Research Article

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Observational data and orbits of the comets discovered at the Vilnius Observatory in 1980–2006 and the case of the comet 322P

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Abstract: This article is devoted to the discovery of comets at the Vilnius Observatory together with the orbital analysis of dynamically interesting comets, namely 322P. We studied the orbital evolution of comet 322P with and without non-gravitational effects. It turned out that many of the comet's orbital clones go into and out of retrograde orbits, sometimes repeatedly. The reason for such dramatic changes in the inclination of the orbit is the origin of comet 322P close to mean motion resonance 3:1 with Jupiter, ejecting them from there and, consequently, bringing the clones closer to the terrestrial group of planets. In this way, the clones of comet 322P enter retrograde orbits and reside there several ky to several My.

Keywords: comets: search, astrometry, orbits

1 Discoveries of comets at the Vilnius Observatory in 1980–2006

During the past few decades (2000–2022), many faint comets were found photographically using CCD images by a group of observers PANSTARRS, Catalina Sky Survey, LINEAR, etc. Other groups of comets were discovered by SOHO (Solar and Heliospheric Observatory) cosmic observatory observing Sun surroundings. However, visual comet hunting, a method put forward a hundred years ago, remained effective. One of the authors (I. W.) continues work on retrograde orbits in the studies of Kankiewicz and Wlodarczyk (2017), Kankiewicz and Wlodarczyk (2018), Kankiewicz and Wlodarczyk (2020), and Kankiewicz and Wlodarczyk (2021).

The discovery probability of detection of a new comet by a particular observer depends on the intensity of his/her sweeping (*i.e.*, sweeping frequency in time) and the ability to reach faint deep sky objects. An important factor is a large aperture telescope, good observational sites with excellent astroclimatic conditions, the amount of clear sky, and the use of a suitable method. The history of comet discoveries is given by Kresak (1966) and Kresak (1982).

Of 1,462 new comets discovered by SOHO from 1996 to 2021, nearly 99% were found at elongations between 8 and 1° from the Sun. Since comets tend to be brightest when are in the vicinity of the Sun, the area within approximately 100° or so of the Sun should be of prime concern to sky surveys, especially in the morning sky (Everhart 1967). All 26 comets discovered by one of the authors (K. C.) were detected at elongations from 1 to 73° from the Sun. Of 23 comets discovered photographically using SOHO/SWAN instruments from 1999 to 2006, 2 comets were discovered by ultraviolet SWAN instrument and 21 comets discovered with LASCO coronographs. Table 1 contains the visual comet searching work data from 1978 to 1997. It presents the number of nights and hours conducted in two observational sites, Vilnius (Lithuania) and Maidanak.

Since 1978, the 20 mm × 110 mm binoculars were used in the dark mountain site (2,550 m above the sea level) in Maidanak (Uzbekistan), allowing the detection of extended objects of 8–10 mag. In 1983, large-aperture visual reflector (the 480 mm reflector f/5 with the magnification ×65) was used for visual comet searching in Maidanak observatory, giving a grasp of 2 mags in comparison with the previous instrument. Table 2 shows 26 comets discovered by one of the authors (K.C.). The first three comets were discovered visually. The discoveries of the two first comets are described in papers by Straizys

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Table 1: The number of nights and hours conducted in two observational sites

Period	Hours	Nights	Vilnius	Maidanak	Comets
1973–1977	431	278	431/278	—	0
1978–1982	593	292	194/123	398/169	1
1983–1987	530	307	130/118	399/189	1
1988–1992	295	164	53/59	242/105	1
1993–1997	156	159	54/103	102/56	0
Total	2,005	1,200	862/681	1,141/519	3

(1980) and Cernis (1984). Other comets not included here (C/1975 O1, 72P, C/1987 B2, 23P, C/1994 P1) were independently discovered more than 3 days after the first discovery by other observers. The author's average search time per discovery for three named comets is 578 visual searching hours during 347 sessions. It should be borne in mind that the searching time noted is only spent with an eye on the eyepiece and with the telescope being moved to scan the sky. Searching for comets using the photographic method (by blinking CCD images taken by SOHO) was done in 1999–2006. Twenty-three comets were detected using SOHO data (Cernis 2000–2006). The limiting magnitude for comets of SWAN images is about 12 mag. The limiting magnitude for comets of coronograph images is about nine mags (for images from C2) and ten mags (for images from C3). The author's average search time per discovery for 23 SOHO comets is 57 searching hours by blinking CCD images in the computer.

Figure 1 presents 18 discovered SOHO comets in Vilnius against the background of all 1,462 discovered SOHO comets until 24 November 2021. In Figure 1, q denotes perihelion distance, e – eccentricity, and i – inclination, angle with respect to the ecliptic plane.

SOHO comets were taken from https://ssd.jpl.nasa.gov/tools/sbdb_query.html#!#results. Comet C/2003

Table 2: Comets discovered by K.C.

Comet	Name	Disc. date UT	Mag (mL)	Elong	Site	Hours	Instrument
C/1980 O1	Cernis-Petrauskas	1980 Jul. 31 17:10	8.5	43	Maidanak	806	110 mm × 20 B
C/1983 O1	Cernis	1983 Jul. 18 21:55	10.8	73	Maidanak	297	480 mm × 65 L
C/1990 E1	Cernis-Kiuchi-Nakamura	1990 Mar. 14 19:10	9.1	45	Vilnius	631	120 mm × 35 R
C/1999 Y2	SOHO	1999 Dec. 29 13:30	5.5	1		67	C2
C/2000 C2	SOHO	2000 Feb. 4 11:25	6	1		14	C2
C/2000 D3	SOHO	2000 Feb. 26 11:55	6.5	4		7	C3
C/2000 J3	SOHO	2000 May. 10 7:25	7	4		38	C3
C/2001 J2	SOHO	2001 May. 5 10:20	8.5	1		186	C2
C/2001 K7	SOHO	2001 May. 23 12:35	7	2		16	C2
C/2001 M7	SOHO	2001 Jun. 25 16:20	7	4		26	C3
C/2002 H1	SOHO	2002 Apr. 17 7:05	8	5		72	C3
C/2002 J8	SOHO	2002 May. 13 16:57	9	1		53	C2
C/2002 J3	SOHO	2002 May. 13 18:16	6	4		1	C3
C/2002 V6	SOHO	2002 Nov. 13 9:35	7	4		42	C3
C/2002 W8	SOHO	2002 Nov. 22 12:48	7	3		18	C3
C/2003 M1	SOHO	2003 Jun. 16 13:34	6.5	1		151	C2
C/2003 R5	322P/SOHO	2003 Sep. 8 7:35	8.5	1		51	C2
C/2004 E1	SOHO	2004 Mar. 9 12:50	7	4		33	C3
C/2004 H6	SWAN	2004 May. 13 10:50	8.5	30		26	SWAN
C/2004 L8	SOHO	2004 Jun. 10 15:45	7.5	4		31	C3
C/2005 B2	SOHO	2005 Jan. 25 16:43	9.5	3		103	C3
C/2005 D3	SOHO	2005 Feb. 22 13:45	8	4		53	C3
C/2005 L10	SOHO	2005 Jun. 9 11:35	9	1		192	C2
C/2005 M10	SOHO	2005 Jun. 29 11:22	8	1		20	C2
C/2005 X4	SOHO	2005 Dec. 6 14:20	8	1		73	C2
C/2006 A1	Pojmanski	2006 Jan. 4 13:30	10.5	51		27	SWAN

Notes: Type of instruments: B – binoculars, FOV = 4.8°; L – reflector, FOV = 1.1°; R – refractor, FOV = 1.9°; C2 – SOHO LASCO coronograph C2, FOV = 1.5°; C3 – SOHO LASCO coronograph C3, FOV = 15.9°; SWAN images, FOV 320°. Hours of searching: observing with visual telescope night sky or blinking CCD images taken from SOHO spacecraft using computer monitor. SOHO coronographs LASCO (Large Angle and Spectroscopic Coronograph) used 1,024 × 1,024 CCD cameras. LASCO C3 used D = 18 mm f/9 telescope, F = 162 mm with scale 11 arcsec/pix. FOV was 14 × 14°. Limiting mag about 9.5. LASCO C2 used D = 110 mm f/3.4 telescope, F = 378 mm with scale 56 arcsec/pix. FOV was 3 × 3°. Limiting mag about 9.

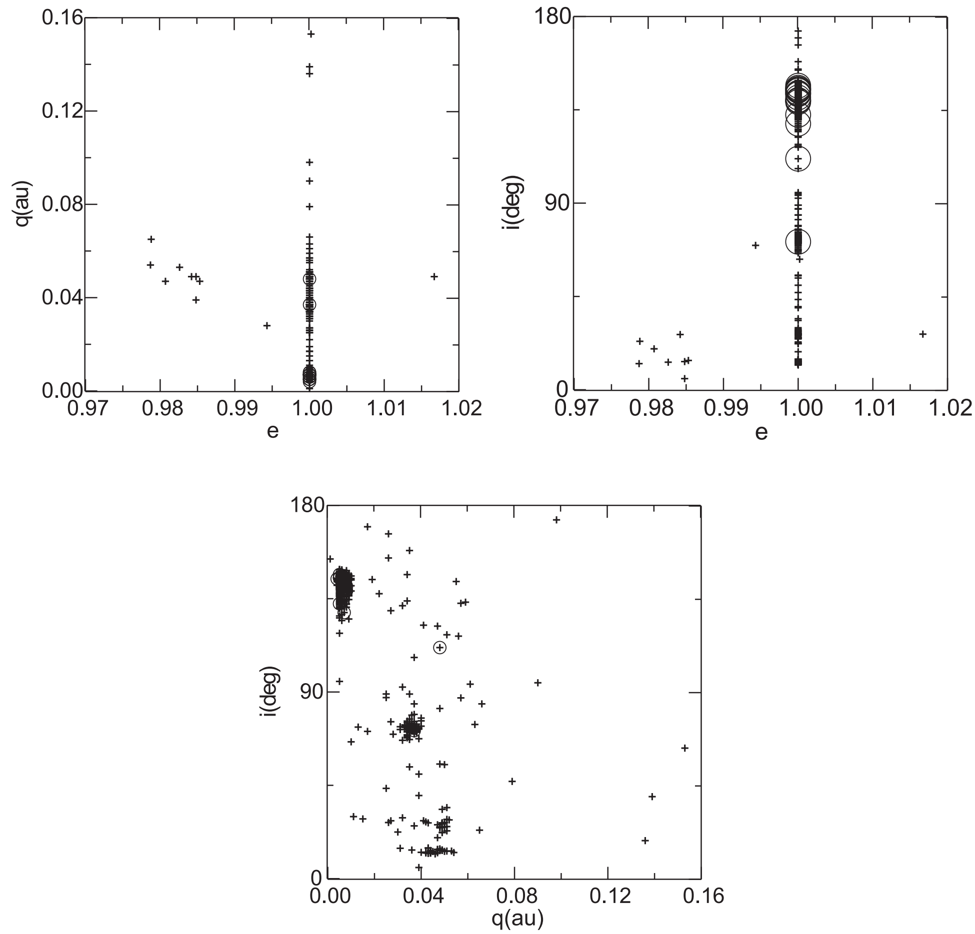

Figure 1: Positions of discovered SOHO comets at the Vilnius Observatory – circles, on the plane of all discovered SOHO comets – crosses, as of 2021 Dec. 24.

R5 = 322 P/SOHO was discovered in the Vilnius observatory (Sep. 8, 2003) as a faint object of 8 mag. about 1° from the Sun. Calculations of orbital elements of comet C/2003 R5 showed that the new comet had similar orbital elements as for comet C/1999 R1, discovered by Lovejoy with a period of about 4 years. Later the comet C/2003 R5 returned near the Sun in 2007 as a comet C/2007 R5 and in 2011 as a comet C/2011 R4, discovered by Zhou (M.P.E.C. 2015-K01). The comet soon got number 322P. The comet search program ended in 2006.

2 Starting orbit of the comet 322P

We analyzed the orbital evolution of dynamically interesting comets, namely 322P. Our motivation to focus on comet 322P is the first periodic comet discovered by SOHO with a very short period of about 4 years.

Table 3 presents initial nominal cometary orbital elements of comet 322P computed for pure gravitational model and with non-gravitational (NG) effects using parameters $A1$, $A2$, and $A3$. Parameters $A1$, $A2$, and $A3$ denote radial, transverse, and normal NG acceleration parameter, appropriately (Marsden *et al.* 1973).

To study the orbital evolution of comet 322P, one should rely not only on the nominal orbit evolution. Each of the orbital elements has an error creating the so-called confidence region (Milani 2006). There are orbits in this region that are slightly different from the nominal orbit but such that their root means square (RMS) falls within the RMS error of the nominal orbit.

To do this, we computed orbital elements of 201 clones or virtual asteroids (VAs) with the use of the OrbFit software v. 5.0.5 and the method of Milani (2006). Following this method, we computed 100 clones on both sides of the LOV (Line of Variation) with the sampling method of the LOV, *i.e.*, computed with the uniform sampling of the LOV sigma parameter (σ LOV).

The exception is clones numbered 1–37 and 139–201, which lie outside the LOV parameterization area. They

Table 3: Initial nominal cometary orbital elements of comet 322P

	q (au)	*e*	*i* (deg)	Ω (deg)	*ω* (deg)	*T* MJD
Pure gravitational model						
	0.05367308	0.97867184	12.5960610	359.607795	48.961738	57269.0665624
RMS	0.00000532	0.00000211	0.0002028	0.002075	0.002643	0.0004404
With NG effects:						
$A1 = (3.3358 \pm 6.391) \times 10^{-8}$ au/d^2						
$A2 = (5.9090 \pm 10.0322) \times 10^{-13}$ au/d^2						
$A3 = (-1.8103 \pm 27.0337) \times 10^{-13}$ au/d^2						
	0.05364534	0.97868326	12.5906944	359.531598	49.029862	57269.0688435
RMS	0.00007676	0.00002568	0.0227389	0.113373	0.118125	0.0105469

The angles ω, Ω, and i refer to Equinox J2000.0. Epoch: 2016-Jan-13 = JD2457400.5 TDB.

are not further considered and propagated. Thus, we consider the evolution of 93 clones of comet 322P. Then we propagate all the VAs forward and backward and search for close approaches and mean motion resonances (MMR) with the planets.

Figure 2 presents LOV for clones of comet 322P. It shows clones calculated according to the LOV method according to the NEODyS (https://newton.spacedys.com/neodys/). The nominal clone is in a circle, cone number 38 on the left side is marked with a cross, on the right side of LOV, clone number 131 is marked with a plus.

Table 4 presents border clones of the LOV of initial nominal keplerian orbital elements of comet 322P.

3 Forward orbital evolution of the comet 322P without NG effects

We study the orbital evolution of clones generated earlier according to the LOV method and are shown in Figure 2.

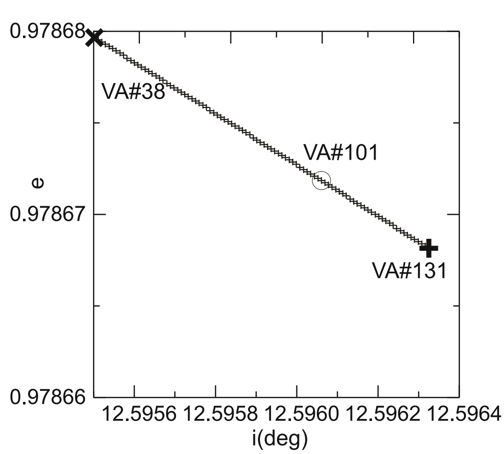

Figure 2: LOV of comet 322P.

In order to shorten the integration time of comet clones on a computer cluster, they were divided into packs of ten and integrated into the future and back. For example, batch no. 1 contains clones no. 38 to 47, the second from 48 to 57, etc. It is worth noting that all clones take off similarly, around MMR 3:1 with Jupiter.

Figure 3 shows the forward orbital evolution of one of the clones, no. 38.

It turned out that there are several such clones generated by us using the LOV method, which ends their lives escaping to a hyperbolic orbit. Remember that they are also initially near MMR 3:1 with Jupiter (3:1J). We also observe the formation of the retrograde orbit, *i.e.* when $i > 90°$ and the return to the prograde orbit, when $i \leq 90°$. So being on the MMR 3:1J, near $a = 2.25$ au, causes the clone to be ejected into a hyperbolic orbit. Although a few clones even further exist, being initially close to the MMR 3:1J.

4 Backward orbital evolution of the comet 322P without the NG effects

Figure 4 presents backward orbital evolution of the clone no. 57 of the comet 322P without NG. In each package containing ten clones, we observe the formation of up to three clones in retrograde orbits, which is already in the period of up to 100 thousand years back. Sometimes they also enter hyperbolic orbits and leave the solar system. It is difficult to predict the behavior of the object beyond the so-called time of stability (Wlodarczyk 2001, 2007). This time depends, among others, on close approaches with planets. The fewer the close-ups, the shorter the stability time.

Table 4: Border clones of the LOV of initial nominal keplerian orbital elements of comet 322P together with their uncertainties (RMS)

Pure gravitational model		
Orbital element	**Clone 38**	**Clone 131**
a(au)	$2.5165358125085402 \times 10^{0}$	$2.5165366341435162 \times 10^{0}$
RMS	2.94824×10^{-7}	2.94640×10^{-7}
e	$9.7867966848591115 \times 10^{-1}$	$9.7866814134343261 \times 10^{-1}$
RMS	2.11568×10^{-6}	2.11538×10^{-6}
i(deg)	$1.2595502271069565 \times 10^{1}$	$1.2596325373135928 \times 10^{1}$
RMS	2.02865×10^{-4}	2.02785×10^{-4}
Ω(deg)	$3.5960278465560270 \times 10^{2}$	$3.5961016478750787 \times 10^{2}$
RMS	2.07654×10^{-3}	2.07508×10^{-3}
ω(deg)	$4.8969591521844045 \times 10^{1}$	$4.8958024295237152 \times 10^{1}$
RMS	2.64777×10^{-3}	2.64593×10^{-3}
M(deg)	$3.2326254398949978 \times 10^{1}$	$3.2325644828464995 \times 10^{1}$
RMS	1.13956×10^{-4}	1.13924×10^{-4}

a – denotes semimajor axis, e – eccentricity, i – inclination, Ω – longitude of the ascending node, ω – argument of perihelion, and M denotes mean anomaly. The angles ω, Ω, and i refer to Equinox J2000.0. Epoch: 2016-Jan-13 = JD2457400.5 TDB.

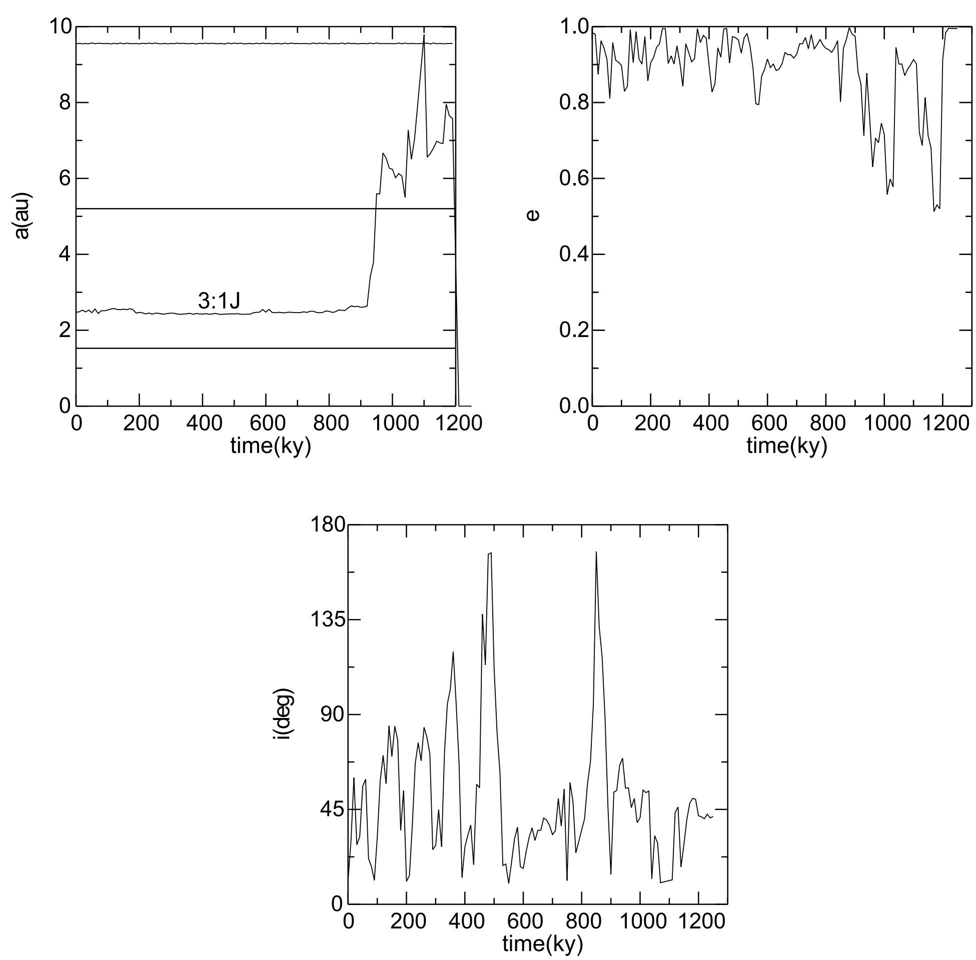

Figure 3: Forward orbital evolution of the clone no. 38 of comet 322P without NG effects.

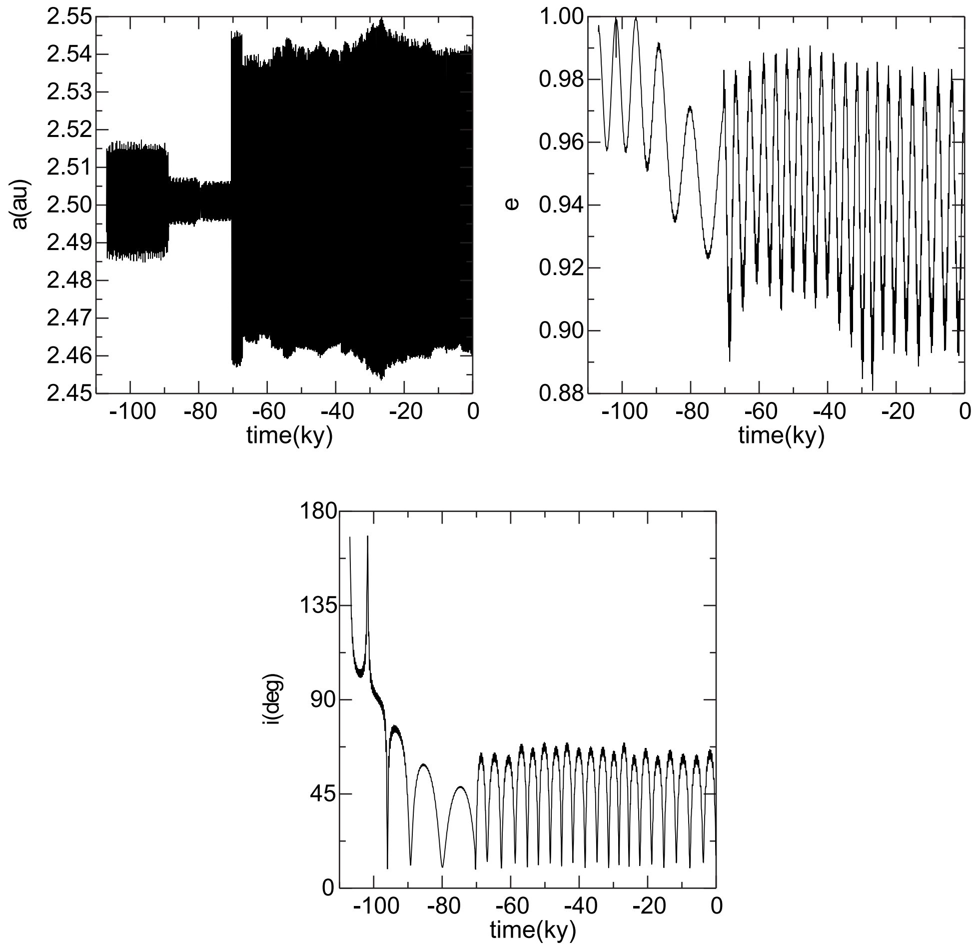

Figure 4: Backward orbital evolution of the comet 322P without NG – clone 57.

This time depends on the Lyapunov time (LT), which we calculated in Table 7. It amounts to several hundred years.

To investigate the propagation of the orbital elements of a given object, we create its clones with a given sigma confidence interval (σ LOV). Then we propagate them. In this way, we can study the behavior of the orbital elements of the comet 322P over an extended period. Hence, the study of the evolution of comet 322P over a period of up to 100,000 years may be more realistic.

5 Orbital evolution of the comet 322P with NG effects A1, A2, and A3

Next, we computed the orbital evolution of comet 322P with the NG effects (NG): $A1$, $A2$, and $A3$, as presented in Table 3. Figures 5 and 6 present forward and backward orbital evolution of the nominal orbit of comet 322P with NG effects. Both orbital evolutions of these clones end with escaping of the Solar System. In the case of forward evolution, the comet is ejected from the Solar System after 1.8 My. As soon as 180 ky, which is ten times shorter, the comet is ejected from the Solar System during backward integration. In both cases, the comet enters a retrograde orbit. In contrast, comet entries into retrograde orbits are pretty frequent in integration without NG effects, as shown in Figures 3 and 4.

6 Close approaches between 322P and planets

Table 5 shows the retrograde orbit times of comet 322P clones during forward integration without NG effects. It shows when the orbit of comet 322P goes retrograde, how

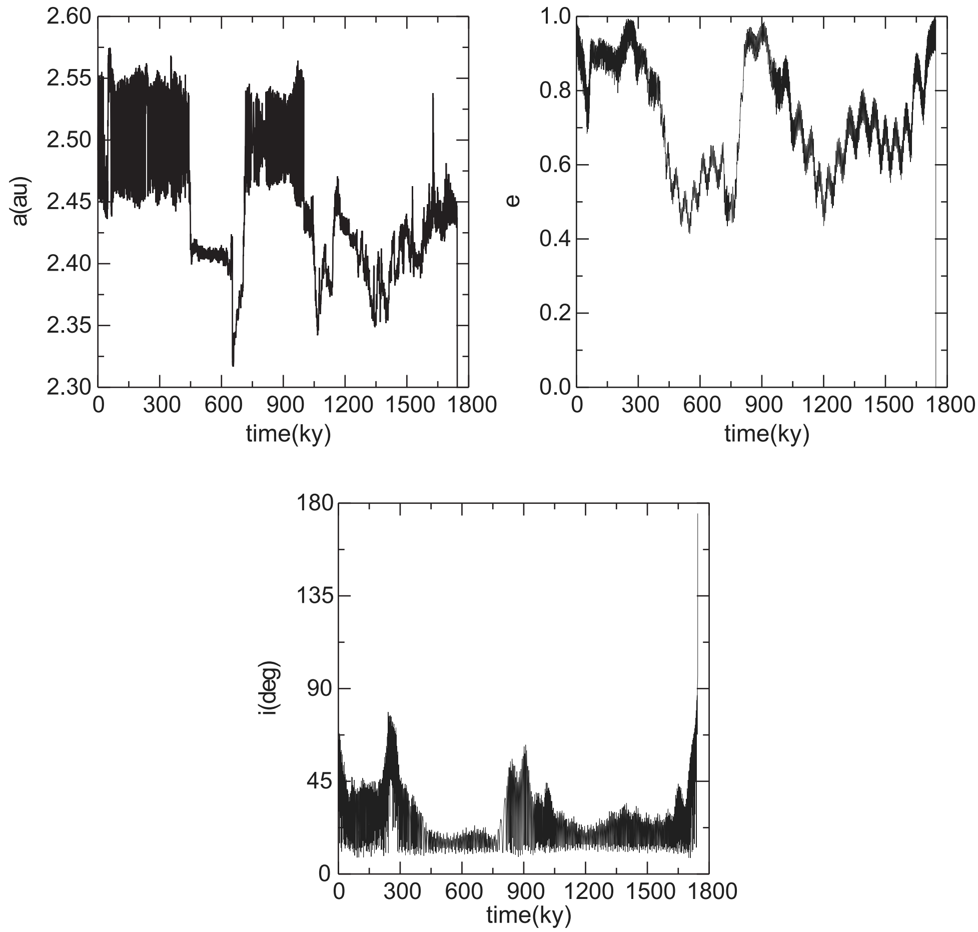

Figure 5: Forward orbital evolution of the comet 322P with the NG effects.

long it lasts, and when it leaves the Solar System. It turns out that many of the comet's clones enter retrograde orbit before they leave the Solar System.

Some of them repeatedly entered and returned from retrograde orbit. Of all 93 clones on LOV, 18 clones were recorded as leaving the solar system. The record holder changed the orbit to retrograde up to five times. The average lifetime of clones in retrograde orbit is about 69 ky, or about 11% of their life.

The same is true for backward integration. Table 6 shows the lifetime on retrograde orbits of comet 322P clones during backward integration without NG effects. These are also clones from different packages. As we can see, packing ends after different times, from 90 to 630 ky, on average around 39 ky. It is much shorter than during the forward integration.

Like in the case of forward integration, individual clones enter retrograde orbits several times, although now there are fewer such cases. They stay there from 2 ky to as much as 200 ky, on average 39 ky, 30 ky shorter than during the forward integration. Those that have entered retrograde orbit at least once are average around 16% of their lifetime, which is longer than they were when they were integrated forward.

7 Reasons for entry/exit to retrograde orbits

Additional integrations were carried out to look for the clones' most extended possible residence times in a retrograde orbit. It amounted to 3.8 My during the forward integration.

Figure 7 shows the orbital evolution of one of the clones, #44, with the longest calculated residence time in retrograde orbit when slotted forward. The clone has been in retrograde orbit from about 2.5 to 3.8 My, close to 1.3 My. The moments of the comet's clone's approach are marked with asterisks, from the bottom: with Venus,

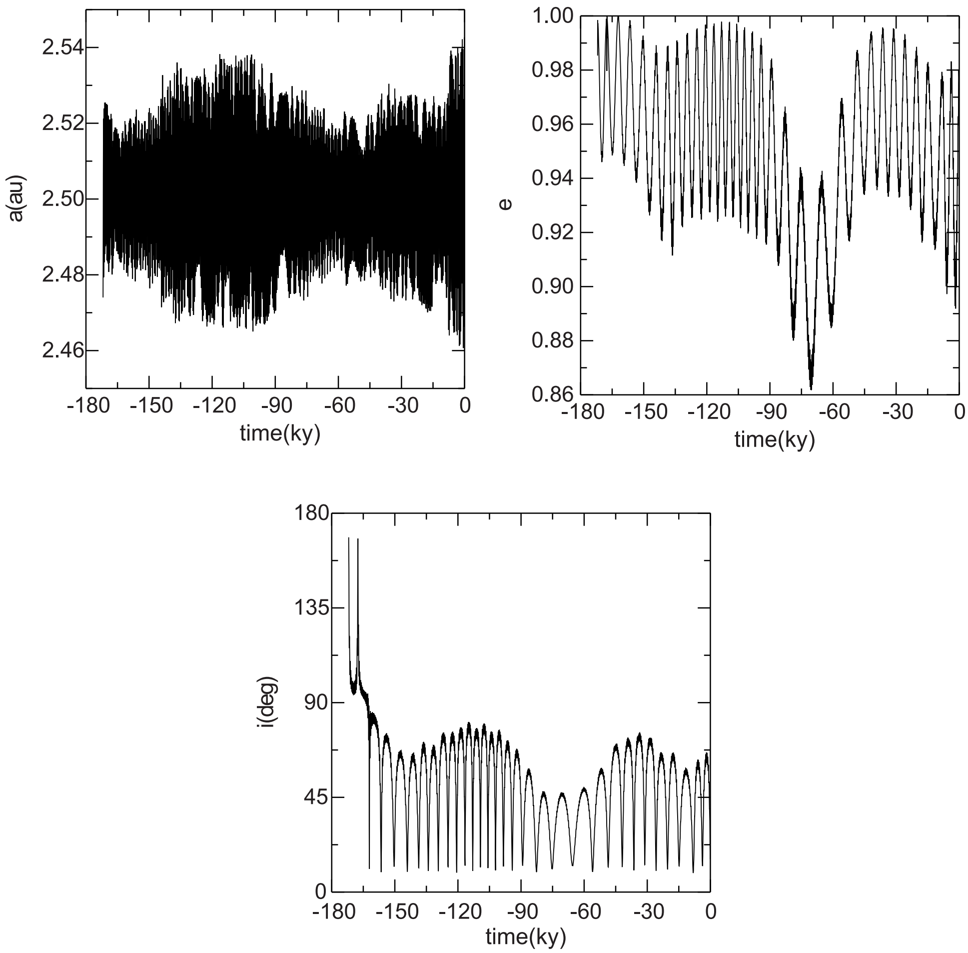

Figure 6: Backward orbital evolution of the comet 322P with the NG effects.

Table 5: Forward integration without NG effects, the lifetime of clones in a retrograde orbit

Clone	Occurrence range	End of integration	Lifetime on retrograde orbit	
No	ky	ky	ky	%
38	350–365, 460–480, 840–860	1,255	55	4
39	90–100, 190–200, 410–600, 620–700, 820–900	1,255	370	29
42	800–820, 1,000–1,020, 1,150–1,170	1,255	60	5
43	190–200	1,255	10	1
44	190–200 400–440	1,255	50	4
46	680–780	1,255	100	8
50	130–165	180	35	19
57	140–170	180	30	17
59	110–120	120	10	8
68	350–440, 460–530, 580–590, 620–700, 1,010–1,040	1,040	280	27
76	340–360, 1,010–1,030	1,030	40	4
85	110–160	160	50	31
88	110–150	360	40	11
89	240–300, 350–355	355	65	18
96	350–355	355	5	1
97	350–355	355	5	1
100	190–210	210	20	10
103	120–240	240	20	8
Mean		673	69	11

Table 6: Backward integration without NG effects, the lifetime of clones in a retrograde orbit

Clone	Occurrence range of integration	End	Lifetime on retrograde orbit	
No	ky	ky	ky	proc
42	100–102	−102	2	2
51	80–107	−107	27	25
52	107–109	−109	2	2
56	100–108	−108	8	8
57	100–112	−112	12	11
59	230–240, 440–630	−630	200	32
63	270–300, 370–410, 560–580, 600–630	−630	120	19
69	170–172	−172	2	1
70	100–125, 170–175	−175	30	17
72	130–175	−175	45	26
81	100–110	−110	10	9
83	100–110	−110	10	9
84	100–110	−110	10	9
86	100–110	−110	10	9
89	92–94	−94	2	2
91	85–90	−90	5	6
99	100–150	−150	40	27
103	90–150	−150	60	40
104	148–150	−150	2	1
111	100–105	−105	5	5
118	145–225	−225	80	36
122	220–225	−225	5	2
125	120–225	−225	105	47
128	110–220	−220	110	50
Mean		−183	39	16

Table 7: Computed values LT of clones of the comet 322P

Clone	LT (years)	
	Forward integration	Backward integration
42	327	402
44	393	375
57	266	699
70	196	636
103	357	383

Earth, and Mars, respectively. We can see the clone's approaches with these planets and the accompanying entry and exit into a retrograde orbit.

So the initial MMR 3:1J causes changes in the eccentricity and approaches to planets, especially Mars, and then enters a retrograde orbit. Some clones are in this orbit, from a few ky to a few My. During the orbital evolution of the clones of comet 322P, the entry/exit process from the retrograde orbit is repeated many times.

8 LT

Next, we computed the value of LT for different clones of the comet 322P. Calculating LT is based on Knežević and Milani (2000) and Milani and Nobili (1988). They used the method of computing parameter $\gamma(t)$ from relation (1):

$$\gamma(t) = \log\left(\text{abs}\left(\frac{D(t)}{D(0)}\right)\right), \tag{1}$$

where $D(t)$ denotes the length of variation vector.

Next, we computed Lyapunov characteristic exponent from fitting of this equation and LT from Eq. (2)

$$\text{LT} = 1/\text{LCE}. \tag{2}$$

To compute the LT of the studied clones of comet 322P, we used the LOV method similar to that in the study of Wlodarczyk (2019). We also used the OrbFit software v.5.0.7, similar to that for asteroid 2012 XH16 in the study of Wlodarczyk *et al.* (2014). Table 7 presents the computed values of LT of several clones of the comet 322P.

It is visible from Table 7 that the LT for 322P clones is several hundred years. So briefly, similar to, *e.g.*, for near-Earth asteroids, see Table 8 in the study of Wlodarczyk (2020b).

The short LT is associated with the chaos caused mainly by the approaches of comet clones to planets.

Note also that LT, which is a measure of chaos, is related to the location of the 322P startup clones near the MMR 3:1J. In addition, LTs are calculated for clones going into or out of retrograde orbits. And as we showed earlier in Figure 7, retrograde orbit entries are due to planetary approaches, particularly Venus, Earth, and Mars. In summary, Lapunov's times for comet 322P entering retrograde orbit are in the order of several hundred years.

9 Summary

We showed discovered comets in Vilnius Observatory. In particular, we have shown the orbital evolution of comet 322P with and without NG effects. It turned out that many of the comet's clones go into and out of retrograde orbits, sometimes repeatedly.

The reason for such dramatic changes in the inclination of the orbit is the origin of comet 322P close to MMR 3:1J, ejecting them from there and, consequently, bringing the clones closer to the planets of the terrestrial group.

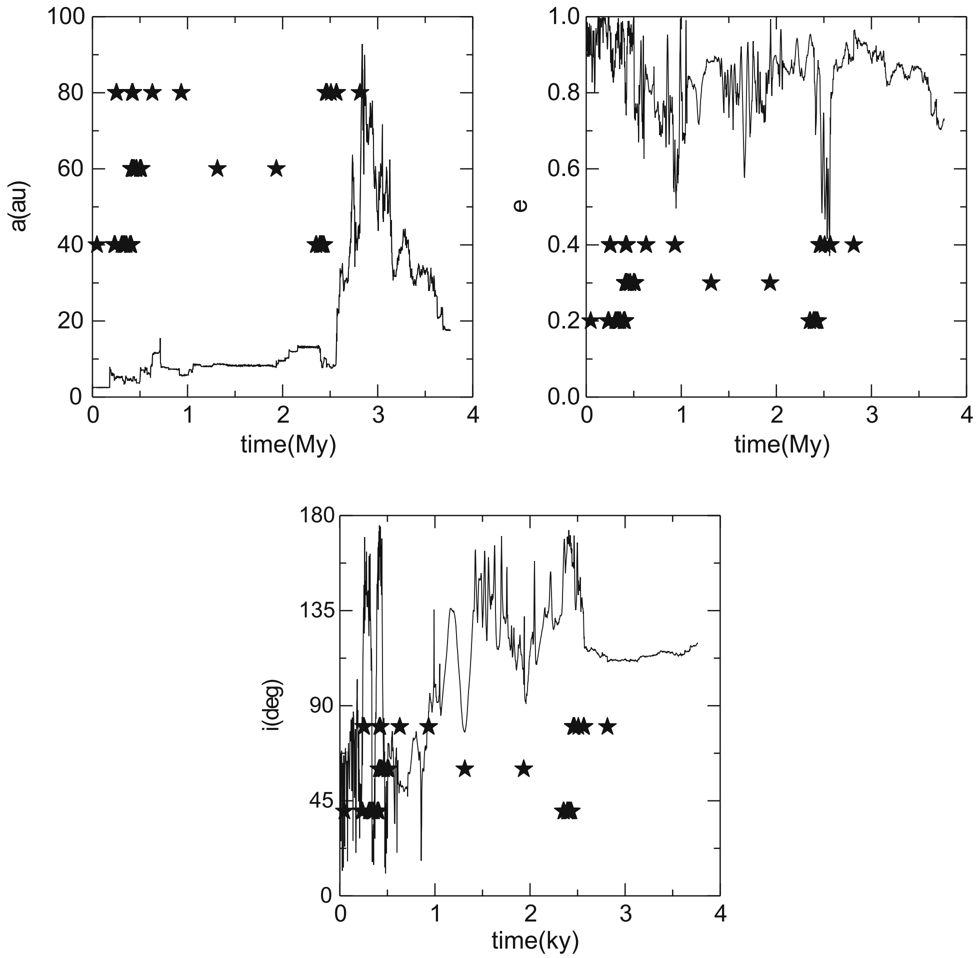

Figure 7: Forward orbital evolution of the clone #44 of the comet 322P without NG effects with the longest time on the retrograde orbit.

In this way, the clones of comet 322P enter retrograde orbits and travel here from a few ky to a few My.

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