Some parameters of selected NEAs

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Abstract.
For studied 146 NEAs we computed non-gravitational parameter, $A2$, Lyapunov time, LT, secular frequency of perihelion and of ascending node and their relationships. In addition, we have extended the study of several of these parameters to all NEAs known so far. We computed their orbits based on all astrometric and radar observations available on December 29, 2017, and used a uniform selection and weighing method for observational material. It appeared that 102 NEAs have $A2 < 0$, from which about 70% have a maximum value in the range (0,-1.0) 10^{-14} au/day^2. It gives of about 15.7% of all NEAs. On the other hand, the remaining 30% NEAs with positive $A2$ have maximum value in the range (+2,+3) 10^{-14} au/day^2.

A maximum value of LT is between 20 and 60 years. In this range we found 50 NEAs, i.e. of about 34%. Studied NEAs with the longest LT are mainly located between the space controlled by the perihelion of Mars and aphelion of the Earth. Here are NEAs which do not cross the orbit of planets.

From all 17506 NEAs, we found secular frequencies close to secular precessions of the perihelion of Saturn, $g6$, for 368 NEAs and of Jupiter, $g5$, for 337 NEAs. Also, we detected secular frequencies close to the secular precession of the ascending node of Saturn, $s6$, for 275 NEAs. It gives about 2.1%, 1.9% and 1.6% of all known NEAs population, respectively.

Key words: astrometry – minor planets, asteroids: parameters

1. Introduction

To study the orbital motion of the Near Earth Asteroids (NEAs), it is necessary to know the precisely computed orbital elements for gravitational and non-gravitational cases including the non-gravitational parameter $A2$, Lyapunov time, LT, the secular frequency of perihelion and of ascending node and their relationships. In particular, they are needed to study Earth's hazard from potentially dangerous NEAs (Farnocchia et al. (2013a,b), Spoto et al. (2014), Chesley et al. (2014) and Wlodarczyk (2015)).

We can take starting orbital elements of NEAs from different sources. Using those updated on January 30, 2018 the JPL Small-Body Database: https://ssd.jpl.nasa.gov/sbdb_$y.cgi\#x$quer according to the keys: Near Earth Objects (NEOs), Asteroids, All Objects i.e. Numbered and Unnumbered we searched 17138 Objects. They contain orbital elements for different osculating dates. Hence we can take non-gravitational parameters $A2$ for different NEAs. Another source of orbital elements of NEAs and their observations is the NEODyS site:
http://newton.dm.unipi.it/neodys/. On the other hand using those updated on January 30, 2018 the Lowell.dat:
ftp://cdsarc.u-strasbg.fr/pub/cats/B/astorb/astorb.html computed by Edward Bowell I got 746843 orbits of asteroids for one osculating epoch December 13, 2017. From this database I chose 17653 NEAs with q<1.3 au including 2566 numbered asteroids to number 507847. In Fig. 1, we presented histograms of selected 17653 NEAs.

The most interesting histograms in Fig. 1 are these of absolute magnitude and the longitude of ascending node. We can compare these two histograms with these ones by JeongAhn & Malhotra (2014) computed using only 9550 NEOs, I used 17653 NEOs - almost twice as much. Despite this, in Fig. 1 we get similar NEOs deficit with the value of H lying in the range of magnitude 20≤H≤25, with minimum at H≈23 mag. Similarly, we got a deficit in longitude of the ascending node around 90 and 270 degrees. According to the paper mentioned by JeongAhn & Malhotra (2014) this deficit is connected with the annual variability in the discovery rate of asteroids. In Fig. 1 we can also see that maxima of NEOs in semimajor axis are around 1.3 au, in eccentricity near 0.5 and in inclination close to 5 degrees. But our research goes mainly towards the calculations of $A2$ and other orbital parameters, as in the next sections.

2. Non-gravitational parameter *A*2

We chose 146 NEAs to study orbital and physical parameters. They are included in Table 1. First 125 NEAs are taken from Table A.1. by Tardioli et al. (2017). Next 21 NEAs, starting from (5604) 1992 FE, are from the JPL DB (https://ssd.jpl.nasa.gov/sbdb_query.cgi) updated January 22, 2018. We choose from the JPL DB only numbered NEAs, which are not given in Table A.1. of Tardioli et al. (2017).

The non-gravitational parameter $A2$ is a parametrization of the Yarkovsky effect. Two additional non-gravitational components $A1$ and $A3$ are measured in the motion of comets. The value of the non-gravitational parameter $A2$ denotes the negative orbital drift, when the value of the drift of the semimajor axis is $da/dt<0$. Positive value of $A2$ denotes $da/dt>0$.

It is worth noting that the JPL NASA database contains 90 NEAs with computed non-gravitational parameter $A2$, of which 69 are numbered, as of May 28, 2018.

To compute the orbit of the asteroids, we used the freely available OrbFit software v.5.0.5 (http://adams.dm.unipi.it/∼orbmaint/orbfit/). We used the method of debiasing of the astrometric observations of asteroids with respect to the reference stars. Star catalog position and proper motion are corrected in asteroid astrometry according to Farnocchia et al. (2015). We used the JPL DE431 and additionally 17 perturbing massive asteroids (Chesley et al. (2014)). We used the error model 'fcct14' included in the OrbFit software. The precision of the orbital computations using the OrbFit software is described in Wlodarczyk (2009).

Fig. 2, similarly to Fig. 1, presents the histograms of orbital elements and absolute magnitudes for 146 selected NEOs computed using the NEODyS database and the OrbFit software, epoch JD2458000.5 (September 4, 2017). Observations are updated on December 24, 2017.

It is visible that the histograms of all NEAs in Fig. 1 and 146 studied in Fig. 2 are similar, also including histogram of H with a similar minimum at H=22.5 mag.

Next we computed orbital elements of the selected asteroids with non-gravitational effects. We computed non-gravitational parameter $A2$, i.e. non-gravitational transverse acceleration parameter. Table 1 presents for the 146 selected NEAs computed: absolute magnitude, H, semimajor axis,

Table 1. Computed orbital parameters of 146 selected NEAs for the epoch JD2458000.5=September 4, 2017. Observations are updated to Dec. 24, 2017

Object	H (mag)	a (au)	e	i (deg)	A_2 (10^{-14}au/d^2)	LT (yr)
101955 Bennu	20.630 ± 0.521	1.126	0.2037	6.035	-4.5501 ± 0.0213	41.8
2340 Hathor	20.225 ± 0.458	0.8438	0.4499	5.8567	-3.0284 ± 0.0706	50.3
152563 1992 BF	19.741 ± 0.469	0.9079	0.2715	7.2563	-2.7389 ± 0.1870	51.7
2009 BD	28.236 ± 0.567	1.0616	0.05153	1.267	-96.5930 ± 15.0570	193.4
2005 ES70	23.712 ± 0.478	0.7631	0.3864	20.8258	-14.0470 ± 0.3304	127.2
437844 1999 MN	21.2 ± 0.561	0.6739	0.6654	2.0222	4.3621 ± 0.2345	41.6
468468 2004 KH17	21.88 ± 0.531	0.7121	0.4984	22.119	-6.5458 ± 0.4787	131.7
85990 1999 JV6	20.149 ± 0.580	1.0078	0.3111	5.3583	-3.2547 ± 0.2160	31.7
2062 Aten	17.122 ± 0.370	0.9668	0.1828	18.9329	-1.3251 ± 0.1096	94.6
6489 Golevka	18.979 ± 0.814	2.4844	0.6128	2.2669	-1.1710 ± 0.1460	67.7
162004 1991 VE	18.066 ± 0.570	0.8907	0.6646	7.2194	2.6869 ± 0.1953	95.2
1862 Apollo	16.071 ± 0.447	1.4701	0.5597	6.3553	-0.2821 ± 0.0311	66
2006 CT	22.28 ± 0.417	1.0969	0.2308	2.7411	-10.7130 ± 1.1592	20.3
2003 YL118	21.564 ± 0.492	1.1302	0.4861	7.6104	-17.8190 ± 1.7967	55.2
1999 UQ	21.74 ± 0.560	1.0942	0.0158	24.8161	-10.1700 ± 1.1799	93.9
33342 1998 WT24	17.831 ± 0.577	0.7189	0.4177	7.3577	-2.7096 ± 0.3155	41.9
326290 Akhenaten	21.707 ± 0.497	0.8788	0.0216	0.4397	0.7148 ± 0.9545	41.5
2000 PN8	22.061 ± 0.534	1.2523	0.2169	22.3913	12.7190 ± 1.4216	229.2
455176 1999 VF22	20.676 ± 0.461	1.3128	0.7385	3.9028	-5.1998 ± 1.0543	106.7
2001 BB16	22.97 ± 0.529	0.8557	0.1715	2.0298	36.0430 ± 5.1955	16.6
216523 2001 HY7	20.513 ± 0.488	0.9138	0.4121	5.2112	5.5686 ± 0.6799	44.8
10302 1989 ML	19.37 ± 0.563	1.2721	0.1363	4.3781	5.9244 ± 0.8078	226.2
3908 Nyx	17.288 ± 0.500	1.9271	0.4595	2.1857	2.2464 ± 0.2672	237.7
85953 1999 FK21	18.076 ± 0.612	0.7387	0.7031	12.609	-0.9992 ± 0.1694	110.4
1995 CR	21.702 ± 0.388	0.9069	0.8683	4.0651	-6.7019 ± 1.3174	62.5
1685 Toro	14.32 ± 0.490	1.3674	0.4361	9.3804	-0.3867 ± 0.0619	136.7
29075 1950 DA	17.06 ± 0.505	1.6985	0.5079	12.1706	-0.5946 ± 0.0867	129.4
2100 Ra-Shalom	16.157 ± 0.545	0.832	0.4365	15.7535	-0.5943 ± 0.1017	111.4
399308 1993 GD	20.639 ± 0.414	1.1024	0.238	15.4645	11.2700 ± 1.370	124.2
363505 2003 UC20	18.26 ± 0.812	0.7812	0.3368	3.8042	-0.7417 ± 0.0915	25.6
4034 Vishnu	18.316 ± 0.518	1.0597	0.444	11.1687	-7.2386 ± 1.1343	76.5
363599 2004 FG11	21.025 ± 0.565	1.5875	0.7237	3.1186	-6.0716 ± 0.6382	44.5
377097 2002 WQ4	19.519 ± 0.524	1.9589	0.5552	3.94208	-2.2440 ± 0.3101	101.7
425755 2011 CP4	21.138 ± 0.337	0.9113	0.8702	9.4526	7.3693 ± 1.3192	143.2
1994 XL1	20.774 ± 0.506	0.6708	0.5263	28.1629	-4.6011 ± 0.2168	165.3
3361 Orpheus	19.19 ± 0.530	1.2098	0.3227	2.6847	1.9624 ± 0.1845	57
397326 2006 TC1	18.986 ± 0.448	1.7201	0.3751	4.4954	3.3784 ± 0.5312	232.5
138852 2000 WN10	20.15 ± 0.490	1.0014	0.2986	21.4995	2.7205 ± 0.3958	61.1
2008 CE119	25.553 ± 0.489	1.2089	0.1766	7.7247	-13.4250 ± 2.6427	53.1
85774 1998 UT18	19.119 ± 0.687	1.4032	0.3289	13.5898	-0.5813 ± 0.1115	52.9
99907 1989 VA	17.858 ± 0.504	0.7284	0.5947	28.8006	1.5957 ± 0.1900	219.6
1566 Icarus	16.278 ± 0.768	1.078	0.8268	22.8243	-0.3919 ± 0.0239	267.7
138175 2000 EE104	20.271 ± 0.602	1.0044	0.2931	5.2387	-6.9842 ± 0.8476	45.9
2008 BX2	23.688 ± 0.407	0.8572	0.341	3.1375	-16.0550 ± 4.0889	40.8
66400 1999 LT7	19.31 ± 0.619	0.8554	0.5725	9.0667	-4.0860 ± 0.5724	59.9
4581 Asclepius	20.735 ± 0.359	1.0224	0.357	4.9192	-4.3633 ± 0.8921	29.6
2007 TF68	22.682 ± 0.555	1.4063	0.2653	26.2023	-17.8550 ± 1.1287	1098
136818 Selqet	18.979 ± 0.682	0.9375	0.3462	12.7783	2.1919 ± 0.3985	86.7
4179 Toutatis	15.156 ± 0.631	2.5362	0.6293	0.4474	-0.5353 ± 0.0930	77
256004 2006 UP	23.018 ± 0.569	1.5851	0.3009	2.2855	-18.4610 ± 3.3045	358
350462 1998 KG3	22.081 ± 0.433	1.1603	0.1181	5.5052	-6.2588 ± 0.6659	9274

Table 1. continued

Object	H (mag)	a (au)	e	i (deg)	A_2 (10^{-14}au/d^2)	LT (yr)
441987 2010 NY65	21.473 ± 0.396	0.9995	0.3697	11.6696	-3.8497 ± 0.8633	80.9
1999 SK10	19.664 ± 0.611	1.7639	0.4413	6.9622	-5.5979 ± 1.0658	326
54509 YORP	22.562 ± 0.535	1.0062	0.2302	1.5993	-7.6732 ± 2.0811	21
85770 1998 UP1	20.401 ± 0.423	0.9982	0.3451	33.1808	-4.6744 ± 0.7682	78.2
152671 1998 HL3	20.076 ± 0.498	1.1288	0.366	2.6795	-7.3990 ± 1.2492	36.9
37655 Illapa	17.788 ± 0.461	1.4777	0.7524	18.0023	-1.3516 ± 0.2702	271
310442 2000 CH59	19.834 ± 0.445	0.8629	0.4232	3.2677	5.0901 ± 0.7861	29
162181 1999 LF6	18.165 ± 0.458	1.4094	0.2804	18.9443	-2.1258 ± 0.4774	263
267759 2003 MC7	18.718 ± 0.589	1.3736	0.1843	21.2108	-2.8745 ± 0.4849	753
2005 EY169	22.11 ± 0.495	1.307	0.2327	20.8854	-15.1260 ± 1.5225	266
41429 2000 GE2	20.353 ± 0.850	1.5925	0.5552	2.1731	-5.5826 ± 1.7642	37.8
401885 2001 RV17	20.425 ± 0.469	0.9146	0.3424	7.5231	-2.4704 ± 1.0187	97.4
306383 1993 VD	21.423 ± 0.490	0.8761	0.5514	2.0595	-3.0399 ± 0.5761	30.4
2009 WB105	23.56 ± 0.350	0.8254	0.2525	38.4054	11.7350 ± 3.3811	153
6037 1988 EG	18.741 ± 0.548	1.2711	0.4997	3.4997	-1.5628 ± 0.6837	29.1
1991 GO	19.9 ± 0.573	1.9261	0.6541	9.5555	-4.5757 ± 1.2351	179.2
164202 2004 EW	20.74 ± 0.488	0.9882	0.2792	4.6697	7.4013 ± 1.7242	29.6
297418 2000 SP43	18.489 ± 0.607	0.8113	0.4669	10.3498	-2.7183 ± 0.7113	85.5
385186 1994 AW1	17.558 ± 0.484	1.1053	0.0758	24.0953	1.3277 ± 0.4144	226
162361 2000 AF6	20.099 ± 0.498	0.8777	0.4113	2.6965	2.4873 ± 1.0215	34.8
154590 2003 MA3	21.604 ± 0.473	1.1053	0.4023	1.4132	-8.1472 ± 0.7711	28.9
2005 GR33	22.184 ± 0.329	0.7783	0.3845	27.9903	-10.9000 ± 3.6556	194.5
416151 2002 RQ25	20.561 ± 0.337	1.1117	0.3063	4.5766	3.6921 ± 1.2270	59.5
164207 2004 GU9	21.122 ± 0.497	1.0014	0.1361	13.6499	-6.9362 ± 1.5011	58.4
467336 2002 LT38	20.53 ± 0.544	0.845	0.3137	6.1955	2.0226 ± 0.8392	41.4
330659 2008 GG2	22.82 ± 0.589	1.5872	0.2778	13.0178	5.9471 ± 1.9410	810
250680 2005 QC5	19.654 ± 0.44	0.8931	0.3645	9.4503	2.3921 ± 0.0921	47
6239 Minos	18.432 ± 0.507	1.151	0.4128	3.9427	1.7149 ± 0.4902	49.3
152664 1998 FW4	19.659 ± 0.434	2.5122	0.7214	3.4693	1.8876 ± 0.6215	224.5
2004 BG41	24.438 ± 0.5175	2.509	0.6099	2.9782	-13.0750 ± 4.2745	172.7
443837 2000 TJ1	19.549 ± 0.578	1.1605	0.0809	39.5402	-2.0636 ± 1.2051	4689
152756 1999 JV3	18.855 ± 0.467	1.4507	0.4149	15.2256	1.2915 ± 0.6600	542
369986 1998 SO	20.429 ± 0.532	0.7315	0.6986	30.3447	2.3144 ± 0.0778	239
163348 2002 NN4	19.982 ± 0.549	0.8765	0.4342	5.4146	2.9329 ± 1.1081	27.4
137924 2000 BD19	17.213 ± 0.515	0.8764	0.8949	25.7159	-0.7407 ± 0.3721	540.5
5381 Sekhmet	16.607 ± 0.565	0.9474	0.2962	48.9693	0.1120 ± 0.3421	130
136770 1996 PC1	20.488 ± 0.658	1.8386	0.4517	25.1097	-3.0174 ± 0.8095	1235
364136 2006 CJ	20.141 ± 0.473	0.6765	0.7548	10.234	-2.9463 ± 0.2166	121.6
422686 2000 AC6	21.46 ± 0.533	0.8532	0.2863	4.6955	3.3288 ± 1.7096	20.3
337248 2000 RH60	19.946 ± 0.528	0.8259	0.5513	19.6473	-2.2392 ± 0.9238	175
4660 Nereus	18.126 ± 0.644	1.4886	0.36	1.4317	2.2694 ± 0.6297	41.8
469445 2002 LT24	22.024 ± 0.463	0.72	0.4958	0.7632	0.3260 ± 2.0387	45
2063 Bacchus	17.25 ± 0.574	1.0779	0.3494	9.4331	-1.3117 ± 0.2984	39
172034 2001 WR1	17.797 ± 0.579	1.2774	0.2026	25.0318	-1.4602 ± 0.5523	1085
138258 2000 GD2	18.799 ± 0.957	0.7577	0.4768	32.1399	-3.9488 ± 1.5665	335
11054 1991 FA	16.92 ± 0.492	1.9784	0.4475	3.0771	-0.3558 ± 0.2211	272
141531 2002 GB	19.051 ± 0.500	0.992	0.529	22.5564	2.6073 ± 1.2694	179
1620 Geographos	15.214 ± 0.604	1.2453	0.3354	13.3374	-0.0130 ± 0.1158	177
2005 QQ87	22.643 ± 0.433	1.0005	0.302	33.9621	-2.8678 ± 5.0707	221
2000 YA	23.778 ± 0.471	2.3859	0.6456	2.6835	-34.5530 ± 9.2667	98
373393 1972 RB	19.148 ± 0.301	2.1468	0.4877	5.2521	1.0961 ± 1.1721	403

Table 1. continued

Object	H (mag)	a (au)	e	i (deg)	A_2 (10^{-14}au/d^2)	LT (yr)
87309 2000 QP	17.57 ± 0.570	0.8474	0.4631	34.7432	-0.2267 ± 0.6030	348
277810 2006 FV35	21.668 ± 0.449	1.0013	0.3775	7.104	3.8188 ± 1.7145	57.2
339714 2005 ST1	20.322 ± 0.472	1.4514	0.3709	20.2344	-1.4575 ± 1.0821	446
1221 Amor	17.267 ± 0.902	1.9191	0.4356	11.8794	-0.2126 ± 0.1540	245.7
2014 UR	26.491 ± 0.521	0.9967	0.0154	8.244	-39.5150 ± 11.4260	41.6
2003 XV	26.601 ± 0.496	1.9425	0.5554	4.556	-4.3960 ± 22.4630	87.8
376879 2001 WW1	21.896 ± 0.379	1.2101	0.1217	21.7408	-6.1163 ± 1.0301	1940
25143 Itokawa	18.932 ± 0.605	1.3241	0.2801	1.6214	-1.3048 ± 1.5064	25.6
86667 2000 FO10	17.566 ± 0.647	0.8594	0.5947	14.2877	-0.4452 ± 0.6404	135
225312 1996 XB27	21.816 ± 0.490	1.1889	0.0579	2.4646	0.6896 ± 1.7706	3215
2009 TK	22.274 ± 0.400	1.3083	0.2047	20.172	-3.1637 ± 2.7426	840
422638 1994 CB	21.116 ± 0.481	1.1494	0.1451	18.2552	0.1094 ± 1.3178	73.5
5797 Bivoj	18.662 ± 0.448	1.8932	0.4441	4.1881	-0.0000 ± 0.5781	482
52381 1993 HA	20.071 ± 0.439	1.2782	0.144	7.7254	0.0490 ± 1.0172	413
345705 2006 VB14	18.557 ± 0.485	0.7669	0.4213	31.0228	-0.6729 ± 0.7332	162
276033 2002 AJ129	18.706 ± 0.486	1.371	0.9149	15.4489	-0.2423 ± 0.4886	281
2000 TH1	22.582 ± 0.407	2.3113	0.5401	12.1485	0.6264 ± 3.1618	297
152742 1998 XE12	19.029 ± 0.559	0.8782	0.739	13.4331	1.0929 ± 0.7147	131
247517 2002 QY6	19.581 ± 0.573	0.8169	0.699	12.753	-1.5487 ± 0.9898	136
2008 HU4	28.265 ± 0.529	1.0714	0.0556	1.3911	-3.8431 ± 12.5040	16.4
3757 Anagolay	19.07 ± 0.319	1.8348	0.4454	3.8678	-0.5742 ± 0.8491	247
161989 Cacus	17.157 ± 0.560	1.1231	0.214	26.0603	-0.4993 ± 0.3171	694
5604 1992 FE	17.237 ± 0.461	0.9288	0.4061	4.7135	-0.3873 ± 0.5072	36
7341 1991 VK	16.837 ± 0.471	1.8415	0.5064	5.4154	-0.6478 ± 0.4317	76
65679 1989 UQ	19.402 ± 0.589	0.915	0.2647	1.2998	-3.6023 ± 0.5838	21.5
99942 Apophis 2004 MN4	18.901 ± 0.541	0.9226	0.1915	3.3368	-7.5403 ± 1.9458	25.9
136582 1992 BA	19.844 ± 0.637	1.3417	0.0677	10.4974	-4.9227 ± 0.0990	455
162117 1998 SD15	19.111 ± 0.582	0.9325	0.3448	26.7989	-1.5792 ± 0.2065	83.6
162783 2000 YJ11	20.602 ± 0.573	1.3131	0.2321	7.2628	-12.5120 ± 2.4516	503
163023 2001 XU1	19.26 ± 0.602	0.7973	0.5463	27.153	3.9747 ± 0.8200	142
192559 1998 VO	20.363 ± 0.554	1.0747	0.2265	10.0611	-2.9000 ± 0.4847	86
226554 2003 WR21	19.52 ± 0.561	1.1186	0.2615	9.274	-5.0476 ± 1.9819	68
283457 2001 MQ3	18.906 ± 0.577	2.2342	0.4545	5.5662	-3.6894 ± 0.7057	419
326354 2000 SJ344	22.67 ± 0.288	1.14	0.1746	5.7671	-16.1930 ± 2.3908	72
348306 2005 AY28	21.528 ± 0.524	0.8724	0.5701	5.8837	-6.7803 ± 1.1497	60
410777 2009 FD	22.133 ± 0.409	1.1637	0.4929	3.1278	-0.2037 ± 3.2519	36
437841 1998 HD14	20.918 ± 0.597	0.9632	0.3127	7.807	-7.5646 ± 1.3729	37.5
467351 2003 KO2	20.433 ± 0.544	0.7276	0.5107	23.5002	9.5899 ± 1.6788	165
474163 1999 SO5	20.941 ± 0.544	1.0859	0.0652	13.3655	-6.6492 ± 1.5922	54.5
480883 2001 YE4	20.859 ± 0.511	0.6768	0.5404	4.8449	-6.8562 ± 0.0598	46.7
481442 2006 WO3	21.631 ± 0.470	0.7997	0.4474	21.2121	-6.5295 ± 0.9720	208.5
499998 2011 PT	24.048 ± 0.365	1.3127	0.215	2.2117	-22.3190 ± 2.0356	32
506590 2005 XB1	21.818 ± 0.518	1.131	0.4186	8.7079	8.9094 ± 1.0956	70

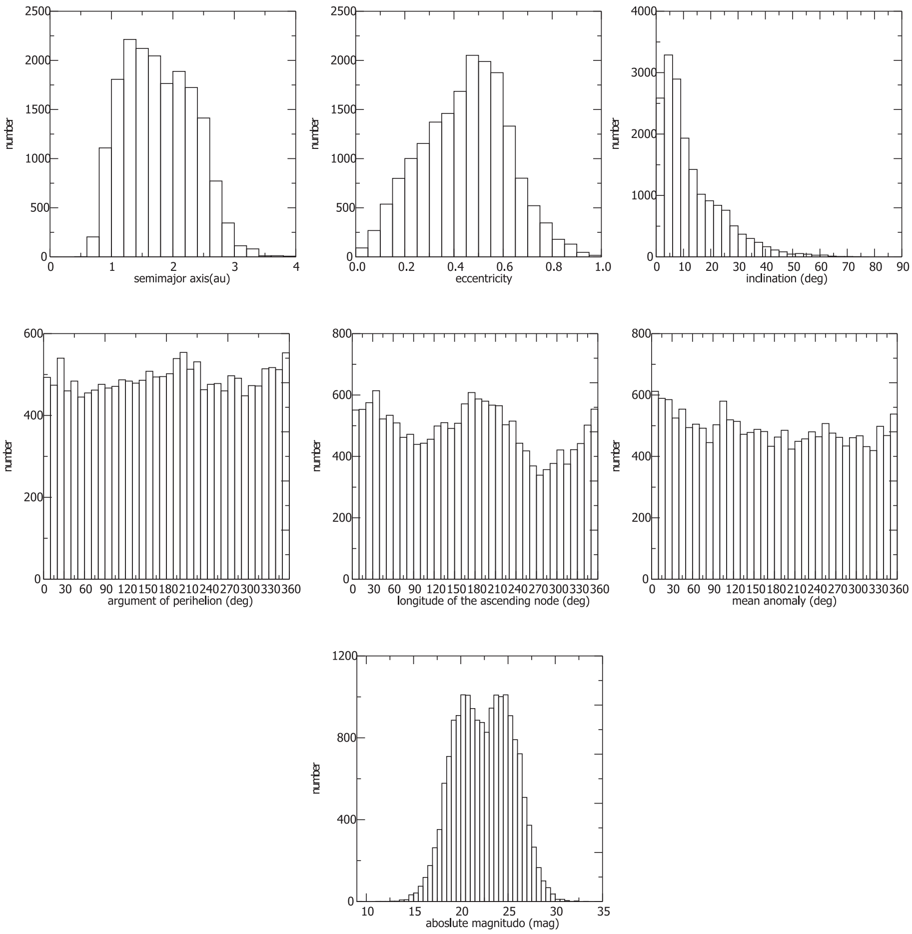

Fig. 1. Histograms of orbital elements and absolute magnitudes for 17653 NEOs from the Lowell catalogue, epoch December 13, 2017 updated on January 30, 2018.

a, eccentricity, e, orbital inclination, i, non-gravitational parameter, $A2$ and Lyapunov time, LT. Orbital elements are computed for the epoch JD2458000.5=September 4, 2017. Observations are updated to Dec. 24, 2017.

The computations of the A2 Yarkovsky parameter were made possible thanks to the new operative version of the OrbFit Software, namely OrbFit5.0. We used the new version 5.0.5 (http://adams.dm.unipi.it/∼orbmaint/orbfit/). Parameter $A2$ was computed directly from the observations. We used the same method of computations of the non-gravitational parameter as in the case of asteroid (99942) Apophis in Wlodarczyk (2017). For the first 121 NEAs we computed sim-

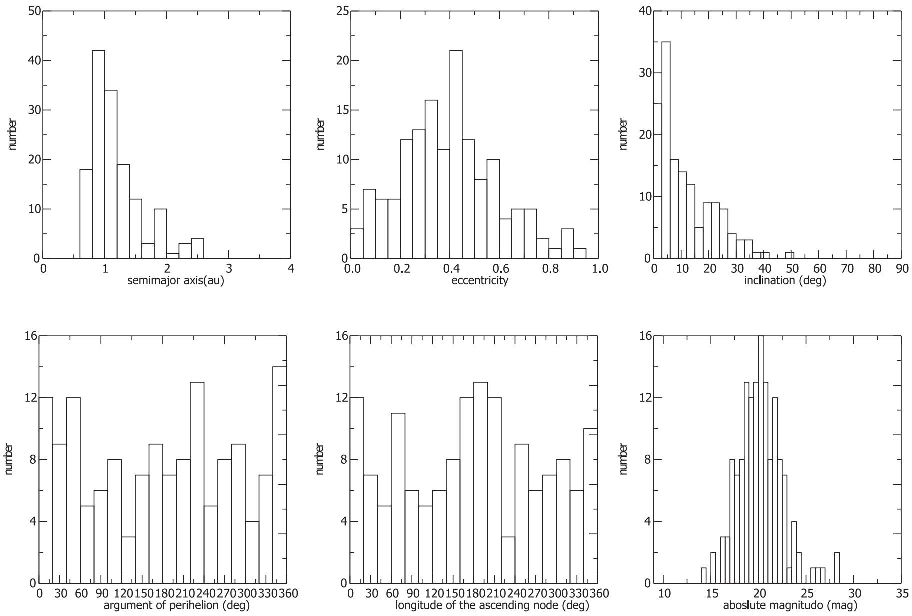

Fig. 2. Histograms of orbital elements and absolute magnitudes for 146 studied NEOs.

ilar values of non-gravitational parameter $A2$ as in the mentioned paper Tardioli et al. (2017).

Fig. 3 presents the histogram of the non-gravitational parameter $A2$ of studied 146 NEAs. We found that 102 NEAs have $A2 < 0$, of about 70% of all studied NEAs and with maximum value in the range (0,-1.0) 10^{-14} au/day^2 which gives about 15.7% of the studied NEAs. On the other hand, the remaining 30% NEAs with positive $A2$ have their maximum value in the range (+2,+3) 10^{-14} au/day^2 which is about 4.5% of studied NEAs.

Fig. 4 presents the interesting relationship between non-gravitational parameter $A2$ of studied 146 NEAs vs. their magnitude H together with their uncertainties. For H>21 mag we observe the advantage of asteroids with $A2$ <0.

Computations of the Lyapunov time are presented in Section 4.

3. Absolute magnitude

Fig. 5 presents the relationship between absolute magnitude and its uncertainty of 146 studied NEAs. Computations were made with the use of the OrbFit software and are presented in Table 1. It is a visibly poor relationship between these values till H=24.5 mag. For observations of NEAs fainter than 24.5 mag, we observe a constant (flat) relation. Additionally, at the end of the H scale, there are a small number of observations of NEAs.

$$\varDelta H = -0.0123 \times H + 0.7685 \quad (1)$$

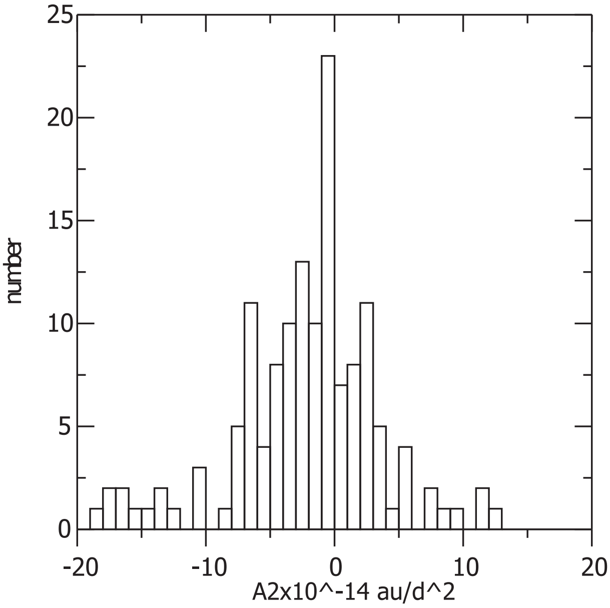

Fig. 3. Histogram of the non-gravitational parameters $A2$ of studied 146 NEAs.

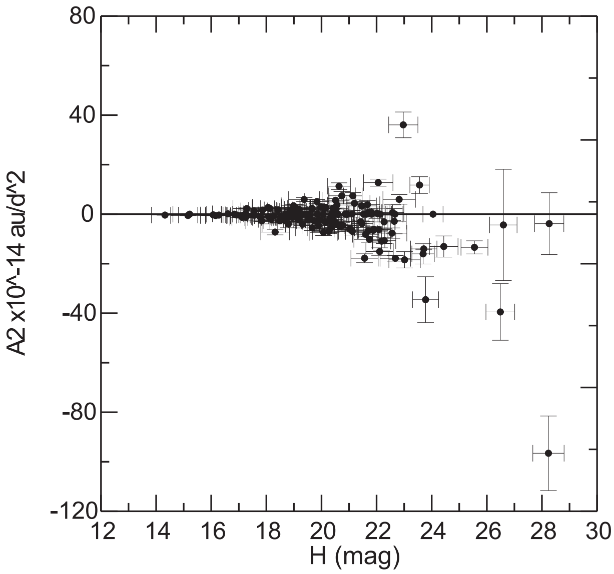

Fig. 4. 146 non-gravitational parameter $A2$ of studied NEAs vs. their magnitude H.

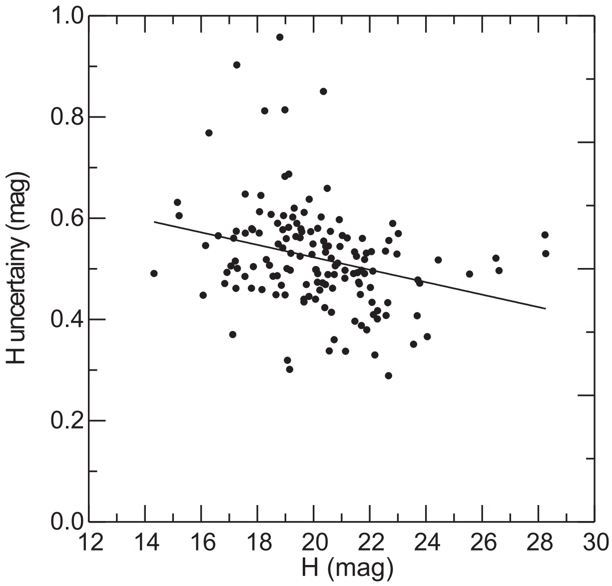

Fig. 5. Values of absolute magnitude H of 146 studied NEAs vs. their absolute magnitude uncertainties.

Eq.1 is based on 146 points. $\overline{H} = 20.1636$, $\overline{\Delta H} = 0.5206$, where $\overline{H}$ denotes average of absolute magnitude, H and $\overline{\Delta H}$ average of uncertainty of absolute magnitude H. Coefficient of determination, R-squared $= 0.077$.

Table 4 presents studied NEAs with chosen H and ΔH. Both the two first cases in Table 4 refer to numbered NEAs. The reason for the difference in computed ΔH can be the Yarkovsky effect. We compute orbit with the non-gravitational parameter $A2$, and with 17 perturbing massive asteroids. In the third case, with the faintest NEAs, we have non-numbered asteroids and the error of the mean absolute magnitude, $\overline{H}$ is equal to 0.5 mag. In fact, photometric measurements have significant biases and there is no robust weighting scheme. NEODyS weights each photometric observation at 1 mag and so the reported uncertainties are more a measure of the number of observations than real uncertainties. Moreover, larger objects should have more observations and in turn smaller magnitude uncertainties. On the other hand, currently discovered NEAs, usually have greater magnitudes of about 22 or so, have smaller magnitude errors because of better telescopes, CCDs, catalogs, and the number of observations speaking for old NEAs has nothing to do with it. Our calculations result from observation analysis, not from theoretical considerations.

Table 2. Studied NEAs with chosen H and ΔH

Object	H(mag)	ΔH(mag)
the smallest errors in absolute magnitude		
326354 (2000 SJ344)	22.67	0.2888
373393 1972 RB	19.148	0.3013
3757 Anagolay	19.07	0.3192
2005 GR33	22.184	0.3298
425755 2011 CP4	21.138	0.3371
the greatest errors in absolute magnitute		
138258 2000 GD2	18.799	0.9578
1221 Amor	17.267	0.9029
41429 2000 GE2	20.353	0.8505
6489 Golevka	18.979	0.8143
363505 2003 UC20	18.26	0.8123
the greatest absolute magnitude with their errors		
2008 HU4	28.265	0.5299
2009 BD	28.236	0.5670
2003 XV	26.601	0.4964
2014 UR	26.491	0.5210
2008 CE119	25.553	0.4896

4. Lyapunov Time

Next we computed Lyapunov time (LT) for 146 selected NEAs - see Table 1. Our method is based on Knežević & Milani (2000) and Milani & Nobili (1988). In computations of LT we used filter 5 yr as is implemented in the software Orbit9 included in the OrbFit software. We used the JPL DE403 with perturbations of the planet from Venus to Neptune and Pluto. For Mercury we used the barycenter correction.

In Whipple (1995) there are computed values of Lyapunov times for the 175 numbered asteroids whose osculating perihelion distances were less than 1.6 au as at August 1, 1993. It appeared that 75% of these asteroids have Lyapunov time shorter than 100 years including 18 asteroids with Lyapunov time shorter than 50 years. In Tancredi (1998), Gladman et al. (1997) and Ito & Malhotra (2006), the typical Lyapunov times of the Jupiter family comets and the Near Earth Asteroids are 100 yr, whereas their dynamical lifetimes are 10^7 yr. In 146 NEAs studied, we computed Lyapunov times from 16.4 yr for asteroid 2008 HU4 to 9274 yr for asteroid (350462) 1998 KG3 – see Table 1. It appeared that we find 103 asteroids with $LT \leq 200$ yr, among other 43 asteroids with $LT \geq 200$ yr 14 NEAs have $LT \geq 500$ yr and 7 have $LT \geq 1000$ yr. Other 22 NEAs have LT in the range (200÷500) years.

For 146 studied NEAs, the maximum value of LT is between 20 and 60 years – see Fig. 6. In this range we observe 50 NEAs, i.e. of about 34% of all studied NEAs. Fig. 7 presents positions of the first 20 selected NEAs with the shortest LT, and first 20 with the longest TL among known 17653 NEAs. It is visible that the NEAs with shorter LT are placed between the Earth and Mars lines where asteroids are dynamically influenced by the perihelia of these planets. On the contrary, studied NEAs with longer LT are concentrated between lines where they are dynamically influenced by aphelia of the Earth and Mars.

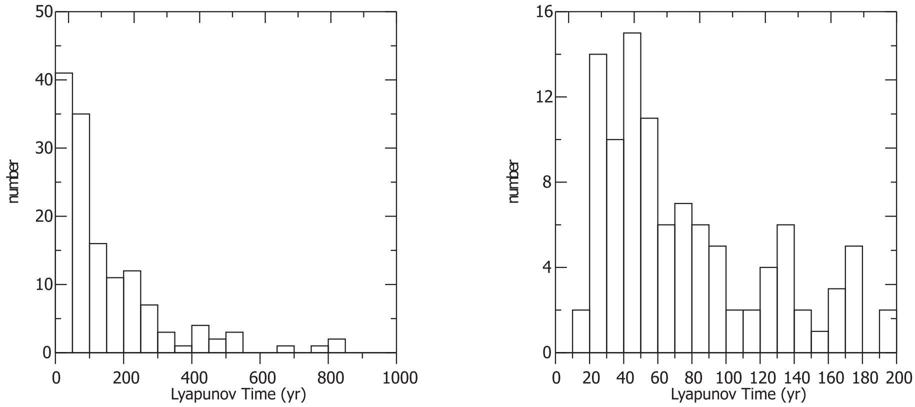

Fig. 6. Histograms of the Lyapunov time of selected 146 NEAs. In the right panel there is truncated histogram to $LT \leq 200$ yr.

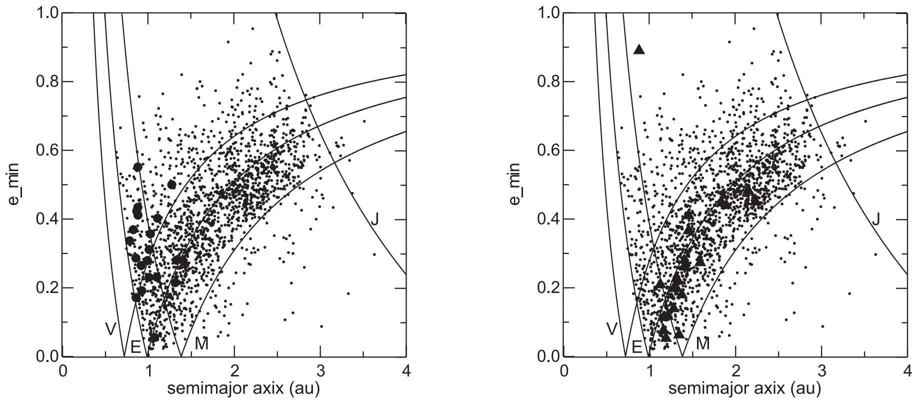

Fig. 7. Positions of the first 20 selected NEAs with the shortest LT - left, and first 20 with the longest TL - right panel. For clarity positions of all existing 17653 NEAs are shown every 10.

Fig. 8 presents the relationship between non-gravitational parameter $A2$, in 10^{-14}au/d^2, and Lyapunov time (LT), in years, of studied 146 NEAs. It is visible, that for $LT \geq$ 400 yr $A2$ is close to 0. For other values of LT, we observe the advantage of negative $A2$ values, about 70% of all studied NEAs – see also Fig. 4.

5. Secular parameters

In Fig. 9 there are presented the positions of the NEAs according to catalog.tot from the NEODYS-2 site:
http://newton.dm.unipi.it/neodys/index.php?pc=5. As of January 21, 2018

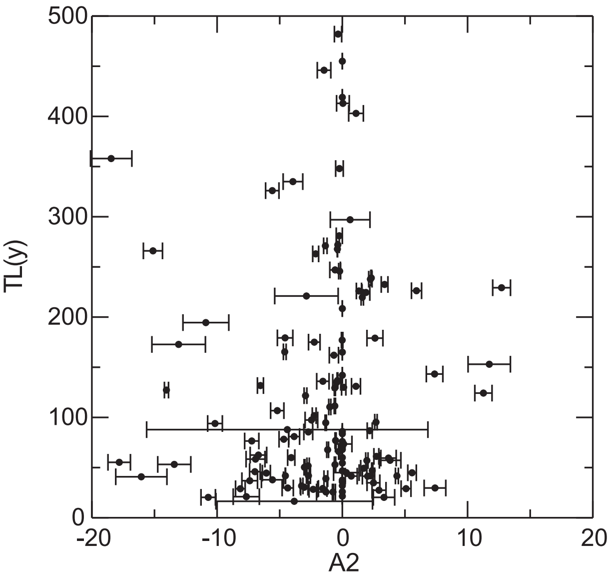

Fig. 8. Non-gravitational parameter $A2$ in 10^{-14}au/d^2 vs. Lyapunov time (LT) in years of studied 146 NEAs. The range of $A2$ is cut to $\pm$ $20{\times}10^{-14}$au/d^2 and TL to 500 yr. Errors of $A2$ are reduced by half.

there are 17506 NEAs. 10 NEAs with $a{>}4$ au are not presented in Fig. 9. Letters V, E and M denote aphelia and perihelia of asteroids controlled by Venus, Earth and Mars, respectively, and J - perihelia controlled by Jupiter. Generally, close encounters of NEAs with planets are possible between their lines of aphelion and perihelion.

In the original figure in the above NEODYS-2 site, there are shown position of asteroids affected by the main secular resonances. Some asteroids have the argument of perihelion in libration; thus the libration frequency is called lf, while g is undefined (A. Milani - private information). We counted 413 and showed them by big dots. They will be needed for the analysis of crossing orbits of NEAs with planets in the further part of this work.

In Fig. 10 we present asteroids whose proper frequency are close to the planetary frequencies $g6$, $g5$ and $s6$. They are denoted by $g60$, $g50$ and $s60$, respectively. They are chosen from 17506 NEAs using the NEODys catalogue.tot. In the bottom right panel, we chose asteroids from our studied 164 NEAs with minimum LT, $LTmin$ (20 NEAs) and maximum LT, $LTmax$ (20 NEAs).

Parameters $g6$ and $g5$ are secular precessions of the perihelion of Saturn and Jupiter with frequency $g6$ and $g5$, respectively. Parameter $s6$ is secular precession of the ascending node of Saturn, with frequency $s6$. In catalogue.tot there are presented g and s of the NEAs, both in arcsec/yr, for which we computed values of $g60$, $g50$ and $s60$ using the following relations:

$g6 - 0.5 < g60 < g6 + 0.5$

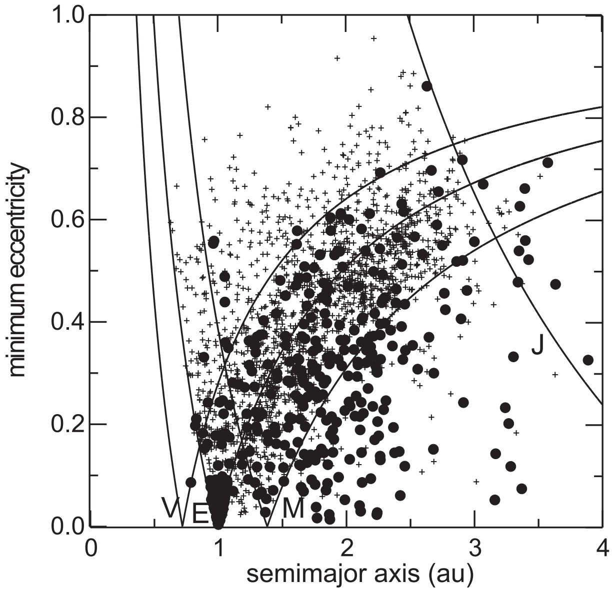

Fig. 9. Position of 17506 NEAs from the NEODyS catalogue updated on January 15, 2018 denoted by crosses; asteroids with the argument of pericenter in libration - by dots.

$g5 - 0.5 < g50 < g5 + 0.5$
$s6 - 15 < s60 < s6 + 15$
where $g5$=4.2575 arsec/yr, $g6$=28.2455 arcsec/yr, $s6$=-26.3450 arcsec/yr. We have chosen 368 NEAs with $g60$, 337 NEAs with $g50$ and 275 NEAs with $s60$. They are presented in Fig. 10. In Fig. 10, bottom right panel, we can see that the studied 146 NEAs with the shortest LT are close to secular resonance $s60$ and with the longest LT are in other places - mainly they are in the space controlled by aphelia of the Earth and by Mars which is intuitive.

The bottom right panel of Fig. 11 is interesting because of the position of asteroids, which does not cross the orbits of planets. We found 810 NEAs of them in the NEODys catalogue.tot. They are mainly located in the space:
–controlled by aphelion of the Earth and perihelion of Mars
–controlled by aphelion of Mars and perihelion of Jupiter.
In the above given space, there are studied NEAs with the longest LT as is shown in Fig. 10 of the bottom right panel. First NEA which does not cross the planet is the Amor asteroid (10302) 1989 ML in studied catalogue.tot. It is a potential spacecraft target asteroid as is depicted in Mueller et al. (2007).

In Fig. 10 we can see that secular parameters are relevant even in the case when Lyapunov times are of the order of decades. Similar connections were studied for other asteroids: Murray and Holman(1999), Wlodarczyk et al. (2014) and Knežević & Milani (2000), and will be studied by the author in the future.

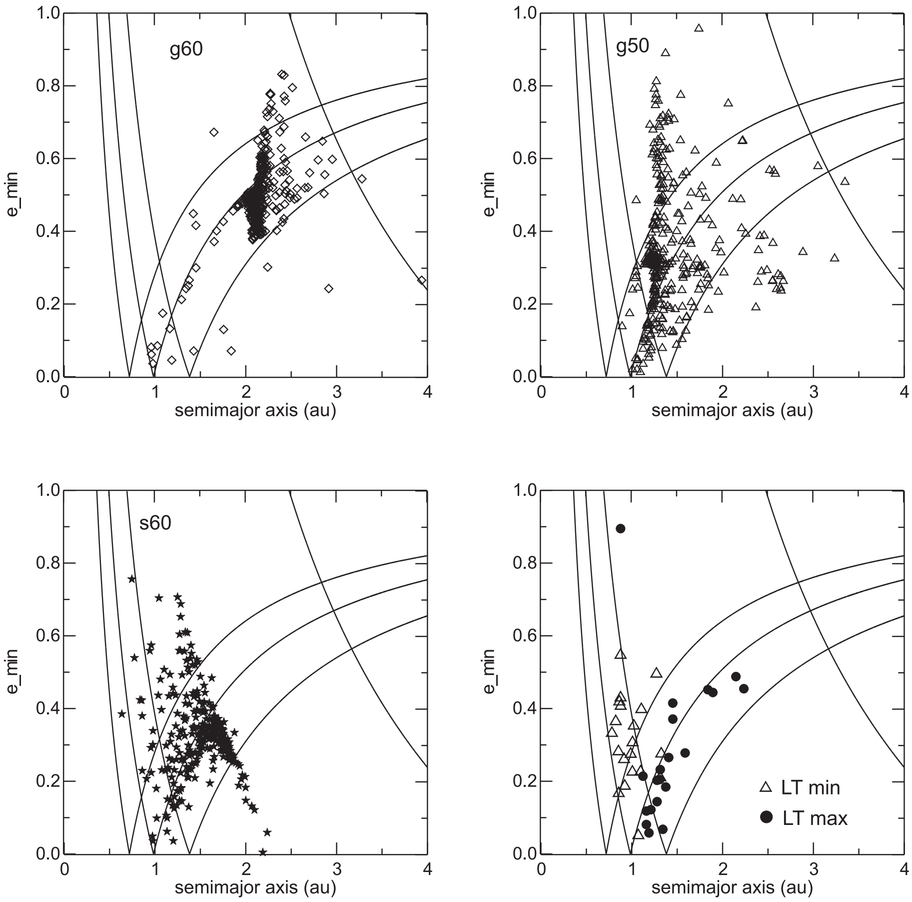

Fig. 10. 17506 NEAs from the NEODys catalogue.tot. Asteroids with a proper frequency close to the planetary frequencies: $g6$, $g5$ and $s6$ are denoted by $g60$, $g50$, $s60$, and presented, respectively. In the bottom right panel are shown asteroids from our studied 164 NEAs with minimum LT, $LTmin$ (20 NEAs) and maximum LT, $LTmax$ (20 NEAs).

Summary

For selected 146 NEAs, we computed their Keplerian orbits, non-gravitational parameters $A2$, Lyapunov times, LT, secular frequencies of perihelia and ascending nodes and their relationships. Also, we have extended the study of these parameters to all NEAs known so far. It turned out that:

–From 146 studied NEAs 102 NEAs have $A2 < 0$, i.e. of about 70% with maximum value in the range (0,-1.0) 10^{-14} au/day^2 which is of about 15.7% of studied NEAs. On the other hand, the remaining 30% NEAs with positive $A2$ have maximum value in the range (+2,+3) 10^{-14} au/day^2 which is of about 4.5% of studied NEAs.

–For 146 studied NEAs the maximum value of LT is between 20 and 60

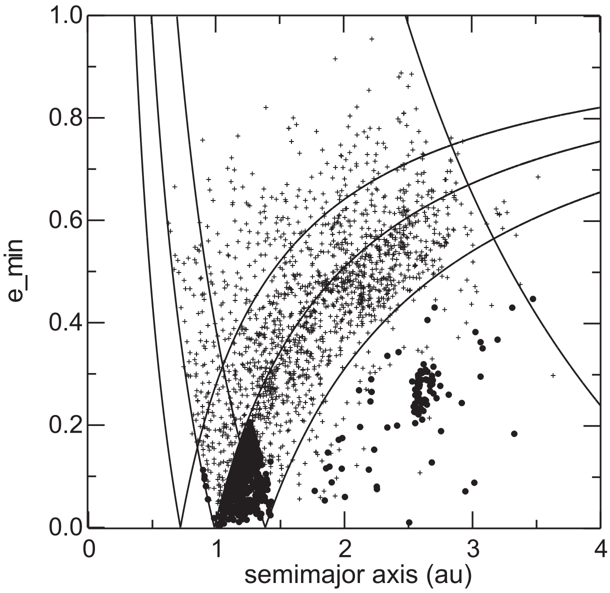

Fig. 11. 810 NEAs that do not cross the orbits of the planet from all NEAs in the NEODyS catalogue.tot. Here there are NEAs with the longest *LT* as is shown in Fig.10.

years. In this range we observe 50 NEAs, i.e. of about 34% of all studied NEAs.

–Studied NEAs with the longest *LT* are mainly located between the space controlled by perihelion of Mars and aphelion of the Earth. Here are NEAs that do not cross the orbit of planets.

-From all 17506 NEAs 368 NEAs have secular frequencies close to secular precessions of the perihelion of Saturn, $g6$, 337 NEAs have secular frequencies close to secular precessions of the perihelion of Jupiter, $g5$, and 275 NEAs have secular frequencies close to the secular precession of the ascending node of Saturn, $s6$, i.e. of about 2.1%, 1.9% and 1.6% of the NEAs population.

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