Special Group of the Potentially Hazardous Asteroids

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Abstract. Up to now, i.e. until March 15, 2019, there have been no uniform and up-to-date computed orbits of so called Special asteroids: 29075 (1950DA), 99942 (Apophis), 101955 (Bennu) and 410777 (2009FD). In this work, based on all available astrometric and radar observations up to March 15, 2019, and a uniform selection and weighing method, I have computed keplerian orbital elements for the epoch October 9, 2018 together with the new computed non-gravitational parameters $A2$. Also, I have calculated the updated risk tables for these asteroids based on all observations, including non-gravitational parameter $A2$, the DE431 version of JPL's planetary ephemerides and perturbation from 16 massive asteroids and the dwarf planet Pluto.

Key words: astrometry – minor planets, asteroids: individual: (29075) 1950 DA, (99942) Apophis, (101955) Bennu, (410777) 2009 FD

1. Introduction

According to the NEODyS site[1], Special group of asteroids are those, which need a more detailed analysis of their motion and whose tables of risk have not been computed by the standard procedure.

List of Special asteroids as of March 15, 2019:

→(29075) = 1950 DA = 2000 YK66

Discovered at Mount Hamilton on February 22, 1950 by C. A. Wirtanen. 662 - Lick Observatory, Mount Hamilton, IAUC 1258.
Orbit type: Apollo. Potentially Hazardous Asteroid.

→ (99942) Apophis = 2004 MN4

Discovered at Kitt Peak on June 19, 2004 by R. A. Tucker, D. J. Tholen, and F. Bernardi. 695 - Kitt Peak, MPC 54280. As a result of its passage within 40 000 km of the earth on 2029 Apr. 13, this minor planet will move from the Aten to the Apollo class: MPC 54567
Orbit type: Aten. Potentially Hazardous Asteroid.

→ (101955) Bennu = 1999 RQ36

Discovered at Socorro on September 11, 1999 by LINEAR. 704 - Lincoln Laboratory ETS, New Mexico, MPS 6197
Orbit type: Apollo.

→ (410777) = 2009 FD

Discovered at Kitt Peak on February 24, 2009 by Spacewatch. 691 - Steward Observatory, Kitt Peak-Spacewatch, MPS 280489
Orbit type: Apollo. Near-Earth Object.

I searched for all Near-Earth asteroids from the astorb.dat of Lowell catalogue updated on March 15, 2019, and for epoch of osculation April 27, 2019, according to the Lowell Observatory site[2].

[1] https://newton.spacedys.com/neodys/index.php?pc=4.1
[2] https://asteroid.lowell.edu/main/astorb

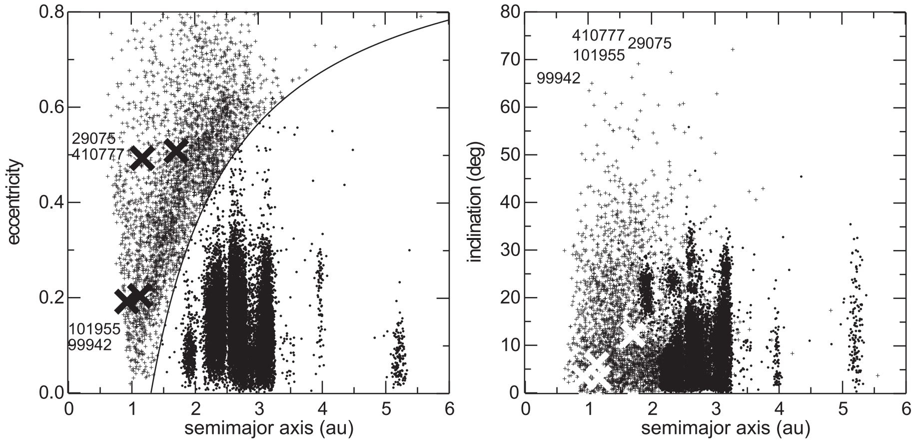

Fig. 1. The Special group of asteroids among the Near Earth Asteroids (NEAs).

Three Special group asteroids belong to the Apollo group, comprising 9924 members as of March 15, 2019 and to the 1969 Potentially Hazardous Asteroids (the minor planets with the greatest potential for close approaches to the Earth) as the IAU Minor Planet Center presents[3]. Another asteroid - (99942) Apophis belongs to the Aten group containing 1498 members.

Fig 1 presents the Special group of asteroids among the Near Earth Asteroids (NEAs) in the semimajor axis - eccentricity, $(a-e)$ and semimajor axis - orbital inclination, $(a-i)$ phase-spaces. 19794 NEAs from 792186 orbits of all asteroids from the astorb.dat of Lowell catalogue updated on March 15, 2019, and for epoch of osculation April 27, 2019 were selected. For clarity I show only every 5th NEAs and every 50th other asteroid. Both panels give interesting distribution of known asteroids relative to orbital elements $(a-e-i)$. Special group of four asteroids are marked by crosses.

1 The initial orbital elements of the Special asteroids

The initial orbits of the Special asteroids are presented in Table 1. They are computed with the use of the new software Orbit v.5.0.5[4] which includes the debiasing and weighting scheme described by Farnocchia et al. (2015). Also, I used the DE431 version of JPL's planetary ephemerides and additional 16 massive perturbing asteroids and dwarf planet Pluto as in Del Vigna et al. (2018), and in Farnocchia et al. (2013b). There are: (1) Ceres, (2) Pallas, (3) Juno, (4) Vesta, (6) Hebe, (7) Iris, (10) Hygiea, (15) Eunomia, (16) Psyche, (29) Amphitrite, (52) Europa, (65) Cybele, (87) Sylvia, (88) Thisbe, (511) Davida, (704) Interamnia and (134340) Pluto.

[3] https://minorplanetcenter.net/iau/lists/Unusual.html
[4] http://adams.dm.unipi.it/∼orbmaint/orbfit/

Table 1. Initial nominal keplerian orbital elements of the Special asteroids. The angles ω, Ω, and i refer to Equinox J2000.0. Epoch: 2018-Oct-09=JD2458400.5 TDB. The orbital elements are computed with the non-gravitational parameter $A2$.

a (au)	e	i (deg)	Ω (deg)	ω (deg)	M (deg)
(29075) 1950 DA					
1.69835367296	0.50800343557	12.1696078780	356.671317484	224.674212073	323.714639855
1.10E-09	3.208E-08	4.561E-06	8.107E-06	9.288E-06	2.420E-06
$A2=(-0.603\pm0.12)\times10^{-14}$ au/d^2					
(99942) Apophis					
9.22558531183E-01	0.19145673758	3.3368745324	204.05614490	126.67909945	300.76130069
1.342E-08	6.67E-09	3.495E-07	2.187E-05	2.136E-05	3.527E-05
$A2=(-5.20\pm2.93)\times10^{-14}$ au/d^2					
(101955) Bennu					
1.125886638463	0.20371438224	6.034326791	2.018410000	66.307358650	282.634767822
1.15E-10	1.885E-08	2.396E-06	3.524E-06	4.932E-06	2.346E-06
$A2=(-4.55\pm0.023)\times10^{-14}$ au/d^2					
(410777) 2009 FD					
1.16376960343	0.49295201486	3.127694422	9.354563395	281.469426514	
7.16E-09	9.20E-09	1.715E-06	8.626E-06	8.383E-06	6.410E-06
$A2=(+7.785\pm2.149)\times10^{-14}$ au/d^2					

Table 1 contains initial nominal keplerian orbital elements of the studied asteroids. The angles argument of perihelion ω, longitude of the ascending node Ω, and inclination i, refer to Equinox J2000.0. Epoch: October 9, 2018=JD2458400.5 TDB. The orbital elements are computed with the non-gravitational transverse acceleration parameter, $A2$.

Everywhere, observations of the Special asteroids are updated on March 15, 2019 and:

→ The orbit of (29075) 1950 is based on 582 optical observations from 1950-Feb-22.23014 to 2018-Feb-09.19461, of which 6 were rejected as outliers, and 12 radar observation from 2001-Mar-03 to 2012-May-01; computed with astrometric RMS=0.5374" and magnitude RMS=0.5068 mag.

→ The orbit of (99942) Apophis is based on 4471 optical observations from 2004-Mar-15.10789 to 2019-Feb-04.875060, of which 31 were rejected as outliers, and 46 radar observation from 2005-Jan-27 to 2013-Mar-15; computed with astrometric RMS=0.3270" and magnitude RMS= 0.5413 mag.

→ The orbit of (101955) Bennu is based on 580 optical observations from 1999-Sep-11.40624 to 2018-May-15.78855, of which 4 were rejected as outliers, and 29 radar observation from 1999-Sep-21 to 2011-Sep-29; computed with astrometric RMS=0.4282", and magnitude RMS=0.5217 mag.

→ The orbit of (410777) 2009 FD is based on 493 optical observations from 2009-Feb-24.36493 to 2019 03 09.440157, of which 6 were rejected as outliers, and 8 radar observation from 2014-Apr-07 to 2015-Nov-04; computed with astrometric RMS 0.4986", and magnitude RMS= 0.4087 mag.

2 Calculation of impact probabilities

Based on Table 1, I searched for possible impacts with the Earth. I presented results in an uniform manner i.e. using the OrbFit software 5.0.5, the DE431 version of JPL's planetary ephemerides, 16 massive perturbing asteroids and Pluto, parameter σ_{LOV}=5 where σ LOV denotes the position along the line of variation, LOV in the σ space and values of σ are in the interval

[-5,5], and with computed from observations non-gravitational parameters $A2$. I used all published observations of these asteroids as of March 15, 2019. Also I used a multiple solution method of Milani et al. (2005a,b).

Table 2 contains for asteroid (29075) 1950 DA predicted possible impacts with the Earth computed for 201 clones (Sitarski (2006)) (Virtual Asteroids) with parameter σ_{LOV}. Table 2 presents also probability of Earth impact and Palermo Scale (PS). PS is the new hazard scale (Chesley et al. 2002). Expected energy denotes impact energy multiplied by impact probability. Units are in megatons MT (1 MT=4.184E15 J).

In the case of asteroid (29075) 1950 DA, I searched for possible impacts until 2890.

Table 2. Impact Table. The asteroid (29075) 1950 DA. The DE431 version of JPL's planetary ephemerides, 16 perturbing asteroids and Pluto; $A2$=(-0.603±0.12)$\times 10^{-14}$au/d^2; σ_{LOV}=5 and 201 Virtual Asteroids.

Date, UTC	σ LOV	Impact probability	exp. energy [MT]	PS
2880/03/16.992	2.199	8.02E-6	9.44E-01	-2.45

I computed only one possible impact of asteroid (29075) in 2880 with probability of about 8.02×10^{-6}. The NEODyS-2 site[5] gives Impactor Table based only on 541 observations of asteroid (29075) between 1950-02-22.230 and 2015-11-18.506. They used information coming only from optical and radar astrometry, without the Yarkovsky effect. Their date of possible impact is the same but probability is 1.42e-4, i.e. greater than our computations.

The JPL NASA Sentry: Earth Impact Monitoring[6] computed Earth Impact Risk Summary based on selected 523 observations spanning 24010.3 days (February 22.230140, 1950 to November 18.504940, 2015). They computed similar date of possible impact and impact probability as the NEODYS-2 site.

Farnocchia et al. (2015) computed Yarkovsky parameter $A2$=(-0.599±0.13)$\times 10^{-14}$au/d^2, i.e. close to my computations. The results have been obtained using the OrbFit5.0 software. The new software includes the debiasing and weighting scheme, star catalog position and proper motion corrections in the asteroid astrometry, and the DE431 version of JPL's planetary ephemerides.

As new observations and the use of new computational techniques come in, the parameters of possible collisions of asteroid (29075) 1950 DA with the Earth have changed, which can be traced on the basis of the work of many authors. For example, tables of risk for asteroid of (29075) 1950 DA computed using shorter observational arc and different Solar System

[5] https://newton.spacedys.com/neodys/index.php?pc=1.1.2&n=29075
[6] https://cneos.jpl.nasa.gov/sentry/details.html#?des=29075

models are published by Farnocchia et al. (2013a,b, 2014) and Giorgini et al. (2002).

Table 3 contains for asteroid (99942) Apophis possible impacts with the Earth computed for 2401 clones with parameter σ_{LOV}=5 together with the probability of Earth impact and Palermo Scale (PS). I searched for possible impacts until 2100.

Table 3. Impact Table. The asteroid (99942) Apophis. The DE431 version of JPL's planetary ephemerides, 16 perturbing asteroids and Pluto; $A2$=(-5.20±2.93)$\times 10^{-14}$au/d^2; σ_{LOV}=5 and 2401 Virtual Asteroids.

Date, UTC	σ LOV	Impact probability	exp. energy [MT]	PS
2036/04/13.371	-3.005	8.28E-06	6.29E-03	-2.50
2042/04/13.724	-3.046	1.72E-08	1.30E-05	-5.31
2044/04/13.295	-2.942	1.64E-08	1.24E-05	-5.37
2053/04/12.915	-2.960	4.58E-08	3.48E-05	-5.05
2068/04/12.636	1.065	1.21E-06	9.16E-04	-3.79
2069/04/13.079	4.877	4.78E-11	3.63E-08	-8.20
2069/10/15.596	3.382	8.88E-10	6.73E-07	-6.93
2069/10/15.975	3.768	1.43E-09	1.08E-06	-6.73
2087/10/16.239	3.767	8.30E-11	6.29E-08	-8.09

In Table 3 there are many possible impacts computed until 2087 with probability of about 8.28×10^{-6} in 2036 to of about 4.78×10^{-11} in 2069.

Similarly, there are many possible impact dates at the NEODyS-2[7] between 2068 and 2116 and JPL NASA Sentry: Earth Impact Monitoring[8] www sites. But they used different starting orbital elements of the asteroid. It is worth noting that my computed dates of possible impacts are based on non-gravitational parameter $A2$ which has great uncertainty because of not well known physical parameter of Apophis. Hence, the first possible impact in 2036 (and others), have great uncertainties, too.

Also, tables of risk for asteroid (99942) Apophis computed using shorter observational arc and different Solar System models are widely published, e.g. in Vokrouhlicky et al.(2015), Farnocchia et al.(2013b), Bancelin et al.(2012), Zizka and Vokrouhlicy(2011), Krolikowska and Sitarski(2010), Krolikowska et al.(2009) and in Wlodarczyk(2017, 2016, 2014a,b,c, 2013).

Table 4 contains for asteroid (101955) Bennu possible impacts with the Earth computed for 601 clones with parameter σ_{LOV}=5 together with the probability of Earth impact and Palermo Scale (PS). I searched for possible impacts until 2202.

I found many possible impacts between 2180 and 2202 with probability about 2.05×10^{-5} in 2196 to about 1.50×10^{-9} in 2192. Similarly, there are many possible impact dates at the NEODyS-2[9] and JPL NASA Sentry:

[7] https://newton.spacedys.com/neodys/index.php?pc=1.1.2&n=99942
[8] https://cneos.jpl.nasa.gov/sentry/details.html#?des=99942
[9] https://newton.spacedys.com/neodys/index.php?pc=1.1.2&n=101955

Table 4. Impact Table. The asteroid (101955) Bennu. The DE431 version of JPL's planetary ephemerides, 16 perturbing asteroids and Pluto; $A2$=(-4.55±0.023)×10^{-14}au/d^2; σ_{LOV}=5 and 601 Virtual Asteroids.

Date, UTC	σ LOV	Impact probability	exp. energy MT	PS
2180/09/24.401	-0.110	4.78E-06	2.07E-02	-3.10
2182/09/24.869	-3.672	1.96E-08	8.47E-05	-5.49
2182/09/24.857	-3.170	2.67E-07	1.15E-03	-4.36
2185/09/24.606	-0.805	5.32E-06	2.30E-02	-3.07
2185/09/24.600	-0.489	1.70E-05	7.37E-02	-2.56
2187/09/25.061	-3.097	4.09E-08	1.77E-04	-5.18
2190/09/24.818	-0.350	1.59E-07	6.88E-04	-4.60
2191/09/25.076	-0.861	6.79E-07	2.94E-03	-3.97
2192/09/24.311	-3.082	1.50E-09	6.51E-06	-6.63
2193/09/24.601	-2.792	7.16E-07	3.10E-03	-3.96
2196/09/24.299	-0.784	1.97E-05	8.53E-02	-2.52
2196/09/24.331	-0.756	2.05E-05	8.89E-02	-2.51

Earth Impact Monitoring[10] www sites. They used different starting orbital elements of the asteroid, and they have computed many possible impacts starting in 2175. Also, tables of risk for asteroid of (101955) Bennu computed using shorter observational arc and different Solar System models are widely published e.g. in Chesley et al. (2014) and Wlodarczyk (2010).

Table 5 contains for asteroid (410777) 2009 FD possible impacts with the Earth computed for 1201 clones with parameter σ_{LOV}=5 together with the probability of Earth impact and Palermo Scale (PS). I searched for possible impacts until 2200.

Table 5. Impact Table. The asteroid (410777) 2009 FD. The DE431 version of JPL's planetary ephemerides, 16 perturbing asteroids and Pluto; $A2$=(+7.785±2.149)×10^{-14}au/d^2; σ_{LOV}=5 and 1201 Virtual Asteroids.

Date, UTC	σ LOV	Impact probability	exp. energy MT	PS
2190/03/30.077	-3.877	2.40E-07	3.45E-05	-5.61

I computed only one possible impact in 2190 with probability about 2.40×10^{-7}. There are many possible impact dates at the NEODyS-2[11] and JPL NASA Sentry: Earth Impact Monitoring[12] www sites. They used different starting orbital elements of the asteroid and different number of observations, and they have computed many possible impacts between 2185 and 2198. Also, tables of risk for asteroid of (410777) 2009 FD computed

[10] https://cneos.jpl.nasa.gov/sentry/details.html#?des=101955
[11] https://newton.spacedys.com/neodys/index.php?pc=1.1.2&n=410777
[12] https://cneos.jpl.nasa.gov/sentry/details.html#?des=410777

using different starting orbital elements and different Solar System models are published, e.g. in Spoto et. al.(2014) and Wlodarczyk(2015a,b).

Summary

In this work, I ordered, standardized and updated computations of orbital elements of so-called Special asteroids: 29075 (1950DA), 99942 (Apophis), 101955 (Bennu) and 410777 (2009FD). Orbital elements are presented for epoch October 9, 2018. They are computed based on all observations of the studied asteroids up to March 15, 2019. Also I updated their risk tables with computed from observations non-gravitational parameters $A2$ which have values:

→(-0.603±0.12)×10^{-14}au/d^2 for asteroid (29075) 1950 DA,

→(-5.20±2.93)×10^{-14}au/d^2 for (99942) Apophis,

→-4.55±0.023)×10^{-14}au/d^2 for (101955) Bennu and

→(+7.785±2.149)×10^{-14}au/d^2 for asteroid (410777) 2009 FD.

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