Dynamical evolution of near-Sun objects

V.V.EMEL'YANENKO

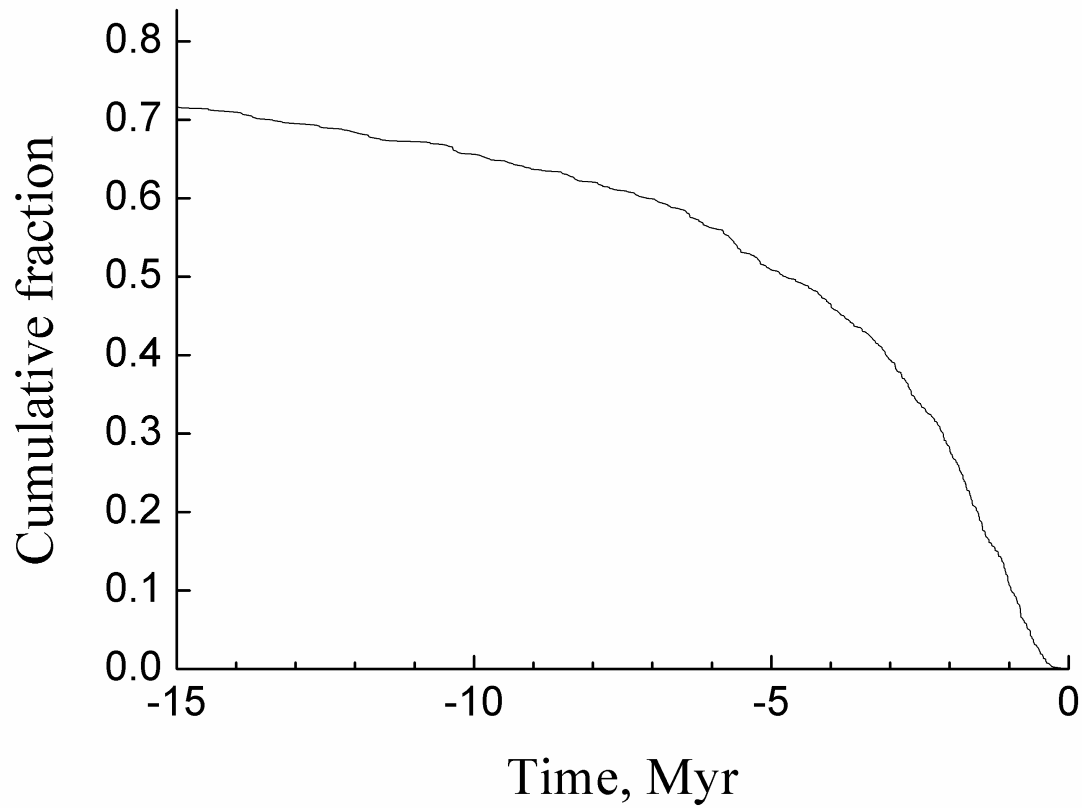
INSTITUTE OF ASTRONOMY RAS

Disruption of a parent body due to the strong solar tide, thermal stresses and interaction with the solar atmosphere at Sun-grazing conditions

It is well known that near-Earth objects evolve frequently to orbits with small perihelion distances (Farinella et al. 1994, Gladman et al. 2000, Foschini et al. 2000, Marchi et al. 2009). It is estimated that up to 70% of near-Earth objects collide with the Sun during their orbital evolution (Marchi et al. 2009).

Photos taken by
Marat Akhmetvaleev

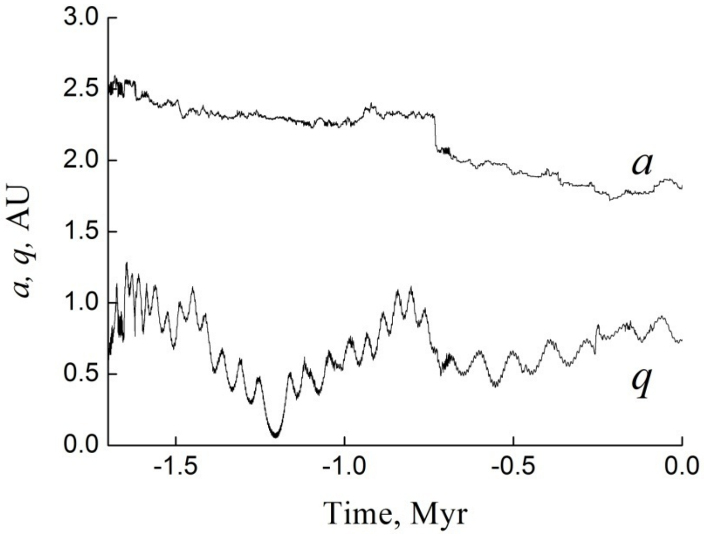
The cumulative fraction of Chelyabinsk clones from the confidence region that reach $q<0.1$ AU in the past (Emel'yanenko, Naroenkov, Jenniskens, Popova, 2014)

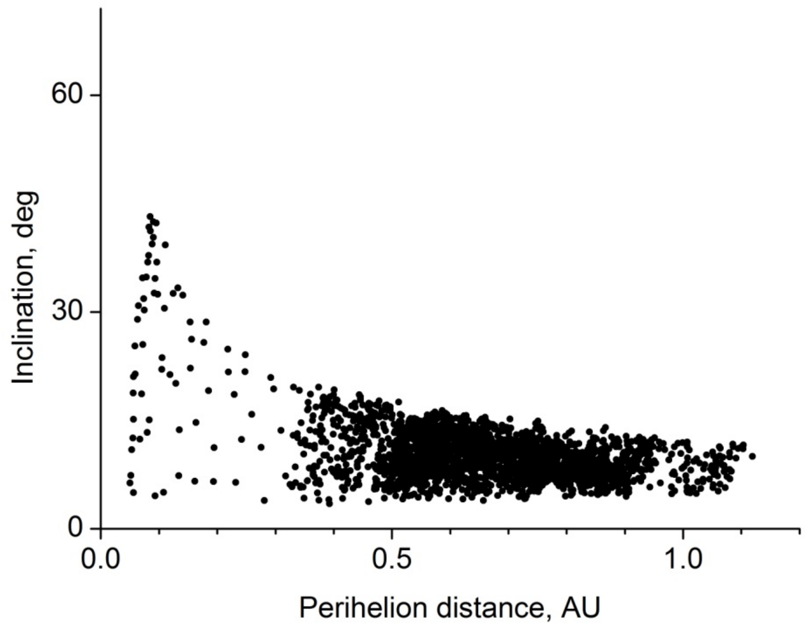


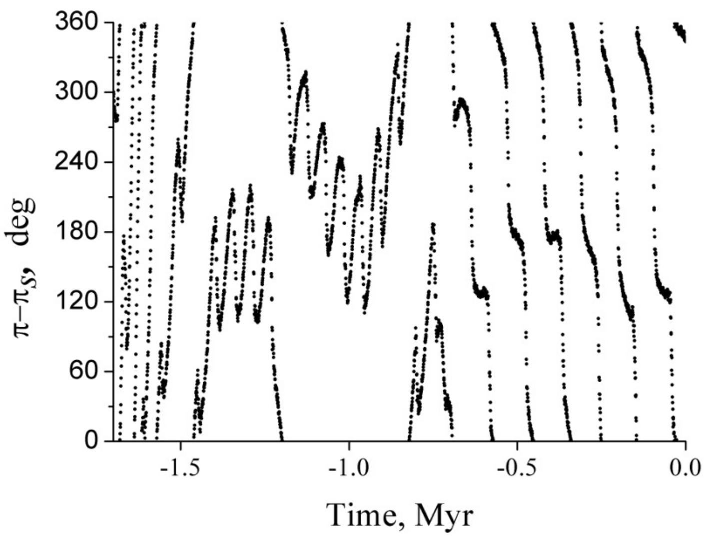
There exists a large probability that the Chelyabinsk object was near the Sun in the past.

The particles become near-Sun objects most frequently in the time interval from 0.8 Myr to 2 Myr. This is consistent with the estimates of a cosmic ray exposure age of 1.2 Myr (Popova et al., 2013; Povinec et al., 2015) and 1.6 Myr (Nishiizumi et al., 2013). It is natural to assume that tidal and thermal effects could lead to disruption of a larger parent body near the Sun.

An example of evolution for a selected particle approaching to the Sun near *t*=1.2 Myr







There are few observed near-Earth objects with small perihelion distances

Object	q, AU	a, AU	i, deg	H
2005 HC4	0.071	1.82	8.4	20.7
2008 FF5	0.079	2.29	2.6	23.1
2015 EV	0.080	2.05	11.4	22.5
394130	0.081	2.60	30.6	17.2
2016 GU2	0.087	2.05	10.2	24.1
137924	0.092	0.88	25.7	17.2
374158	0.093	1.27	23.8	18.8
394392	0.096	0.84	20.8	18.5

Only a few very rare cases (e.g., comet P96/Machholz, in ~ 1 Kyr, Bailey et al. 1992; 2004 LG, in 3.5 Kyr, Vokrouhlicky and Nesvorny, 2012) have definite predictions about solar encounters of real objects in the past (due to uncertainties in the orbital evolution).

Secular perturbations in the restricted circular problem

$$\sqrt{1-e^2}\cos i = c = \mathrm{const}$$

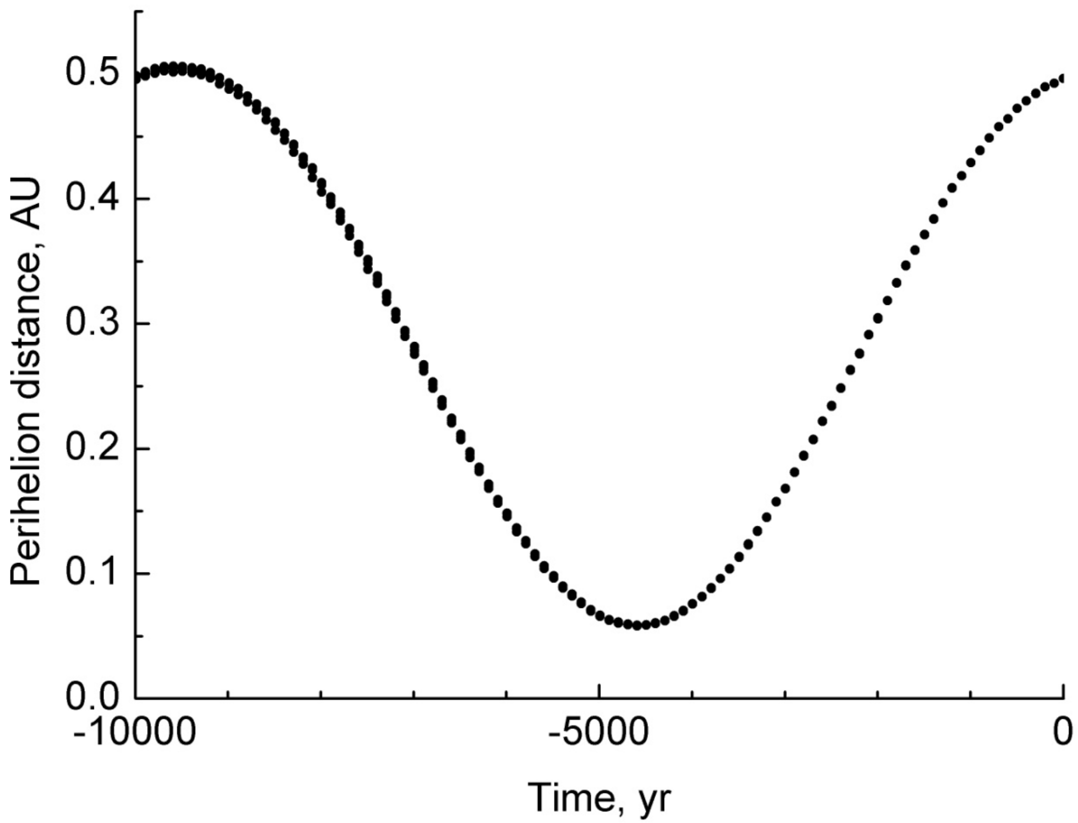
$$q = a(1-\sqrt{1-c^2/\cos^2 i})$$

$$q_{\min} = a(1-\sqrt{1-c^2})$$

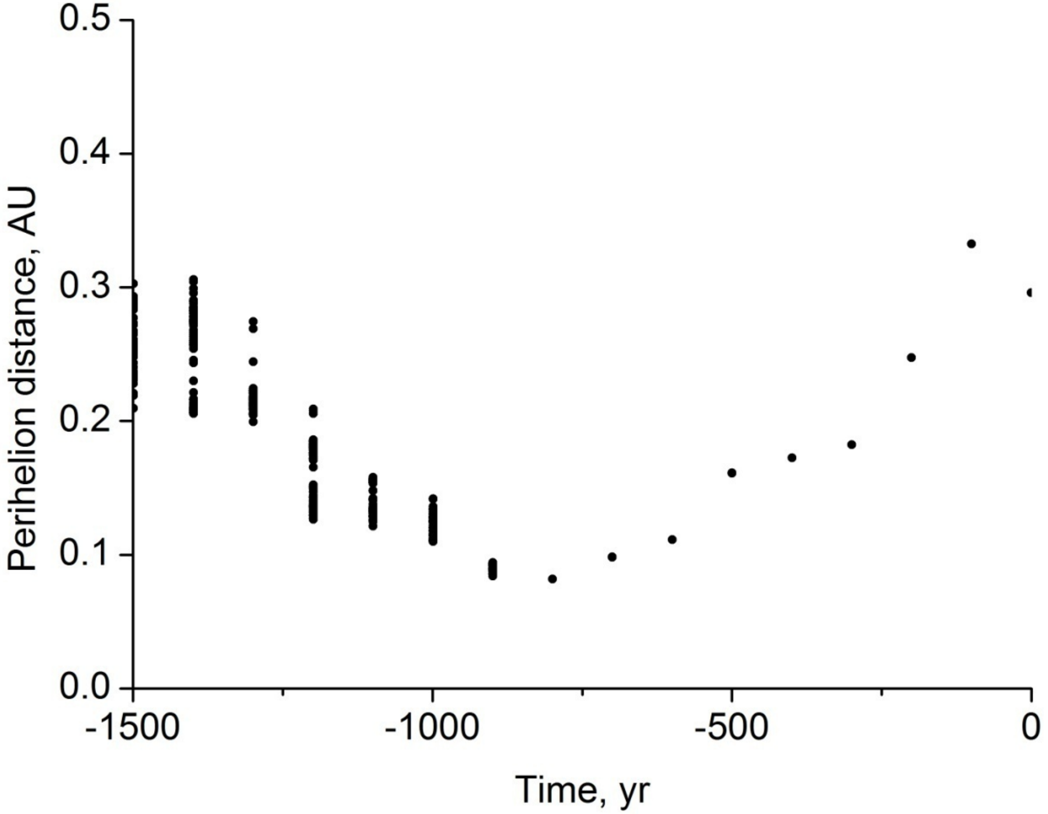
Recent approaches of observed asteroids to the Sun

Object	q_min, AU	t, 10^3 yr	*q*, AU	*a*, AU	*i*, deg	*H*
2004 LG	0.026	-2.4	0.21	2.07	70.9	18.0
2012 FZ23	0.065	-2.9	0.98	2.49	75.4	18.2
2008 KP	0.066	-9.2	0.23	1.10	59.8	19.0
2015 AZ245	0.059	-4.6	0.50	1.86	68.9	16.8
2010 KY127	0.082	-0.8	0.30	2.50	60.5	17.0
2013 JA36	0.095	-6.7	0.14	2.67	42.5	21.0
2011 XA3	0.090	-1.3	0.11	1.47	28.0	20.4
2012 US68	0.071	-7.6	0.11	2.50	25.8	18.2
2015 HG	0.081	-3.4	0.11	2.10	17.8	21.0
2008 HW1	0.098	-2.0	0.10	2.58	10.6	17.4
2011 KE	0.088	-6.4	0.10	2.23	5.9	19.8

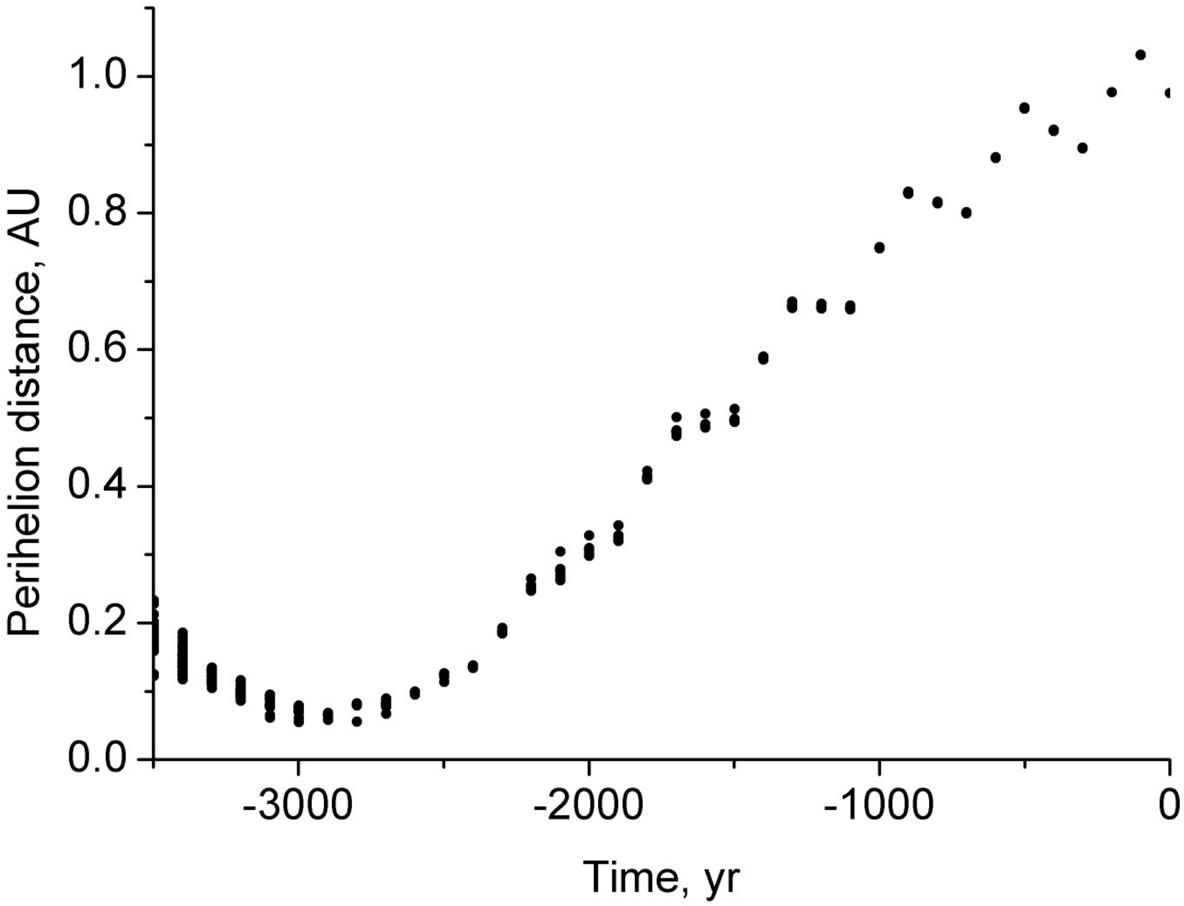
Changes of *q* for 2015 AZ245



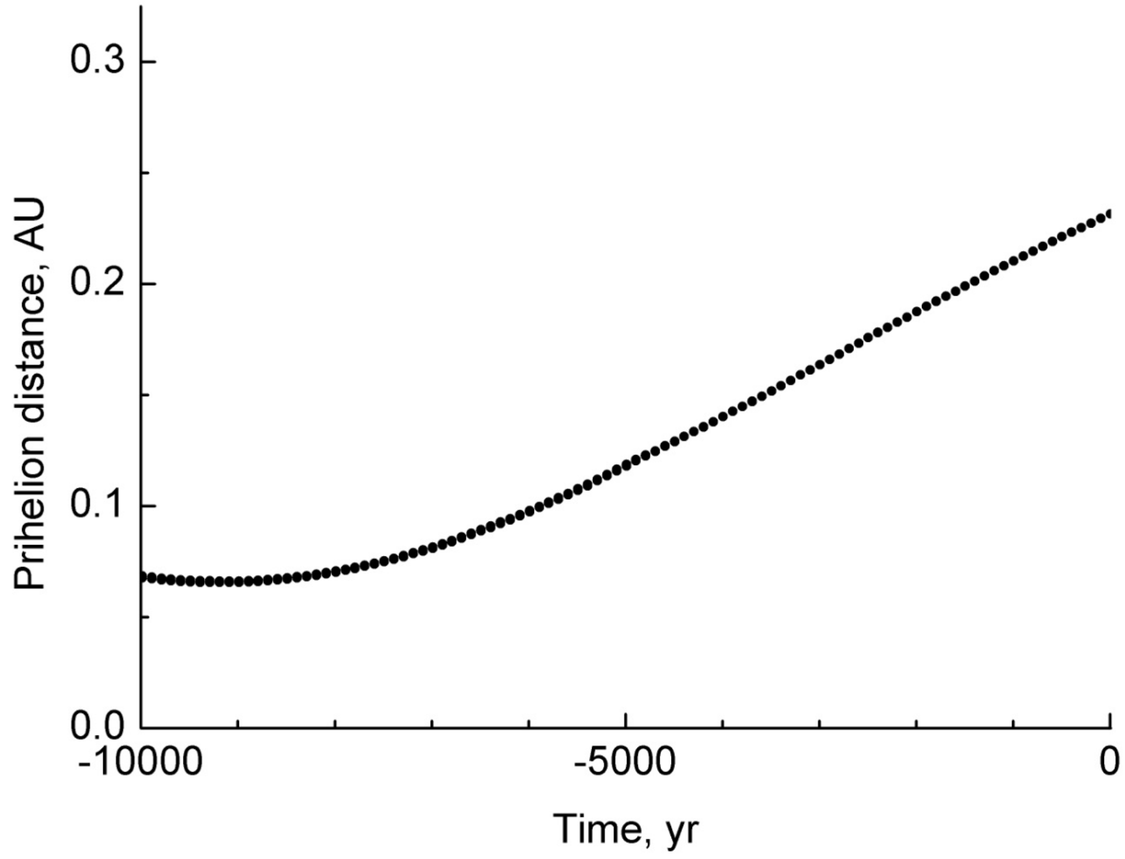
Changes of *q* for 2010 KY127



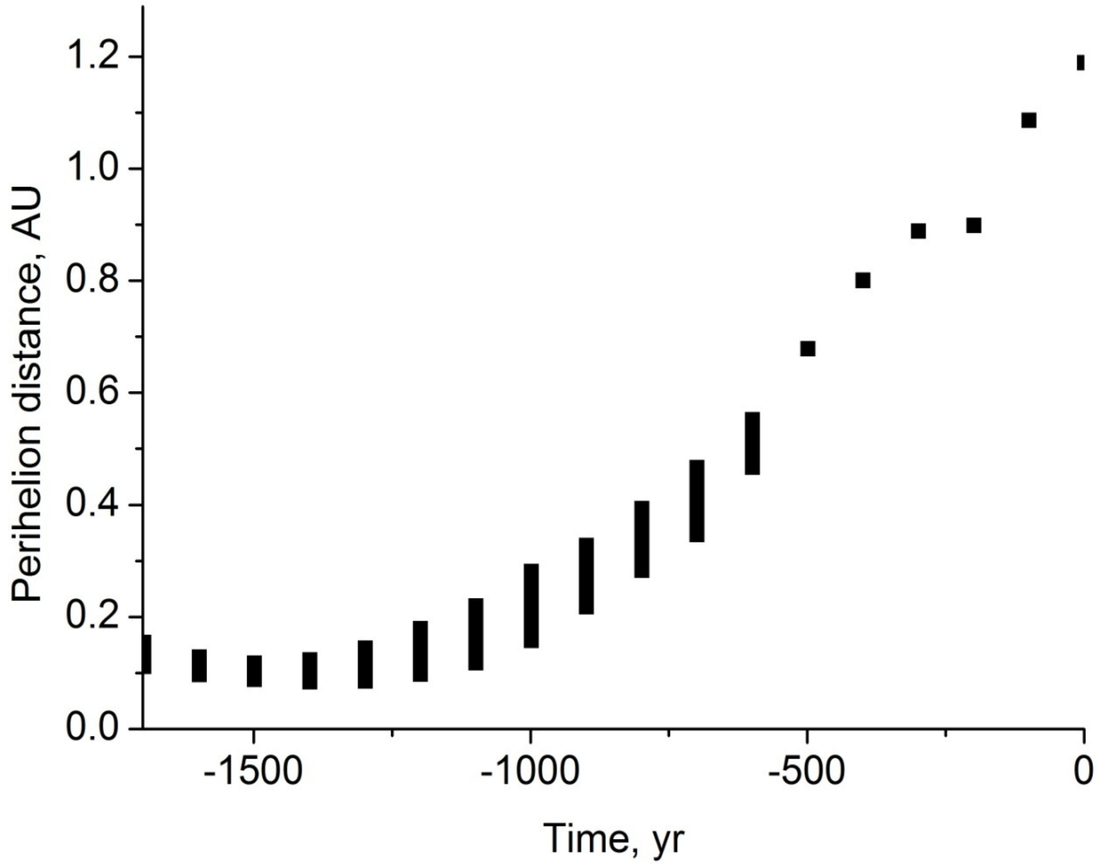
Changes of *q* for 2012 FZ23



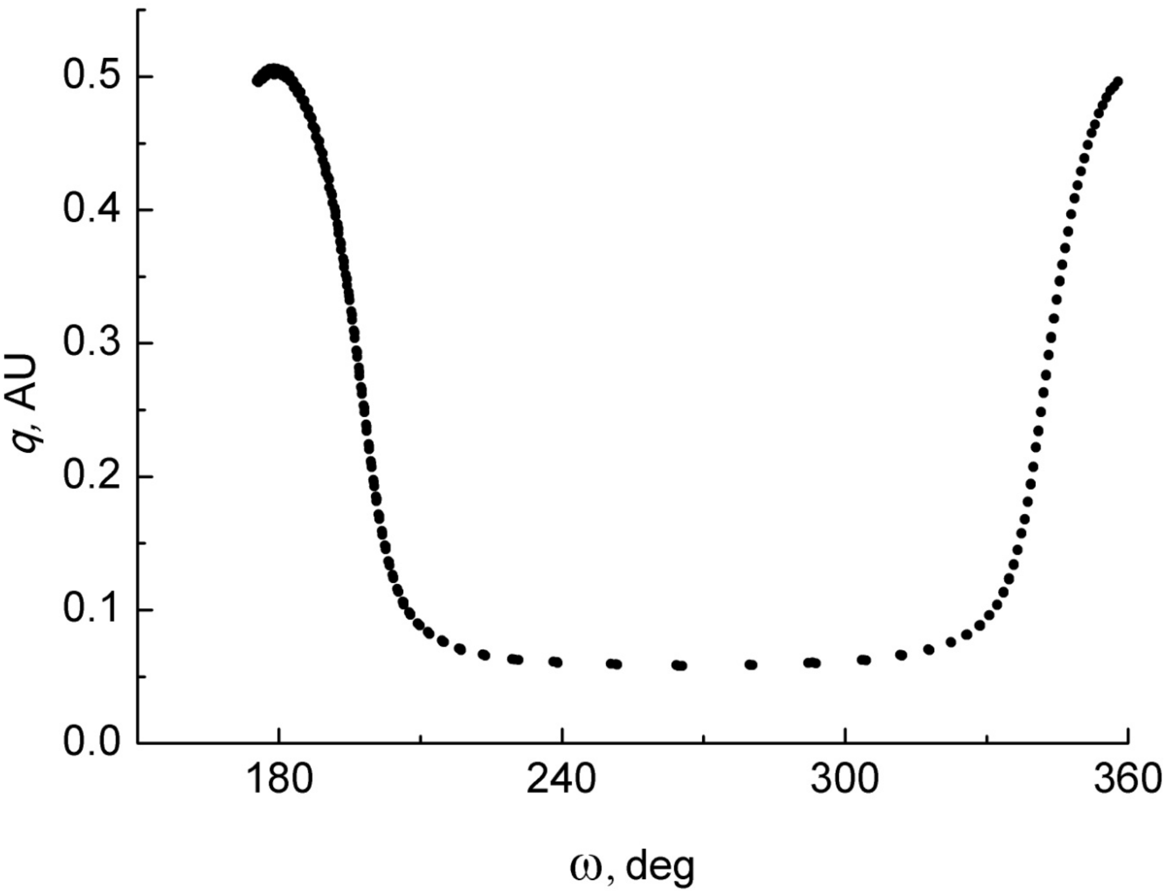
Changes of *q* for 2008 KP



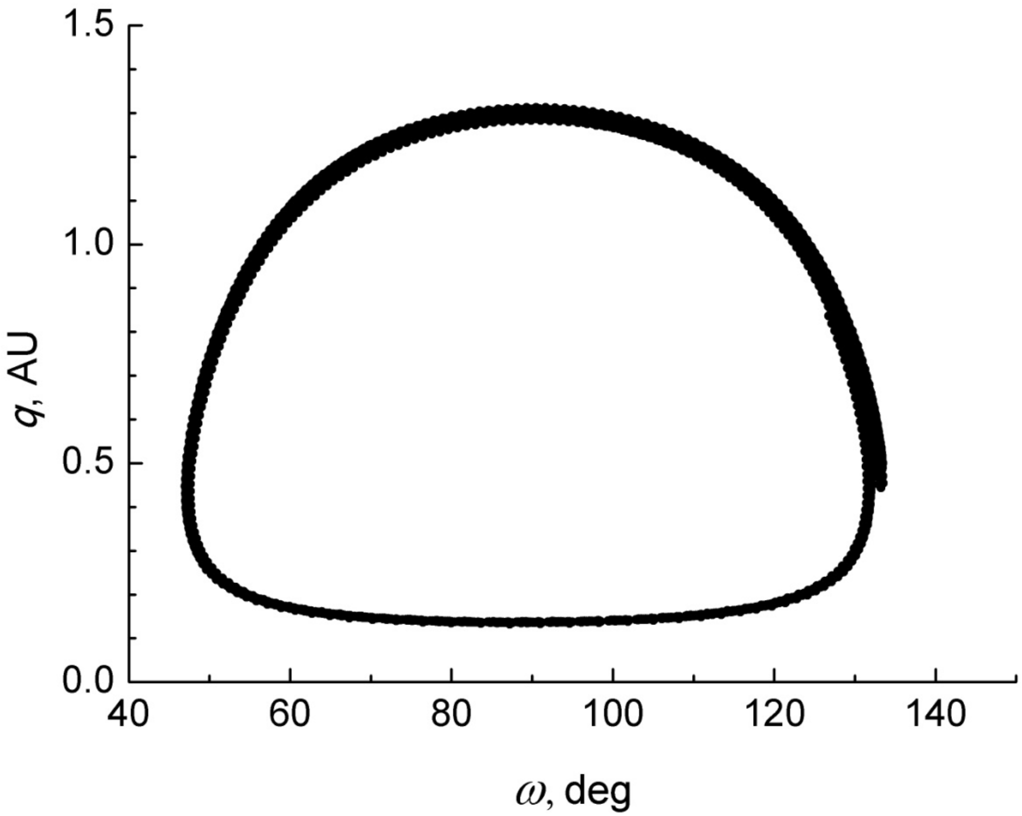
Changes of *q* for 2003 EH1



The Kozai-Lidov oscillation for 2015 AZ245

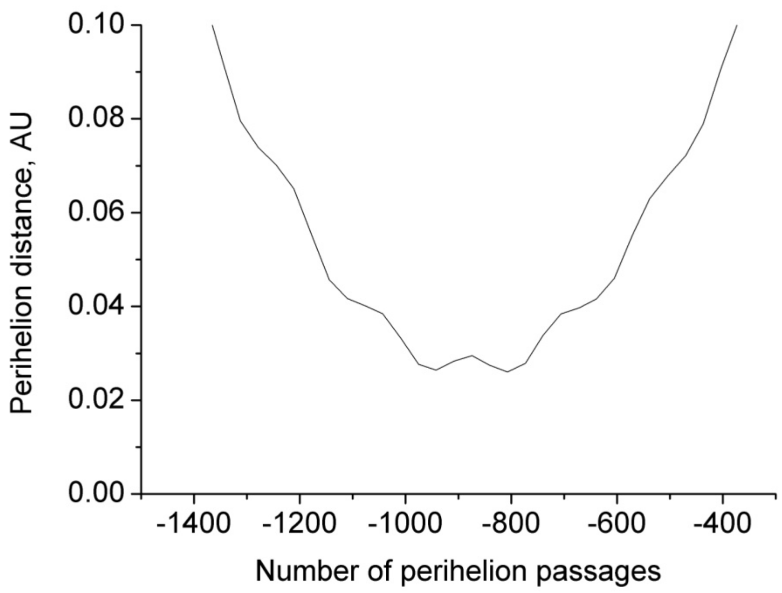


The Kozai-Lidov libration for 2011 LD19

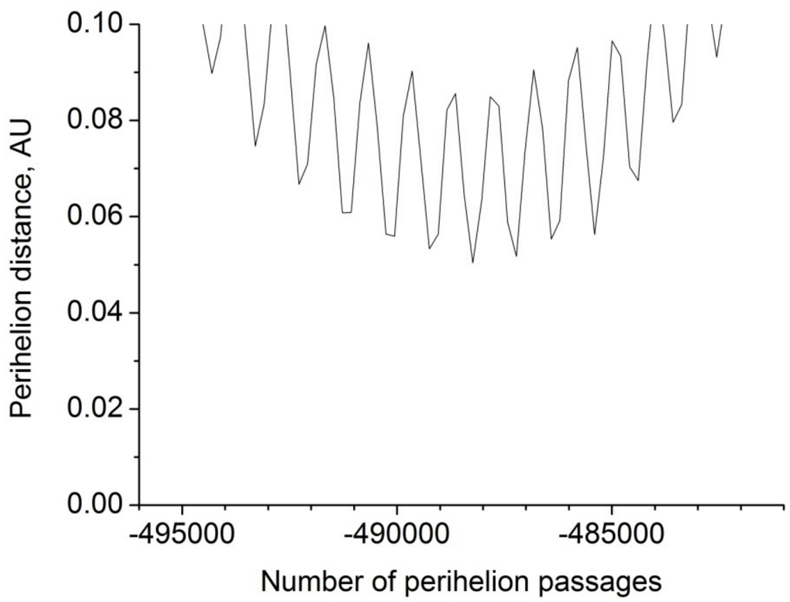


The time elapsed by NEOs at close distances to the Sun can be considerably high, reaching 10% of the typical lifetimes (10 Myr) or, in a few cases, even more (Marchi et al., 2009).

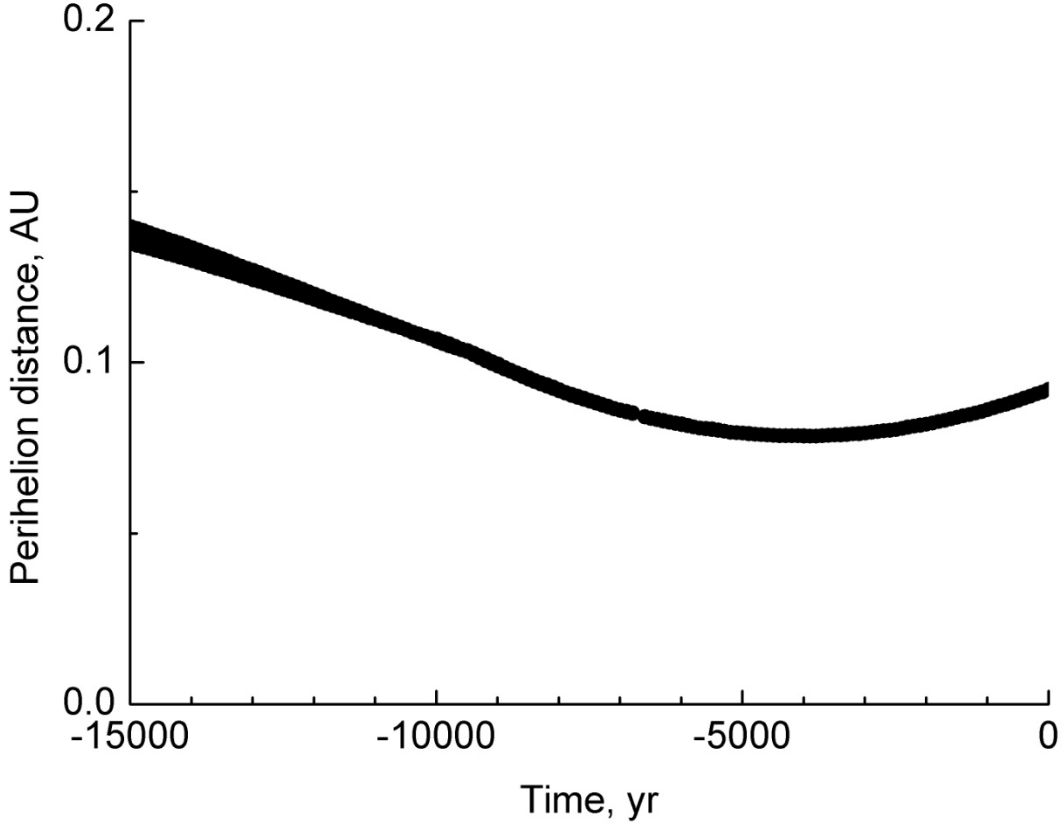
2004 LG (Lidov-Kozai)



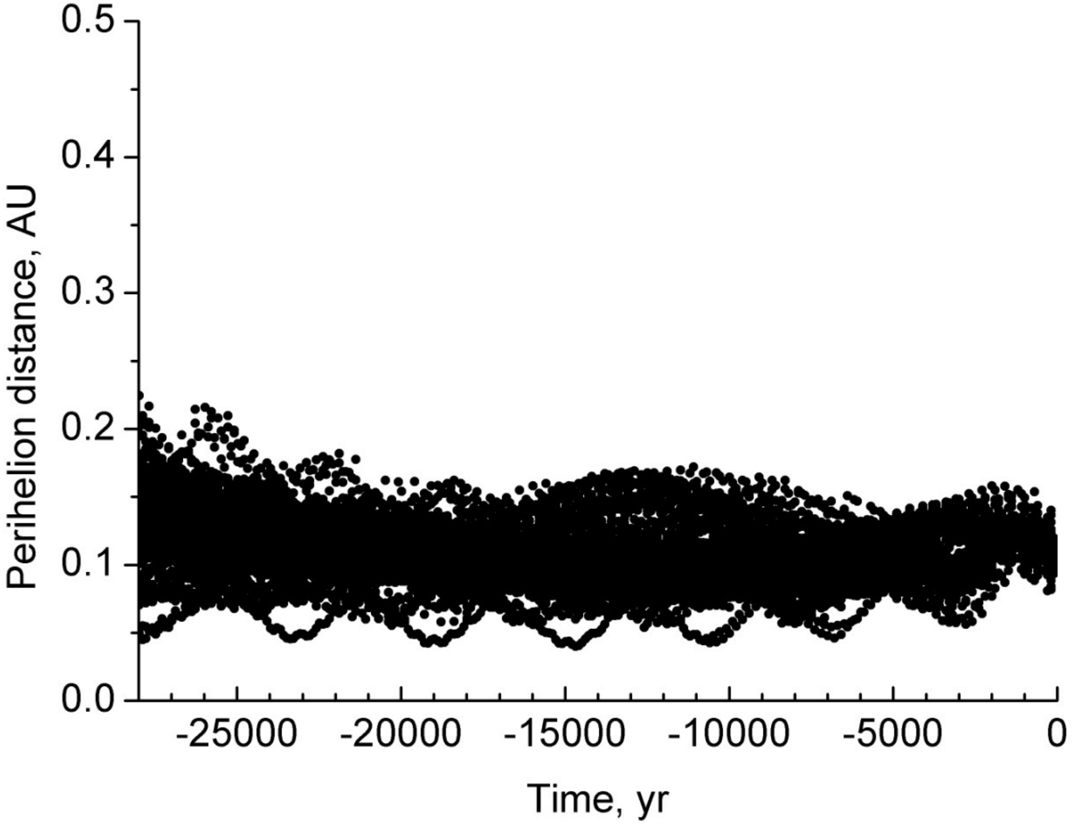
Chelyabinsk-type (ν_6)



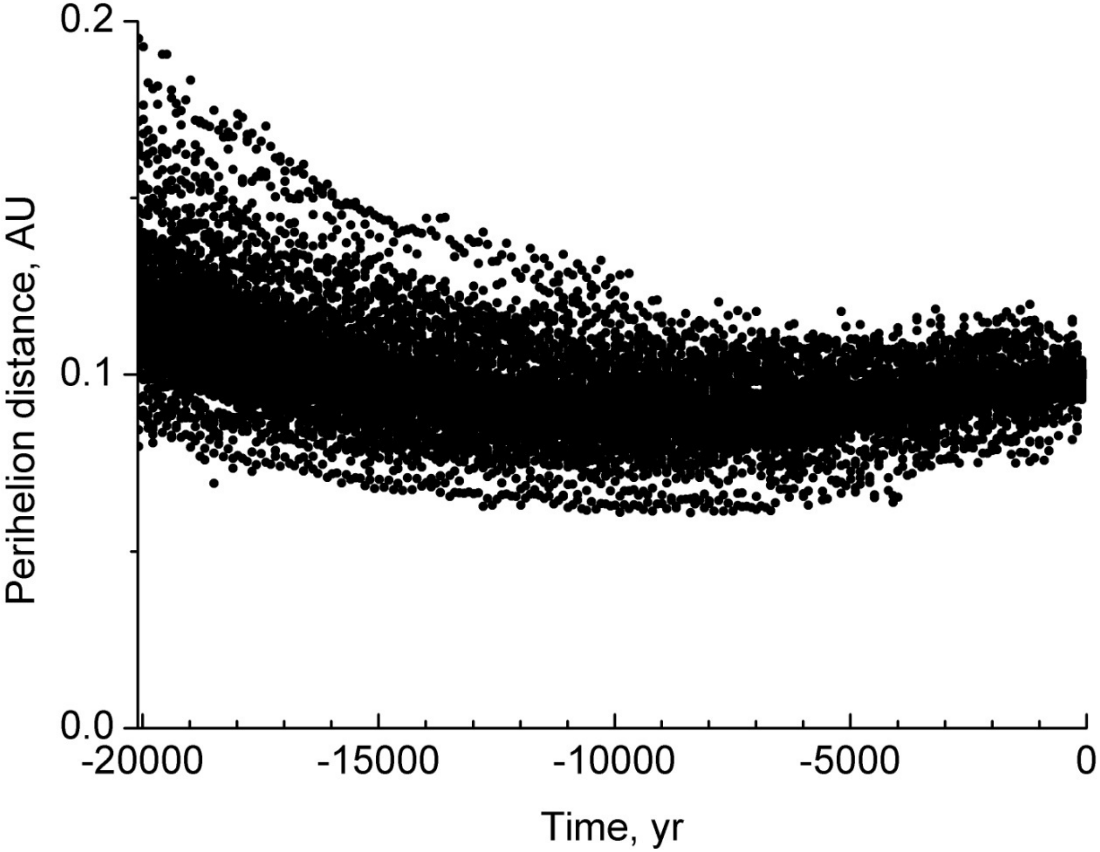
Changes of *q* for 137924



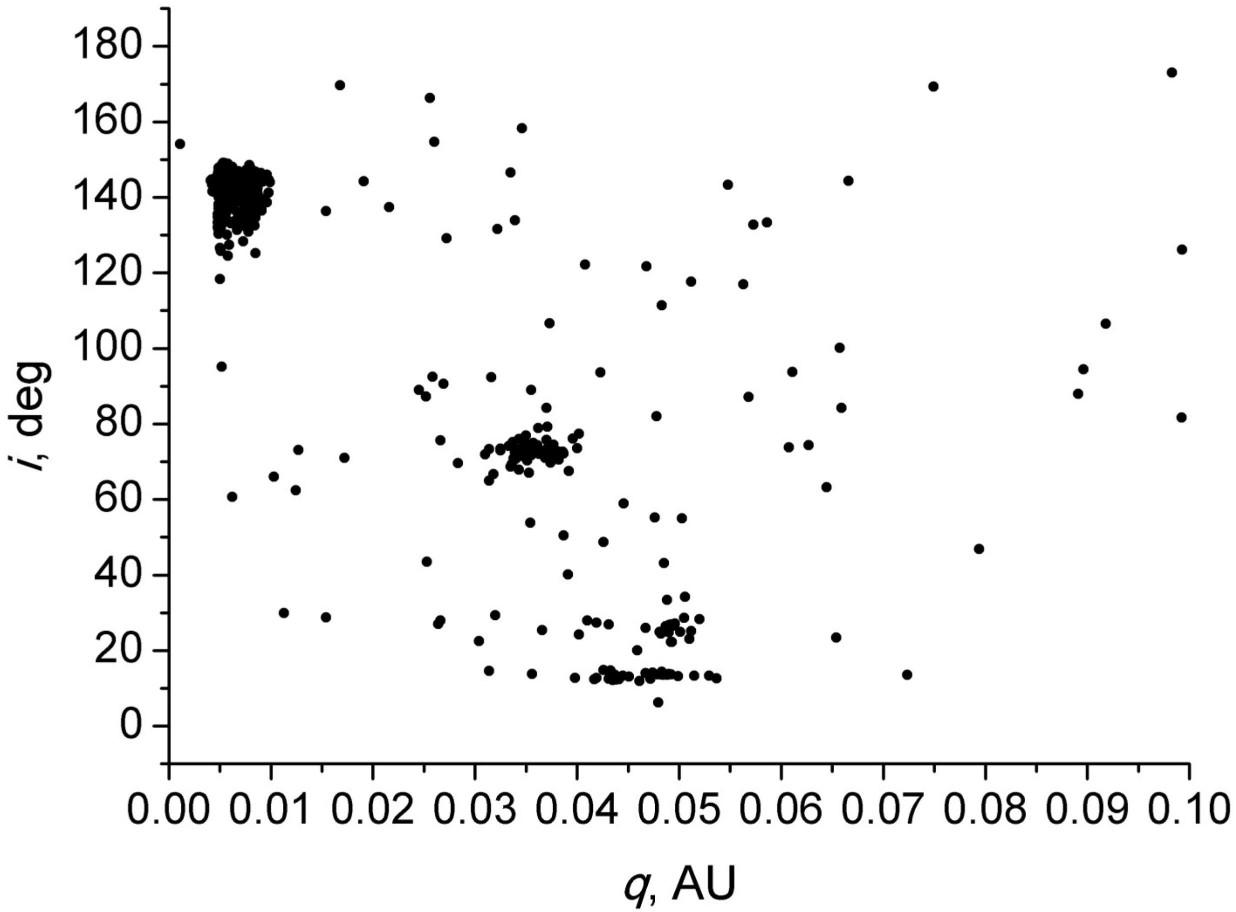
Changes of *q* for 2015 HG



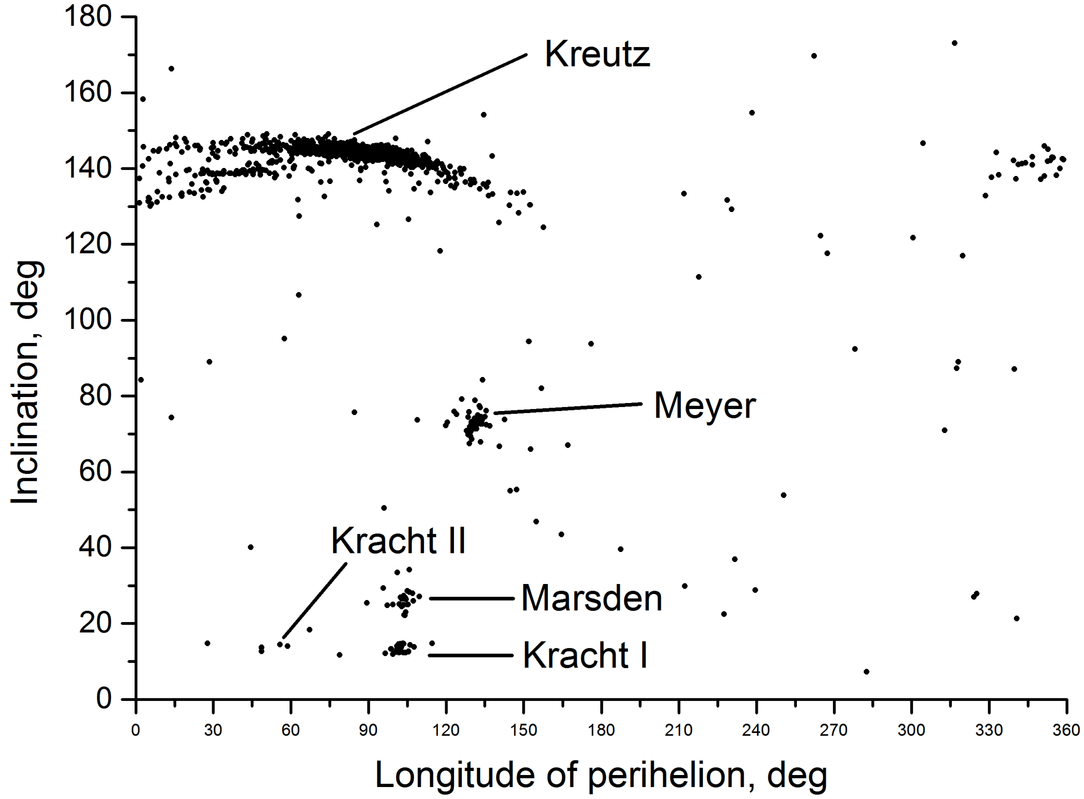
Changes of *q* for 2011 KE



There exists a large population of sungrazing comets



Distribution of $\pi=\omega+\Omega$ and i for comets with q<0.1 AU (Marsden, Williams, 2008)



Sungrazing comets (mainly the Kreutz family) move in long-period orbits. The description of dynamics can be done in terms of *w*=1/*a* changes for the near-parabolic motion (Petrosky,1986; Chirikov, Vecheslavov, 1986) on the basis of the generalized Kepler map (Emel'yanenko, 1991):

$$w^{(m+1)} = w^{(m)} + \frac{4\pi}{\mu^2} \sum_{P=1}^{N_P} \sum_{j=1}^{\infty} \sum_{\alpha=j}^{\infty} \sum_{k=j}^{\alpha} \sum_{s} G_{\alpha,k,s}^{(j,P)} \sin[(2s + j)\omega + j\Omega - j\lambda_P^{(m)}],$$

$$\lambda_P^{(m+1)} = \lambda_P^{(m)} + \frac{2\pi\, n_P}{\mu\, {w^{(m+1)}}^{3/2}},$$

where coefficients $G_{\alpha,k,s}^{(j,P)}(q,i)$ can be written analytically.

The observed sunskirting ‘comets’ of the Kracht and Marsden families move in short-period orbits with q~0.05 AU.

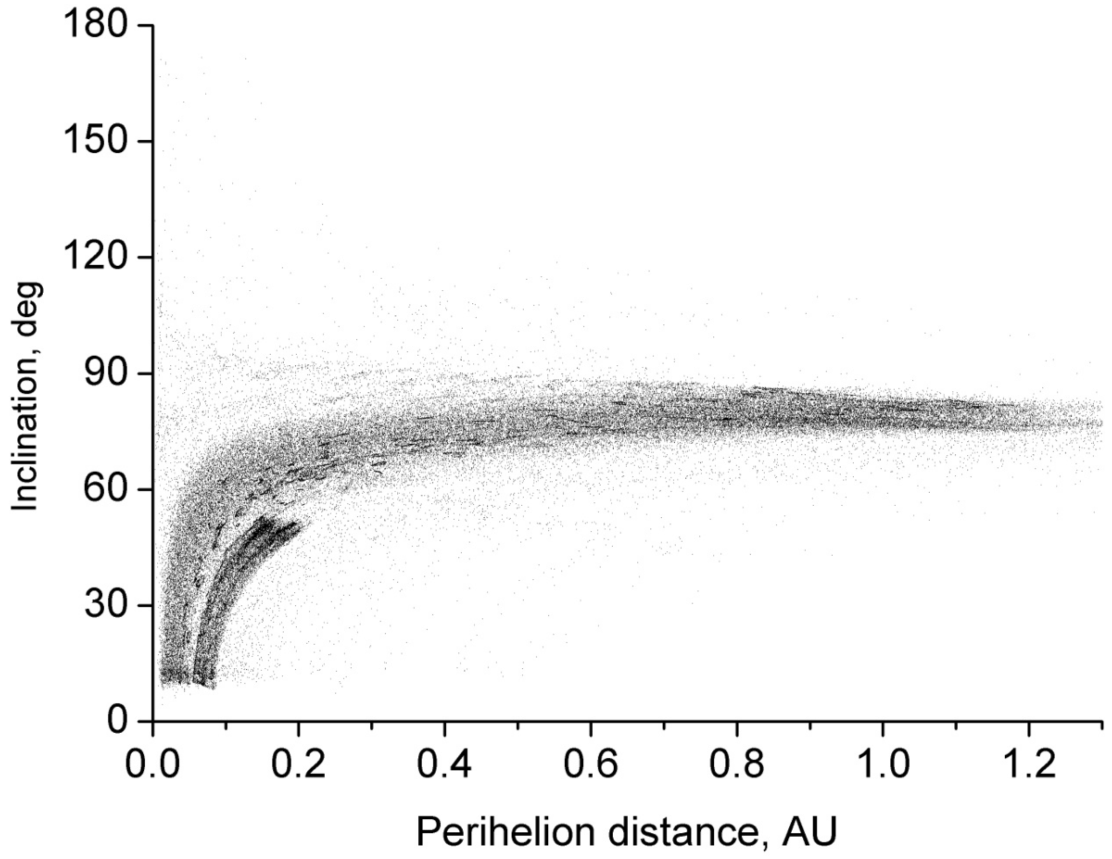
Many comets of the Kracht and Marsden families have been observed in a few apparitions.

Numbered sunskirting objects

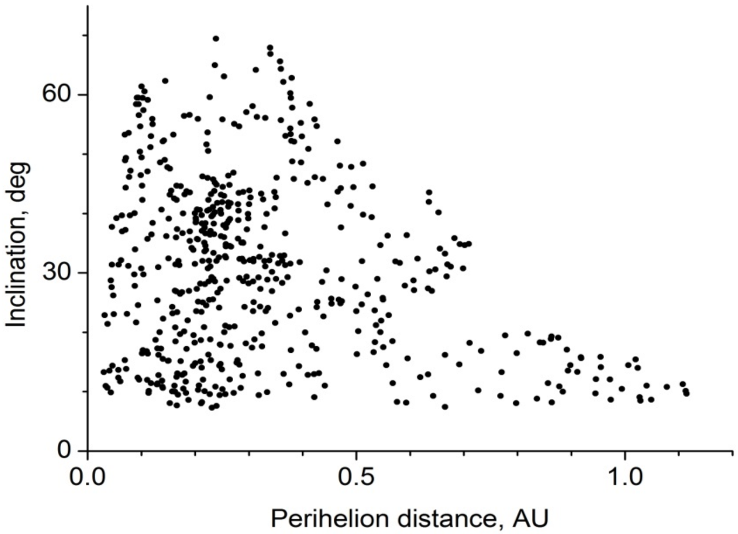
Name	Family	Number of apparitions	Nongrav. effects
321P	---	5	yes
322P	Kracht 2	5	no
323P	---	4	no
342P	Kracht	4	yes

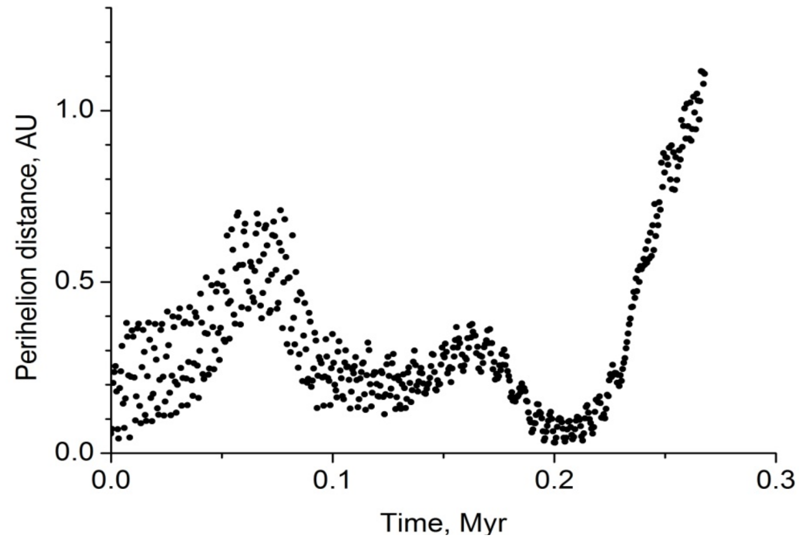
Ten Marsden and Kracht group comets observed at two or more apparitions have been investigated. Orbits of these objects have been obtained by linking all apparitions. On this basis, we have integrated equations of motion for ~10^4-10^6 years taking into account all planetary perturbations. 100 clones from the confidence region have been integrated for each object, using the symplectic integrator (Emel'yanenko, 2007).

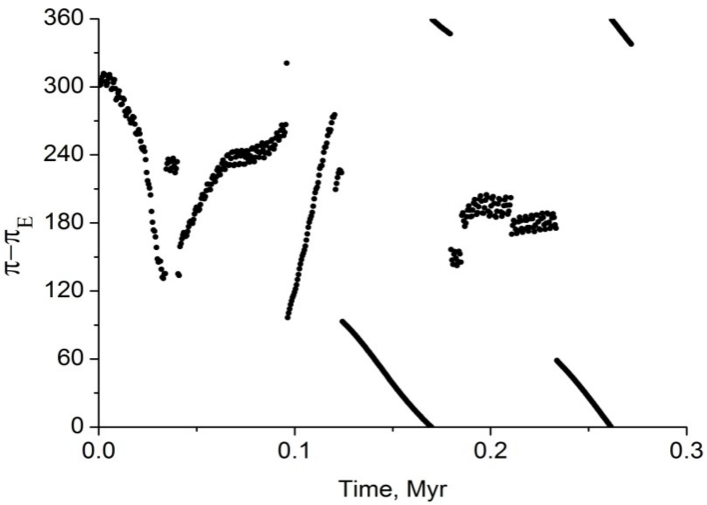
Evolution of *q* and *i* for the Kracht and Marsden families of sunskirting objects for 10,000 years

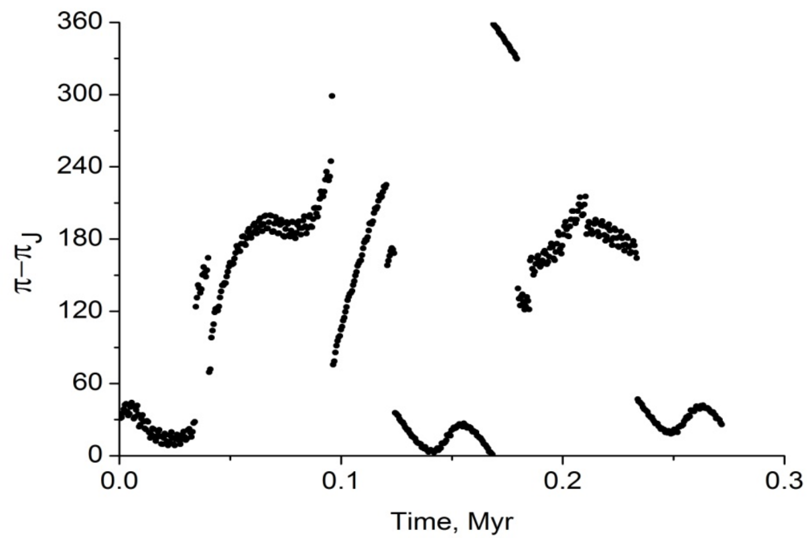


322P

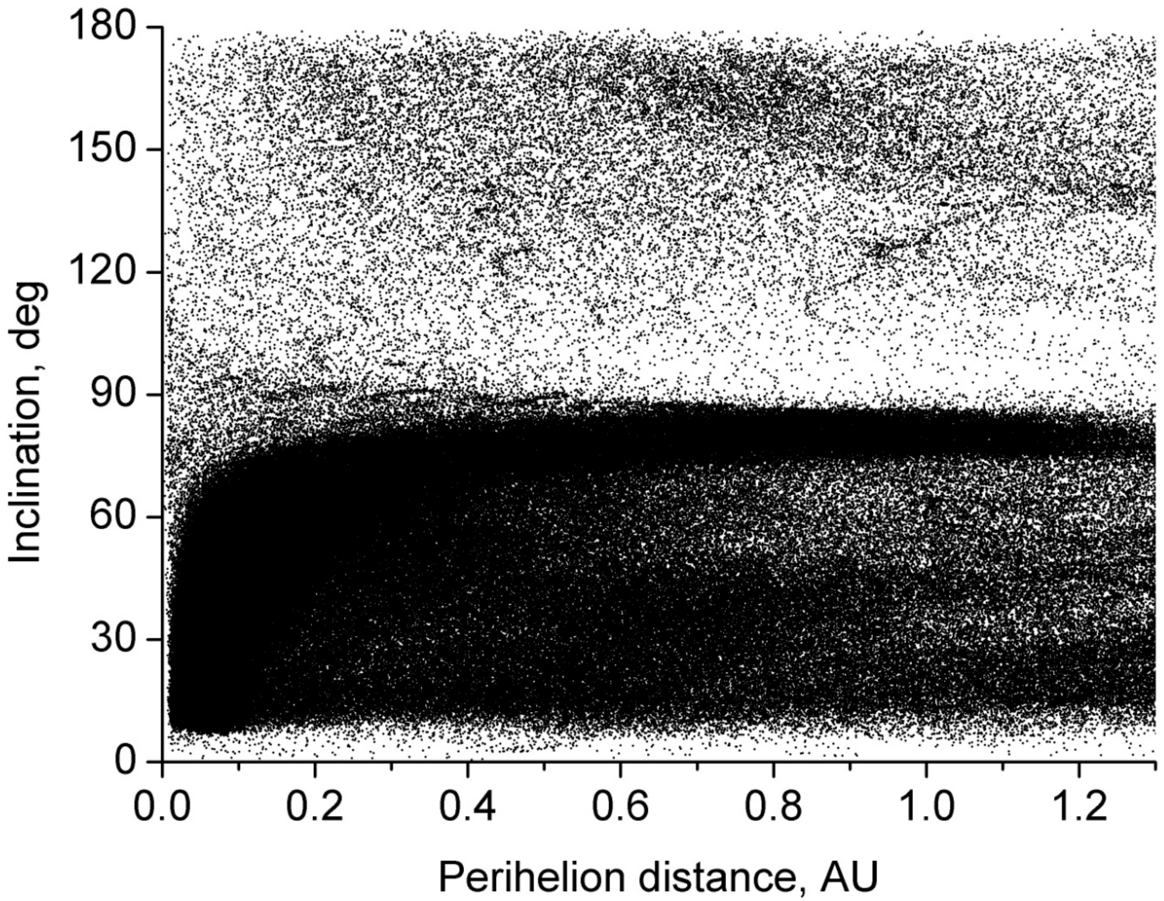

Inclination, deg
60
30
0
0.0
0.5
1.0
Perihelion distance, AU


Perihelion distance, AU
1.0
0.5
0.0
0.0
0.1
0.2
0.3
Time, Myr

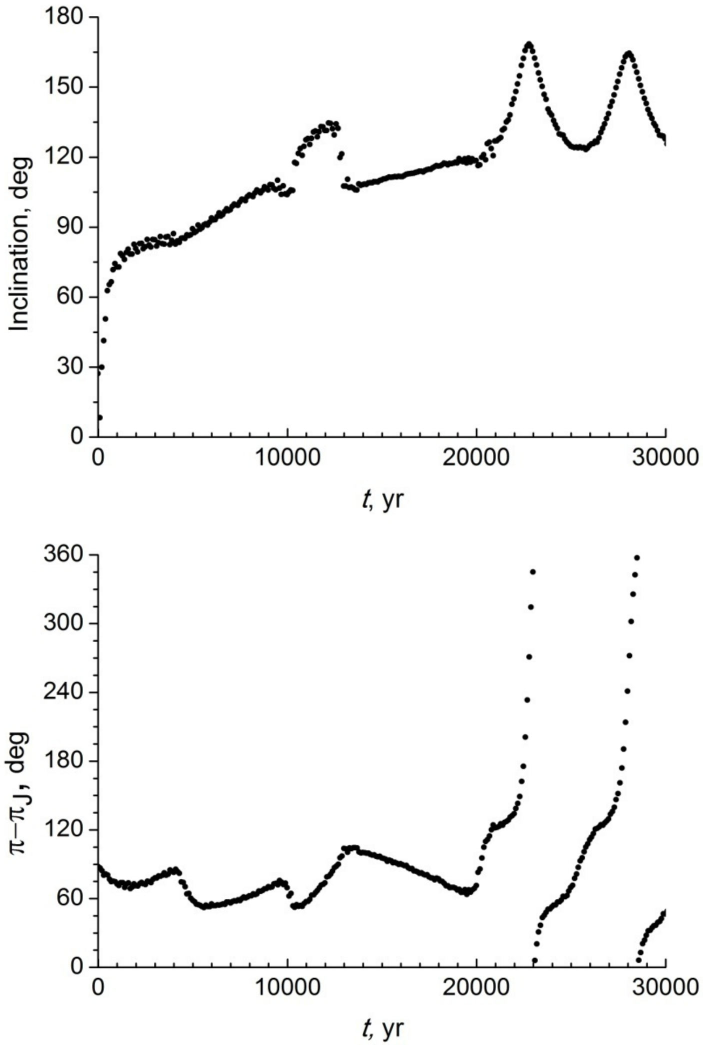

360
300
240
180
120
60
0
$\pi-\pi_E$
0.0
0.1
0.2
0.3
Time, Myr


360
300
240
180
120
60
0
$\pi-\pi_J$
0.0
0.1
0.2
0.3
Time, Myr

Evolution of *q* and *i* for the Kracht and Marsden families of sunskirting objects for 1 Myr



1992 U2 = 2005 W5



343158 (2009 HC82)

q=0.489 AU

a=2.527 AU

i=154.375 deg

Summary

- With a high probability, the Chelyabinsk object approached to the Sun ~ 1 Myr ago.
- We have found many observed near-Earth asteroids reaching small perihelion distances on short timescales in the past .
- The short-term evolution of these objects is mainly determined by the Kozai-Lidov secular perturbations.
- The time spent by NEOs at close distances to the Sun can be considerably high, reaching 10 and more percent of the typical dynamical lifetime (10 Myr).

- Orbits of the multiple-apparition sunskirting objects have been calculated.
- The short-term evolution of the Kracht and Marsden family members is mainly determined by the Kozai-Lidov secular perturbations. These objects are dynamically connected with high-inclination near-Earth objects.
- The long-term evolution of the observed sunskirting objects is much more complicated. In particular, these objects can evolve to retrograde orbits.