au/d^2$ with the step of 0.2 $\times 10^{-15} au/d^2$. It appears that main possible impacts may occur with values of the non-gravitational parameter A2=(-33.0 and -32)$\times 10^{-15} au/d^2$.

It is interesting how do these accelerations, due to the Yarkovsky effect, reflect the final solution. We computed the Minimum Orbit Intersection Distance (MOID) with the Earth and the asteroid on nominal orbit for the epoch of possible impact, i.e. for March 29, 2198 with and without these accelerations. Using the OrbFit software we computed values of MOID equal to 0.00022 au and 0.00027 au with and without the Yarkovsky effect, respectively. So we can see the significance of the Yarkovsky effect in our solution.

A2 is proportional to the non-gravitational acceleration da/dt, related with the spin of asteroid and is proportional to cos(γ), where γ is the obliquity of the asteroid equator with respect to its orbital plane (Farnocchia et al. 2013). Hence, impacts are possible only when asteroid rotates in retrograde direction.

Table 2. Asteroid 2009 FD. Main possible impact solutions computed for different non-gravitational parameter A2

	A2=$-33 \times 10^{-15} au/d^2$					
date	2185-03-29	2186-03-29	2191-03-30	2192-03-29	2196-03-29	2198-03-29
impact prob.	9.78E-03	2.63E-06	3.50E-05	8.90E-06	1.13E-05	6.19E-08
	A2=$-32 \times 10^{-15} au/d^2$					
date	2185-03-29	2186-03-29	2191-03-30	2192-03-29	2194-03-30	2196-03-29
impact prob.	2.14E-03	7.38E-07	3.05E-05	4.55E-06	9.03E-07	3.10E-05

Table 2 lists possible impact solutions for different years computed for different values of the non-gravitational parameter A2 connected with the Yarkovsky effect where:
-date of impact
-impact prob. is impact probability
It is interesting that we computed impact solutions only for negative value of the non-gravitational parameter A2. Hence, if the asteroid 2009 FD has a prograde spin rotation, i.e. where A2 is greater than 0, then possible impacts with the Earth are excluded.

In all solutions presented in Table2 computed impact velocity, Vimpact, i.e. a geocentric velocity of the asteroid 2009 FD at atmospheric entry is in the range (19.40÷19.42) km/s.

Also, the kinetic energy of impact: 0.5 $*$ Mass $*$ Vimpact^2, measured in Megatons of TNT, is about 125, where the mass has been computed assuming a uniform spherical body with the computed diameter and a mass density of 2.6 g/cm3. The diameter of asteroid is computed using the absolute magnitude, H based on all observation, which gives H=22.130±0.442.

New observations of the asteroid 2009 FD, probably in observational window in January, 2015, can refine the orbit of the asteroid and give more precise possible impacts solutions in the future.

Conclusion

We computed impact solutions of the asteroid 2009 FD based on its 296 optical observations from 2009 February 24.36493 UTC to 2014 April 02.15110 UTC, and 1 radar observations from 2014 April 07 20:21:00 UTC. We detect possible impacts of the asteroid 2009 FD in 2185, 2186, 2191, 2192, 2194, 2196 and in 2198 with the non-gravitational parameter, A2<0. It denotes that impacts are possible if 2009 FD rotates in retrograde direction.

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