Near-parabolic comets observed in 2006–2010. II. Their past and future motion under the influence of the Galaxy field and known nearby stars.

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ABSTRACT
In the first part of this research we extensively investigated and carefully determined osculating, original (when entering Solar system) and future (when leaving it) orbits of 22 near-parabolic comets with small perihelion distance ($q_{osc} < 3.1$ au), discovered in years 2006-2010. Here, we continue this research with a detailed study of their past and future motion during previous and next orbital periods under the perturbing action of our Galactic environment. At all stages of our dynamical study, we precisely propagate in time the observational uncertainties of cometary orbits. For the first time in our calculations, we fully take into account individual perturbations from all known stars or stellar systems that closely (less than 3.5 pc) approach the Sun during the cometary motion in the investigated time interval of several million years. This is done by means of a direct numerical integration of the N-body system comprising of a comet, the Sun and 90 potential stellar perturbers. We show a full review of various examples of individual stellar action on cometary motion. We conclude that perturbations from all known stars or stellar systems do not change the overall picture of the past orbit evolution of long-period comets (LPCs). The future motion of them might be seriously perturbed during the predicted close approach of Gliese 710 star but we do not observe significant energy changes. The importance of stellar perturbations is tested on the whole sample of 108 comets investigated by us so far and our previous results, obtained with only Galactic perturbations included, are fully confirmed. We present how our results can be used to discriminate between dynamically new and old near-parabolic comets and discuss the relevance of the so-called Jupiter-Saturn barrier phenomenon. Finally, we show how the Oort spike in the $1/a$-distribution of near-parabolic comets is built from both dynamically new and old comets. We also point out that C/2007 W1 seems to be the first serious candidate for interstellar provenience.

Key words: Solar system : general, Oort Cloud, comets: general

1 INTRODUCTION

This is a second part of our extensive investigation of dynamics of long-period comets discovered during the period of 2006–2010. In Part I [Królikowska & Dybczyński 2013], we described in detail the astrometric data and their tailored numerical treatment which allowed us to obtain the most accurate osculating orbits, with nongravitational forces taken into account wherever possible. Then we propagated these orbits forward and backward up to the distance of 250 au from the Sun to obtain original (i.e. before entering the planetary perturbations zone) and future (i.e. when leaving it) orbits. All planetary perturbations were strictly taken into account as well as relativistic effects. We also took into account the existence of nongravitational accelerations in the motion of studied comets, and in up to half of the cases we were able to obtain satisfactory nongravitational orbits. In some cases of well-observed LPCs, we used subsets of astrometric observations, omitting those near perihelion, where violent cometary activity can disturb the motion noticeably.

At the stage of the osculating orbit, we augmented the nominal orbit of a comet with 5000 of its clones (virtual comets, VCs) which all represent astrometric observations on the same level as the nominal orbit does. This allowed us to control the observational uncertainties at each step of our dynamical studies. The results and a deep discussion of all the above may be found in Part I.

Here, we present the result of the natural next step of cometary orbits investigation, namely examination of their evolution.

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for one orbital period to the past and future. Some elements of our numerical methods are presented in Section 2. Similar analysis for two different samples of near-parabolic comets we published earlier, see Królikowska & Dybczyński (2010), hereafter Paper I, Dybczyński & Królikowska (2011), hereafter Paper II, and Królikowska et al. (2012) (Paper III). In these papers, we generally ignored stellar perturbations, according to our early tests Dybczyński (2000) and more detailed examinations taken later Dybczyński (2006).

However, in some recent papers the authors pointed out, that stellar perturbations play a significant role in long term simulations of cometary dynamics (see for example: Fouchard et al. 2011) and almost simultaneously a new and comprehensive compilation of modern stellar data have been published – XHIP catalogue (Anderson & Francis 2012). This catalogue, prepared mainly on the basis of the new reduction of Hipparcos measurements (van Leeuwen 2007, 2011) and augmented with over 46 thousand radial velocities from various modern sources, can serve as an ideal tool for searching for potential stellar perturbers of the observed LPCs.

For that reason, we decided to include stellar perturbations from known stars in our dynamical model of near-parabolic comets motion. We performed an extensive search for potential stellar perturbers and found about 90 stars which visited solar neighbourhood in the recent past or will visit it in the near future. The details are given in Section 3. Please note that we use the most up to date stellar data compilation. While we are rather convinced that none of the slow moving and massive stars visiting recently the solar neighbourhood remain unknown we must admit that any new findings might happen to change our results and conclusions for a particular comet. The ongoing mission GAIA will greatly improve the accuracy of the available data on nearby stars and may discover a new potential stellar perturber of cometary motion in next years.

In Sections 3 and 5 we present an analysis of past and future dynamical evolution of a complete sample of small-perihelion LPCs discovered during the period of 2006-2010. We show how these results can be used to discriminate between dynamically old and new LPCs. We call a comet dynamically new if the observed orbit was not perturbed by planets during its previous perihelion passage. In other words this comet makes its first visit in the solar neighbourhood. The rest of LPCs we call dynamically old or uncertain.

Special attention was given to the comparison of the results obtained with and without stellar perturbations to verify their importance. This is discussed in Section 3.

2 METHODS OF CALCULATIONS IN BRIEF

The starting point for the calculations described in this paper is an original/future orbit of each comet, when past/future evolution is examined, respectively. In fact, we use not only the nominal barycentric orbit at 250 au from the Sun but also 5 000 clones of it, together constituting a swarm of 5 001 original/future barycentric orbits for each examined comet. The procedure of determining the oscillating orbits from astrometric observations, the cloning algorithm and the method of obtaining original and future swarms of orbits are described in detail in Part I.

Original and future LPCs orbits were followed numerically taking into account Galactic perturbations (where both disk and central terms were included) and any possible stellar perturbation from known stars, their selection and treatment are described in detail in the next section. Generally, we stop our calculation at a previous or next perihelion but for hyperbolic or extremely elongated elliptic orbits in the swarm of VCs we apply so called “escape limit” of 120 000 au. The final orbits obtained from these calculations we call previous and next.

In this paper we call a comet (or more precisely each individual VC) as returning [R] if it goes no further than 120 000 au from the Sun. All other comets (or VCs) are named escaping [E], but among them we separately count escapes along hyperbolic [H] orbits.

For the detailed description of the dynamical model as well as its numerical treatment the reader is kindly directed to Paper I. Basing on the conclusions from that work we used both, Galactic disk and Galactic centre terms in all calculations. All the parameters of the Galactic gravity field are kept unchanged, including the local disk mass density, $\rho = 100 \, M_{\odot}/pc^3$. The recently quoted value (Irrgang et al. 2013) equals 0.102 ± 0.010. As we showed in one of our previous papers (Królikowska & Dybczyński 2010) even assuming the 50 per cent uncertainty it influences our results on a less than 1 per cent level. The only one but important modification of the dynamical model is the incorporation of any possible known stellar perturbations (Section 3).

Dynamical behaviour of VCs within an individual swarm forced the rules of stopping the numerical integration. We decided to treat each VC in a given swarm as uniformly as possible, thus, we distinguish between the following three cases.

(i) When all VCs of a particular comet were returning then all of them were stopped in two ways:
   - at previous/next perihelion (basic variant),
   - simultaneously when the nominal VC reached previous/next perihelion (synchronous variant).

   The reason of introducing the synchronous variant is that for some purposes it more convenient to have all VCs stopped at the same moment of time, which is not satisfied in the basic variant.

(ii) When all VCs were escaping then the calculation was stopped synchronously, at the moment when the fastest VC crossed the escape limit (usually very close to 120 000 au).

(iii) When a swarm of VCs consists of both returning and escaping VCs then we also decided to stopped them in two ways:
   - the returning part was stopped at previous/next perihelion and the rest (escaping ones) when the fastest escaping VC crossed the escape limit (mixed variant).
   - all VCs (both returning and escaping) were stopped at the moment when the fastest VC crossed the escape limit (synchronous variant).

Similarly, as in the first case, this synchronous variant were used to examine more homogeneous orbital elements distributions, i.e. when all VCs were stopped at the same epoch.

3 STELLAR PERTURBATIONS

To obtain a more reliable picture of the past and future motion of the investigated comets, we decided to include stellar perturbations in
our dynamical model of the distant cometary motion. For this purpose, we completely revised our list of potential stellar perturbers acting on the LPCs motion in large heliocentric distances. While the detailed analysis of all available stellar data and their current accuracy will be presented in a future paper (Dybczyński and Berski, in preparation), now we use a recently published compilation called XHIP [Anderson & Francis 2012] as a source of 6-D stellar data. At the moment, we completely rely on the results presented in this catalogue and accept all data refinement rules adopted by the authors. As it concerns the completeness of the available stellar data the objections expressed by [Rickman et al. 2013] are based on a simulated stellar passage frequency obtained from the estimations done by [García-Sánchez et al. 2001]. Their estimations should be treated as the “long time mean”. It is easy to guess that this frequency will vary significantly with time. As a simple proof lets consider stars in the sphere of 20 pc radius around the Sun. A relatively fast star, with the total velocity of 40 km/s moves about 20 pc in 0.5 million years. None of the known stars pass as close as 1 pc in 1 million years centred at present epoch. Note, that our knowledge of stars in 20 pc range is rather complete except spectral type M and smaller (Jahreiß & Wielen 1997). The Garcia-Sánchez estimation predicts 2-3 stars in each million years but currently we cannot find any. As we go to slower and more massive stars, which are most important perturbers of cometary motion our knowledge extends to larger time intervals, comparable with one orbital period of investigated long-period comets.

However, the reader should be warned that any new discovery of a new, strong stellar perturber, while of little probability in our opinion, may change our results and conclusions concerning one or another particular comet.

3.1 The model

We extracted from the XHIP catalogue all stars with the calculated proximity distance (Dmin in XHIP) less than 3.5 pc from the Sun. There are 96 such stars in this catalogue. One of them (HIP 72511) must be excluded due to the evident parallax error. Taking into account its spectral type (M1) and the apparent magnitude (m_V=11.7) its parallax must be much smaller, perhaps, the value of 30 mas presented in some older sources (see for example Auer et al. 1978). HIP 30344 is much closer to the reality than the Hipparcos value of 248 mas. Moreover, if this large parallax had been real, this star would have been included in the RECONS list of the 100 nearest stellar systems [1] which is not the case.

Additionally, we decided to replace individual members of four stellar systems with their centres of mass. We merged HIP 13769 with HIP 13772 (GJ 120.1 AB+C), HIP 26369 with HIP 26373 , HIP 70890 with HIP 71681 and HIP 71683 (Proxima + α Centauri A+B) and finally HIP 104214 with HIP 104217 (GJ 280 A+B).

All of these changes, reduced the sample of the stellar perturbers to 90 stars or stellar systems. This list we divided into three parts:

- 11 current neighbours (group C), i.e. stars that are currently closer than 3.5 pc
- 39 past visitors (group P) - stars that have passed closer than 3.5 pc from the Sun in the past (the oldest such an event among stars for which we have complete spatial data occurred more than 7 million years ago)
- 40 future visitors (group F) - stars that will make close passage in the future (the most distant in time event, included for these stars (again, with complete spatial data available) will occur almost 5 million years from now).

As the method of cometary motion calculation, we chose the numerical integration of the equation of motion expressed in the rectangular, heliocentric, Galactic coordinates. We used the popular and well-tested RA15 routine (Everhart 1985). We decided to use the so called “local Galactic potential” (see for example Jiménez-Torres et al. 2011) acting on both a comet and each stellar perturber. We also include all N-body mutual interactions between stars (including our Sun) and their gravitational influence on a comet. As it concerns Galactic perturbations we used exactly the same model for disk and centre tides as that described in detail in Paper I.

3.2 Overall characteristics of stellar influence on the motion of actual near-parabolic comets

For a preliminary review of stellar action on all LPCs studied by us so far, we performed a special numerical integration of the past and future motion of nominal orbits of 22 comets investigated in Part I of this study Królikowska & Dybczyński 2013 and, additionally, of all 86 comets investigated in our previous papers (Paper I and Paper II).

At first, we compared previous and next nominal perihelion distances for all these 108 comets (except of the next perihelion of C/2010 X1 Elenin because this comet disintegrated near perihelion) with the values obtained without stellar perturbations.

It appears that in the backward motion no important (especially from the point of view of discerning dynamically new/old comets) changes can be observed. The largest observed difference is on the level of 38 per cent: the nominal previous perihelion of C/2006 OF3 decreased from 36.2 au (model without stellar perturbations) down to 22.5 au (with the stellar action switched on). The previous perihelion distances of only two from among 108 near-parabolic comets is slightly “moved” across the adopted limits of 10 or 15 au (used in Paper II), i.e. their dynamical status has to be reclassified. Namely, the previous nominal perihelion distance changed from 9.58 au to 10.16 au for C/1996 E1, and from 15.05 au to 14.80 au for C/2001 K3. As a result both comets should be classified as dynamically uncertain. None of all 108 comets is moved across the 20 au threshold value, this is an additional reason why we adopt this value as defining dynamically new comets in this paper.

We have also checked all minimal distances between comets (on their nominal orbits) and stars, finding that the proximities closer than 1 pc are very rare in the past. In fact only two stars, HIP 30344 and HIP 84263, passed near some of comets investigated by us so far closer than 1 pc. The closest passage of HIP 84263 was at a distance of 0.52 pc from C/1987 W3, and the closest flyby of HIP 30344 was at 0.85 pc from C/2006 OF2. HIP 30344 is a moderate perturber ( with mass of 0.79 M⊙ and a velocity of 18.3 km s⁻¹) while HIP 84263 can potentially act much stronger (1.3 M⊙, v=12.6 km s⁻¹). But even such a slow and massive star acts rather weakly from a distance greater than 150,000 au – it increases the nominal previous perihelion distance of C/1987 W3 from 78.9 au up to just 83.8 au.

The situation is a bit more complicated when we look at the future cometary motion under the stellar perturbations. It is a well-
known fact that the star Gliese 710 (HIP 89825) will pass near the Sun in 1.4 million years at a very close distance. The predicted proximity distance strongly depends on the 6-D initial data and the method of a stellar trajectory calculation. Using our model and data taken from XHIP catalogue, we obtained its closest heliocentric proximity distance as small as 0.23 pc, almost equal to the 0.24 au value from the linear approximation presented in XHIP. This makes an arbitrarily close approach of this star to some LPCs with favourable alpha Centauri system but almost exactly at the 1 pc distance. According to our calculations, it will nominally pass as close as 0.23 pc, almost equal to the 0.24 au value from the linear approximation presented in XHIP. This makes an arbitrarily close approach of this star to some LPCs with favourable orbit orientations quite possible to occur. While the mass of Gliese 710 is not so big (estimated to be 0.6 M⊙) its arbitrarily close approach can potentially perturb cometary orbit drastically. Gliese 710 is the only star from the tested sample of 90 potential perturbers which can pass in the future closer than 1 pc from any of investigated comets. We registered only few additional events with the alpha Centauri system but almost exactly at the 1 pc distance.

Therefore, Gliese 710 acts on almost all investigated comets during their next orbital revolution, except from these which change their orbits (due to the planetary perturbations during the observed apparition) into much more bound ones. With the orbital period smaller than 1.3 million years (semimajor axis less than 12 000 au) they cannot experience any significant perturbation caused by Gliese 710. Comets with larger semimajor axes received smaller or bigger “kicks” from Gliese 710, which change their future orbits substantially in some cases. However, from among the 22 comets studied in this paper only three LPCs escaping in the future (C/2006 K3, C/2006 L2 and C/2009 O4) were affected, as well as many of them to the P group and one to the F group (they act significantly or bigger “kicks” from Gliese 710, which change previous/next perihelion passages of any tested comet by less than 1 per cent. Additionally, three stars should be reclassified from C group, two of them to the P group and one to the F group (they act significantly only in the past or future motion of comets respectively).

As a result we found that 9 stars from the P group, 12 from the F group and 4 from the C group can be safely removed from our list of potential stellar perturbers since they change previous/next perihelion passages of any tested comet by less than 1 per cent. Additionally, three stars should be reclassified from C group, two of them to the P group and one to the F group (they act significantly only in the past or future motion of comets respectively).

After these modifications, we have 4 stars or stellar systems in group C, 32 in group P and 29 in group F. As a result, we can include only 36 stellar perturbers (P+C) when integrating the past cometary motion and only 33 stars (F+C) for the future motion instead of using all 90 stars for each cometary swarm of thousands of VC, which significantly speed-up our calculations.

4 PAST MOTION OF THE SAMPLE OF 22 LPCS DISCOVERED IN 2006-2010

Our main purpose when analysing past motions of LPCs is to search for the apparent source/sources of these comets. At the first step we attempt to discriminate between dynamically old and new comets. As we conclude in our previous papers, one cannot do it

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### Table 1. The past distributions of swarms of VCs in terms of returning [R], escaping [E], including hyperbolic [H] VC numbers for dynamically old comets.

| Comet & quality class | Number of VCs | $q_{\text{prev}}$ au $10^3$au $q_{\text{prev}}$ au $10^3$au | Q_{\text{prev}}$ au | $l/q_{\text{prev}}$ $10^3$au$^{-1}$ |
|----------------------|---------------|------------------|---------------------|---------------------|
| [1]                  | [2]           | [3] [4] [5] [6]  | [7] [8] [9]         |
| C/2006 HW51 Siding Spring | 5001 | 0 | 0 | 38.8 - 42.3 - 46.6 | 2.44 - 2.81 - 3.72 | 47.21 ± 3.37 |
| C/2006 K3 McNaught | 5001 | 0 | 0 | 29.8 - 32.7 - 36.2 | 2.34 - 2.35 - 2.39 | 61.11 ± 4.63 |
| C/2006 P1 McNaught | 5001 | 0 | 0 | 32.1 - 34.9 - 38.5 | 0.079-0.093-0.106 | 57.20 ± 4.03 |
| C/2006 Q1 McNaught | 5001 | 0 | 0 | 32.1 - 34.9 - 38.5 | 0.073-0.094-0.110 | 57.21 ± 4.03 |
| C/2007 Q3 Siding Spring | 5001 | 0 | 0 | 39.15 ± 0.37 | 4.944 ± 0.090 | 51.09 ± 4.08 |
| C/2007 Q3 Siding Spring | 5001 | 0 | 0 | 47.71 ± 0.60 | 9.59 ± 0.44 | 41.90 ± 0.53 |
| C/2008 A1 McNaught | 5001 | 0 | 0 | 16.56 ± 0.28 | 1.0599 ± 0.0006 | 120.82 ± 2.03 |
| C/2009 K5 McNaught | 5001 | 0 | 0 | 43.95 ± 0.53 | 3.70 ± 0.15 | 45.50 ± 0.55 |
| C/2009 Q4 Hill | 5001 | 0 | 0 | 32.1 - 35.7 - 40.3 | 1.69 - 1.97 - 2.15 | 55.94 ± 4.91 |
| C/2009 Q4 Hill | 5001 | 0 | 0 | 32.2 - 35.7 - 40.3 | 1.58 - 1.86 - 2.05 | 55.96 ± 4.91 |
only on the basis of the original semimajor axis (as it is still widely discussed in many papers) but it seems to be necessary to examine the previous perihelion distance of each comet. Similar to our Paper II we decided to apply three different threshold values for $q_{\text{prev}}$, namely 10, 15 and 20 au. In our calculations all comets are replaced with 5 001 VCs, so these thresholds are applied individually to each returning VC. If $q_{\text{prev}} < 10$ au we call this VC a dynamically old one. If $q_{\text{prev}} > 20$ au we call it a new one. Finally, for $10 \text{ au} < q_{\text{prev}} < 20$ au we call it uncertain. Taking all this together, we are rather careful in drawing conclusions: we call a particular comet the dynamically new only if all its VCs are dynamically new, and we call a comet the dynamically old if all its VCs are dynamically old. In the rest of cases, we treat a comet as having the uncertain dynamical status.

The results of our past motion investigations are presented in three tables: Table 1 containing eight dynamically old comets, Table 2 containing nine dynamically new comets and Table 3 showing five uncertain cases. In each table we present two rows of results for each comet: first one (highlighted by grey shading) consists of the results obtained from calculations which include all stellar perturbations described earlier. The second row presents, for comparison purposes, the results obtained when the stellar perturbations are completely omitted. We present such a detailed comparison to validate our general opinion that stellar perturbations from all known (so far) stars do not change past motion of any analysed comets significantly, especially from the point of view of their dynamical status. Note, that throughout all these studies, we use a modified original and future orbit quality classes, described in detail in Part I of this investigation [Królikowska & Dybczyński 2013] as well as recently in Królikowska (2014). For the description of model names see also Part I.

All comets from Table 1 have entire swarm of their VCs elliptical and returning, i.e. their aphelion distances are smaller than the adopted here escape threshold of 120,000 au for all VCs. Only one comet (C/2007 Q3) has previous perihelion close to 10 au, all other have $q_{\text{prev}} < 5$ au. There are four comets (C/2006 K3, C/2006 P1, C/2008 A1, C/2009 Q4) with previous perihelion distances even smaller than the observed one (see also Fig. 1). These four comets have relatively small semimajor axes. It is rather counter-intuitive: they have very slow orbital evolution resulting from Galactic perturbations, so they should have visited the inner planetary system several times in the past (if not tens of times). This fact, together with their small perihelion distances, make them suspiciously immune from planetary perturbations and physical ageing.

The largest semimajor axis in dynamically old comets group is about 24 000 au, what corresponds to the orbital period of about 4 Myr. We are rather convinced that it is really improbable that we missed an important (i.e. massive and/or slow) stellar perturber which visited the solar neighbourhood closer than 0.5 pc in this time interval. As a result, we can deliberately state that this eight comets are certainly dynamically old and they visited the inner part of the Solar system at least once in the past.

Among nine dynamically new comets (Table 2) the situation is more complicated. We have one comet, C/2007 W1, with all VCs escaping in the past along hyperbolic orbits. This object is the only serious candidate for an interstellar comet among all LPCs investigated by us so far. Comet C/2010 H1 has also a negative $1/q_{\text{prev}}$ value but its orbit is poorly known. We have other two comets (C/2007 N3 and C/2010 X1) with a whole swarm of VCs returning and one comet, C/2008 T2, with all VCs elliptical but escaping, i.e. crossing our escape threshold of 120 000 au. The remaining five comets have their VCs swarms mixed – some of VCs are returning and some are escaping. The smallest semimajor axis in this group is about 34 000 au.

The remaining five comets (Table 3) we have classified as of uncertain dynamical status. Comet C/2006 OF2 seems to be dynamically new but 22 per cent of its VCs have their previous perihelion distances below 20 au (and among them 3 per cent placed below 15 au). Due to relatively large semimajor axis of this comet (about 48 000 au) its motion is rather sensitive even to weak stellar impulses. On the other hand, comet C/2007 Q1 has the orbit of poorest quality in the sample studied here (data-arc span of only 24 days), and as a result it has almost 50 per cent of hyperbolic VCs as well as the mean previous perihelion as small as 3 au for the returning part of its VCs swarm.

In Fig. 1 we present the overall dependence of the perihelion distance change during the last orbital revolution on the original semimajor axis. Full dots represent nominal orbits of dynamically new and old comets, open circles denote uncertain dynamical status. Accompanying curves represent errors derived from swarms of VCs, truncated at 1σ level. Note that the horizontal scale is logarithmic right from 10 au and linear otherwise.
third quarter, which corresponds to the decreasing phase of the perihelion distance distribution. The main concept of this figure is inspired by Fig. 3 from Foucheard et al. (2011), but instead of their schematic draw, the real dynamical evolution are plotted here. This figure is a clear evidence that perturbations from any known star do not change significantly the past motion of the studied comets. For a comparison purpose, we present similar plot for 86 LPCs studied in Paper I and II, see Fig. 3. Again, all dynamically new comets have their argument of perihelion (in a Galactic frame) in the first or third quarter. One can also notice, that we did not obtain even one case in which a significant stellar action can be seen.

5 FUTURE MOTION

As it regards future motion of 21 LPCs studied in this paper (C/2010 X1 disintegrated during the observed perihelion passage) the situation is quite typical and completely different from the past orbital evolution. Generally, we obtain two types of motion. Six comets will leave the Solar system along hyperbolic orbits (Table 3) as a result of planetary perturbations. The same planetary action resulted in significant shortening of the semimajor axes of remaining 15 comets studied here (Table 5), with the extreme case of C/2007 N3, for which $\Delta a_{\text{init}} \approx 1215$ au, obtained from $a_{\text{orig}} \approx 34000$ au.

Only two comets in the later group have mixed VCs swarms. The extremely dispersed VCs swarm of C/2007 Q1 (as a result of largest orbital uncertainties) consists of 1306 returning clones and 3695 escaping ones (3657 of them are hyperbolic). The mixed swarm of C/2009 R1 consists mainly of returning VCs but about 20 per cent of clones are escaping (most often along hyperbolic orbits). This swarm is highly dispersed since future orbit of this comet is rather uncertain – all observations were obtained before its perihelion passage, for details see Part I. The remaining 13 comets from Table 5 have all their VCs returning with a typical perihelion distance of about 1 au or even less.

There is a significant difference between past and future motion in the context of the importance of stellar perturbations. As it was clearly presented in Figs. 2 and 3 stellar perturbations do not affect the past orbital evolution. The same situation is quite typical and completely different from the past orbital evolution.
Near-parabolic comets observed in 2006–2010. II

Figure 2. Last orbital period evolution of the osculating argument of perihelion and the perihelion distance of nominal orbits of 22 comets investigated in this paper. For each comet a plot in polar coordinates is presented, in which the distance from the centre equals the osculating perihelion distance while the “phase angle” equals the osculating argument of perihelion. Open circles denote start of each calculation with the original orbit, full dot marks a previous perihelion. For escaping comets we stopped the calculation at 120,000 au from the Sun and this fact is marked with a cross. Two different calculations are presented for each comet: red one with all stellar perturbations included, overprinted with the black plot where only Galactic perturbations are taken into account. In the yellow area ($q < 5$ au, the observability zone) the scale of the radial coordinate is linear while outside this area it is logarithmic.

Figure 3. The same as in Fig. 2 but for 86 LPCs studied in Paper I and II (note that a radial coordinate scale has to be changed to show all these comets in one figure).

Figure 4. The same as in Fig. 2 but for future motion (only 21 comets are here since C/2010 X1 disintegrated during the observed perihelion passage).

change the past dynamical cometary evolution in a significant manner during their last orbital period. As it concerns their future motion situation might be completely different since we expect at least one very close stellar encounter with the Sun. The star Gliese 710 (HIP 89825) will pass as close as about 0.24 pc from the Sun in 1.4 Myr. As a result, arbitrarily small comet-star distance may occur, provided the orbital period is longer than 1.4 Myr (we restricted our calculations to one orbital period to the past and in future). None of the comets from Table 5 has orbital period long enough to meet Gliese 710, but all comets from Table 4 suffer from weaker or stronger gravitational kick from this star, as it is shown in Fig. 4 and will be discussed in detail in Section 6.4 on the past dynamical evolution of C/2009 O4. However, even the strongest effects, visible in cases of C/2006 K3 and C/2006 L2, do not change their fate – they will still leave our planetary system along (only slightly modified) hyperbolic orbits.

All significant stellar perturbations visible in Fig. 4 are caused by Gliese 710. We performed additional test calculation with this star excluded and all effects of any stellar action almost disappeared making the character of this plot in this respect similar to that of Fig. 2.

Table 4. The $1/a_{\text{next}}$ values for six comets with all 5001 VCs escaping in the future in hyperbolic orbits. We present two rows for each comet: the upper row (highlighted by grey shading) contains the results with the stellar perturbations included, and the second row (presented here for comparison) shows results where stellar perturbations were ignored in the dynamical calculations.

| Comet       | model & quality class | $1/a_{\text{next}}$ $10^{-6}$au$^{-1}$ |
|-------------|-----------------------|----------------------------------------|
| C/2006 K3   | [1] NG, 1a            | -130.27 ± 4.64                        |
|             |                       | -130.26 ± 4.65                        |
| C/2006 L2   | [2] GR, 1a            | -93.97 ± 1.41                         |
|             |                       | -93.96 ± 1.41                         |
| C/2006 OF$_2$ | [3] NG, 1a+         | -658.76 ± 0.23                         |
|             |                       | -658.76 ± 0.23                         |
| C/2007 O1   | [4] GR, 1a            | -496.94 ± 4.69                         |
|             |                       | -496.99 ± 4.69                         |
| C/2008 J6   | [5] GR, 1b            | -479.37 ± 3.99                         |
|             |                       | -479.35 ± 3.99                         |
| C/2009 O4   | [6] GR, 1b            | -57.2 ± 4.83                           |
|             |                       | -57.89 ± 4.83                           |

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Table 5. The future elements distributions of 16 comets with returning or mixed swarms of VCs in terms of returning [R], escaping [E], including hyperbolic [H] VC numbers. We present two rows for each comet: the upper row (highlighted by grey shading) contains the results with the stellar perturbations included and the second row (presented here for comparison) shows results where stellar perturbations were ignored in our dynamical calculations. Next aphelion (col. 6) and perihelion (col. 7) distances are described either by a mean value of the approximate normal distributions, or three decimals at 10, 50 (i.e. median), and 90 per cent in cases where the normal distribution is not applicable. In the case of mixed swarm the mean values or decides of Q and q are given for the returning (suffix ‘R’) part of the VCs swarm, where the escape limit of 120 000 au was generally adopted. Last column presents the value of 1/\(q_{\text{next}}\). Suffix ‘S’ denotes a result for the swarm synchronously stopped.

| Comet model & quality class | Number of VCs | \(q_{\text{next}}\) \(10^3\)au | \(q_{\text{next}}\) au | \(1/q_{\text{next}}\) \(10^{-6}\)au\(^{-1}\) |
|--------------------------|--------------|----------------|----------------|----------------|
| C/2006 HW_{51}           | GR, 1a       | 5001 0 0       | 22.25±0.84    | 3.33 - 2.35 - 2.37 | 9.02±e+3.37 |
|                          |              |                | 22.25±0.84    | 2.34 - 2.35 - 2.37 | 9.01±e+3.37 |
| C/2006 P1                | NG, 1b       | 5001 0 0       | 4.28±0.03     | 0.17214±0.00005 | 467.6±e+3.56 |
|                          |              |                | 4.28±0.03     | 0.17222±0.00002 | 467.6±e+3.56 |
| C/2006 Q1                | NG, 1a+      | 5001 0 0       | 2.824±0.001   | 2.759±0.001   | 707.45±e+0.31 |
|                          |              |                | 2.824±0.001   | 2.759±0.001   | 707.4±e+0.31 |
| C/2006 VZ_{13}           | NG, 1b       | 5001 0 0       | 4.07±0.17     | 1.012±0.001  | 491.6±e+20.1 |
|                          |              |                | 4.07±0.17     | 1.012±0.001  | 491.6±e+20.1 |
| C/2007 N3                | NG-POST, 1a  | 5001 0 0       | 2.427±0.006   | 1.215±0.0004 | 823.6±e+2.06 |
|                          |              |                | 2.427±0.006   | 1.218±0.0005 | 823.6±e+2.06 |
| C/2007 Q1                | GR, 3a       | 1306 3695 3657 | 2.16 - 5.61 - 26.2R | 12.75-2.97-2.99R | -463±741S |
|                          |              |                | 2.16 - 5.61 - 26.2R | 2.70-2.97-2.99R | -463±741S |
| C/2007 Q3                | GR-POST, 1a  | 5001 0 0       | 15.18±0.42    | 2.171±0.008  | 131.8±e+3.63 |
|                          |              |                | 15.18±0.42    | 2.174±0.008  | 131.8±e+3.63 |
| C/2007 W1                | NG-POST, 2a  | 5001 0 0       | 3.61±0.05     | 0.846±0.002  | 554.5±e+7.09 |
|                          |              |                | 3.61±0.05     | 0.846±0.001  | 554.5±e+7.09 |
| C/2007 W3                | NG, 1b       | 5001 0 0       | 5.82±0.31     | 1.770±1.770  | 344.3±e+18.10 |
|                          |              |                | 5.82±0.31     | 1.772±1.770  | 344.3±e+18.10 |
| C/2008 A1                | NG-POST, 1b  | 5001 0 0       | 8.11±0.09     | 1.071±0.003  | 246.5±e+2.82 |
|                          |              |                | 8.11±0.09     | 1.070±0.005  | 246.5±e+2.82 |
| C/2008 C1                | GR, 2a       | 5001 0 0       | 3.98±0.09     | 1.265±0.0008 | 502.3±e+1.77 |
|                          |              |                | 3.98±0.09     | 1.262±0.008  | 502.3±e+1.77 |
| C/2008 T2                | GR, 1b       | 5001 0 0       | 7.25±0.03     | 1.202±0.0002 | 275.9±e+1.06 |
|                          |              |                | 7.25±0.03     | 1.201±0.0001 | 275.9±e+1.06 |
| C/2009 K5                | GR-POST, 1a  | 5001 0 0       | 3.616±0.003   | 1.419±0.0001 | 552.9±e+0.41 |
|                          |              |                | 3.616±0.003   | 1.419±0.0001 | 552.9±e+0.41 |
| C/2009 R1                | NG, 1b       | 3909 1092 986  | 4.51 - 9.05 - 32.1R | 0.380-0.406-0.502R | 166.3±e+17.18 |
|                          |              |                | 4.51 - 9.05 - 32.1R | 0.390-0.406-0.446R | 166.3±e+17.18 |
| C/2010 H1                | GR, 2b       | 5001 0 0       | 3.70±0.07     | 2.74±0.0006  | 541.0±e+10.77 |
|                          |              |                | 3.70±0.07     | 2.74±0.0001  | 541.0±e+10.77 |

6 EXAMPLES OF STELLAR PERTURBATIONS ON LPCS

In this section we present examples of dynamical evolution of cometary nominal orbits under simultaneous gravitational action of the whole Galaxy and individual potential stellar perturbers. During the past and future comet motion it is possible to observe slow orbital elements evolution caused by Galactic tides overlapped by (usually very small) local variations due to the action of passing stars. In many cases, we identified a star or stellar system responsible for the individual orbital element fluctuation.

Figures 5–9 show several examples of the dynamical evolution of orbits of LPCs, four of them are comets discovered in the years 2006–2010. In each picture, the horizontal time axis extends from the previous perihelion passage through the observed perihelion up to the next perihelion passage or to the moment of escape (understood here as crossing the threshold heliocentric distance of 120 000 au). The left vertical axis is expressed in au and corresponds to the osculating perihelion distance plot (\(q\), green line) as well as the heliocentric distance plot (\(r\), thin blue lines). Due to the scales of this pictures the heliocentric distance plot takes the form of vertical blue lines exactly at perihelion passage moments.

The right vertical axis is expressed in degrees and describes the evolution of the osculating inclination (\(i\), magenta line) and the ar-
argument of perihelion (\(\omega\), red line). Both these angular elements are expressed in the Galactic frame. The thick lines depict dynamical evolution under the simultaneous stellar and Galactic perturbations while the thin lines mark the evolution with the stellar perturbations excluded. Horizontal dashed lines call attention to the beginning of the second and fourth quarter of \(\omega\), which values (90° and 270°) are important from the point of view of the Galactic perturbations. The vertical dashed lines show closest approaches of a comet with the star or stellar system, which name is placed at the top of the picture. It is worth to mention, that the timing of stellar perturbation is not necessarily strictly aligned with this closest approach moment – it strongly depends on the geometry since the final, heliocentric orbit change is a net effect of a stellar gravitational action on both, a comet and the Sun.

6.1 Comets discovered in the years 2006–2010

Four characteristic examples how known stellar perturbation can affect the dynamical evolution of actual near-parabolic comets are illustrated in Figures 5–8.

6.1.1 C/2006 OF2 – comet with the largest change of perihelion distance in the past due to stellar action

The largest change in a previous perihelion distance caused by stellar perturbations can be observed in the case of comet C/2006 OF2. The cumulative perturbations from all stars change the previous perihelion distance of this comet from 36.3 au down to 22.5 au (these are medians of a non-Gaussian VCs distributions, compare also with nominal orbital elements given in Table 3). Large orbital period (over 10 Myr) have amplified this effect. In Fig. 5 one can easily note a prominent perturbation by HD 155117 (HIP 84263, 1.3 M\(_{\odot}\), minimal distance from C/2006 OF2 of 0.56 pc happened 6.4 Myr ago). Algol system (HIP 14576, 5.8 M\(_{\odot}\), minimal distance from C/2006 OF2 of 2.72 pc occurred 7.5 Myr ago) causes only a moderate variation of the comet inclination. A small local variations of comet inclination and perihelion distance result from the passage of Theta Columbae (HIP 29034, 4.14 M\(_{\odot}\), minimal distance from C/2006 OF2 of 1.96 pc occurred 4.7 Myr ago). No significant change in the argument of perihelion resulting from the action of these three massive stars is observed. On the contrary, the cumulative (but weak) perturbations from HD 37594, HIP 30344 and GJ 217.1 change slightly all three elements plotted in Fig 5. In its future motion, C/2006 OF2 do not suffer any noticeable stellar perturbations and escape from the Solar system along the strongly hyperbolic orbit (evolution is stopped when a comet reach the distance of 120 000 au from the Sun).

6.1.2 C/2006 P1 – example of cumulative action of stellar perturbation

Comet C/2006 P1 was observed at a very low perihelion distance of 0.17 au. According to our calculations its previous perihelion distance was even much smaller, with a median value of about 0.1 au (see Table 1). It can be seen in Fig. 6 that the cumulative action of stars on the comet’s dynamics does not change the previous perihelion distance and inclination values noticeably, while its previous argument of perihelion is changed by over 35 degrees (from 117° down to 82°). Several individual weak stellar perturbations are marked in Fig. 6 but the overall evolution of orbital elements is also affected by a cumulative effect of other numerous stellar perturbers. The narrow range of the left vertical scale of the picture (0–0.20 au) allows to show the discontinuity between original and future orbit (caused by planetary perturbations during the observed perihelion passage), especially in the perihelion distance. As it is clearly depicted, planetary perturbations have shortened the semimajor axis of this comet considerably. Thus, this comet will appear in the next perihelion passage in a relatively short time of order of 100 thousand years having the similarly small perihelion distance. It is worth noting, that comet C/2006 P1 McNaught is a very interesting object. It was very bright with a spectacular tail spread over half of the sky. Surprisingly, it exhibited moderated nongravitational effects in the sense of deviation from the pure gravitational motion, and the nucleus activity became very low soon after perihelion. This probably can explain how it can survive even several such a close perihelion passages.
6.1.3 C/2007 O1 – example of a series of weak stellar perturbation

The case of comet C/2007 O1 is a good example of a very common phenomenon, when a series of weak stellar perturbations compensate each other. This is a nature of a single stellar gravitational action on a comet that the change in osculating elements gained during the star approaching phase is sometimes completely reversed during its moving away. When a series of different stellar perturbation occur such a mutual compensation is a typical feature. In Fig. 7 one can easily notice, that the net effect of weak perihelion distance (and inclination) perturbations caused by HD 37594, HIP 30344, GJ 217.1 and HD 54958 is invisible in the plot. The same situation can be observed in a case of inclination perturbations by Algol system, fully compensated by the action of HD 155117. However, the perihelion distance perturbations by these two massive stars do not completely compensate each other. When following the past motion of C/2007 O1 we obtained its previous perihelion distance larger by approximately 0.5 au (the swarm of VCs is rather highly spread for this comet) after including stellar perturbations in the dynamical model. It is worth to note that in this case no changes in osculating argument of perihelion are observed.

6.1.4 C/2009 O4 – comet with largest change of perihelion distance due to GJ 710 in the basic sample of 22 comets

As it was mentioned earlier, the stellar perturbations along a comet future motion orbital branch can be much more spectacular. This results from a future close approach of the star GJ 710 (HIP 89825) and can potentially lead to an arbitrarily large change in cometary orbits. However, among 22 LPCs studied in detail in this paper, we did not found such a drastic case. The largest difference in the future comet motion we observe in the case of C/2009 O4. This comet escapes from our planetary system along a hyperbolic orbit \(1/a_{\text{fut}} = -56 \pm 5 \text{ au}^{-1}\). In 1.38 Myr, it will make a moderately close approach to GJ 710 (at a distance of 0.45 pc, approximately 93 000 au) and significant changes in its osculating elements can be observed, see Fig. 8. This is an escaping comet, so, we stopped calculations of its future motion at a threshold heliocentric distance of 120 000 au. The angular elements, after significant local “jumps” remain almost unchanged at the end of the calculation. It should be noted that the character of the future motion of C/2009 O4 remains also unchanged and it will escape along the hyperbolic orbit with almost the same energy.

6.2 The additional sample of 86 near-parabolic comets

As stated earlier we have incorporated stellar perturbations in our standard dynamical model used in long term cometary dynamics investigations. As a result we decided to check all 86 LPCs previously investigated by us for any significant changes in orbital elements that result from the stellar gravitational action.

As it was described in section 6.1 we have not observed any strong stellar perturbations in the past motion of these comets but their future motion exhibits several interesting cases. As this paper is mainly devoted to LPCs discovered in 2006-2010 we present only one extreme example.
ing of the quarters border at 270° causes the switch in the Galactic dynamical evolution phase. Osculating inclination of C/1999 F1 is also significantly influenced by GJ 710, decreasing from 137° down to 105°.

Such a large orbit change caused by GJ 710 remains in drastic contrast to barely noticeable results of cumulative stellar perturbations during the C/1999 F1 past orbital revolution.

7 DYNAMICALLY NEW VERSUS OLD NEAR-PARABOLIC COMETS

In this section, we discuss the dynamical status of 22 comets analysed here in details in comparison to the entire sample of 108 comets investigated by us in last few years. However, for nine comets considered in Papers I–III (C/1999 K1, C/1993 A1, C/1997 A1, C/1999 F1, C/1999 N4, C/2002 J4, C/2003 K4, C/2003 S3 and C/2005 K1), we updated the orbital solutions by taking the newer osculating orbits described as new solution in Table A.1 of Królikowska (2014) for the dynamical evolution. As a result, the overall histogram of 1/\(a_{\text{orig}}\) shown in thick black ink in Fig. 10 is slightly different from that presented in Fig. 9 in Królikowska & Dybczyński (2013). Additionally, we repeated all our previous dynamical calculations using a model with stellar perturbations described in Section 3. However, we should emphasise that in a statistical sense, stellar perturbations have not changed any of histograms presented in Fig. 10.

For constructing the histograms, we treated each VC from the swarm individually. This means that overall distribution given in Fig. 10 is composed of the 108 individual and normalised 1/\(a_{\text{orig}}\) distributions (each based on 5001 VCs). Additionally, to prepare the statistics of dynamically old/new/uncertain, we also considered each VC individually: a VC was defined as a ‘dynamically old’ when its \(q_{\text{prev}}\) was smaller than 10 au and \(Q_{\text{prev}}\) was inside a sphere of 120,000 au, the dynamical status was called ‘uncertain’ for 10 au \(\leq\) \(q_{\text{prev}}\) \(<\) 20 au and \(Q_{\text{prev}}\) \(<\) 120,000 au, the remaining VCs were dynamically new. The effect of this approach can be seen in Fig. 10 where the coloured histograms in the upper panel show the distributions of dynamically old part of distributions and dashed parts of bars represent the uncertain VCs, whereas the colour histograms in the lower panel highlight dynamically new parts of the entire distributions.

The distributions of dynamically new and dynamically old comets of the sample of 22 comets seems to be statistically similar to the respective distributions representing the entire sample of 108 comets, with the exception of the occurrence of one definitely hyperbolic previous orbit of C/2007 W1.

The percentage contribution of dynamically new/old/uncertain to the respective bins in the range 0 \(\leq\) 1/\(a_{\text{orig}}\) \(<\) 0.0000100 au\(^{-1}\) is given in Table 6. One can see that in the range of 0.000030 au\(^{-1}\) \(\leq\) 1/\(a_{\text{orig}}\) \(<\) 0.000040 au\(^{-1}\), we have less than 60 per cent of the dynamically new comets, and up to 25 per cent of comets certainly being dynamically old. Even in the range of 0.000020 au\(^{-1}\) \(\leq\) 1/\(a_{\text{orig}}\) \(<\) 0.000030 au\(^{-1}\) (33,000 au \(\leq\) \(a_{\text{orig}}\) \(\leq\) 50,000 au), we are not sure about the dynamical status of comets, because, qualitatively speaking, every twenty-thirtieth can be dynamically old comet. This fully confirms conclusions made earlier with simpler models (Dybczyński 2001, 2006). It seems worth to note that many authors still erroneously treat LPCs from all rows of Table 6 as visiting the inner planetary system for the first time, which is not necessarily true.

Finally, it is worth to pay attention to these comets, which according to our investigation come to the Solar system on hyperbolic orbits. It turns out that we have 3.5 per cent of such VCs in a sample of 108 cometary swarms. It would be formally translated to 3.6 objects, where 1.8 objects belong to sample of 22 comets analysed here. In fact, we have, however, only one comet, which is a good candidate for interstellar comet. This is C/2007 W1 Boattini, widely discussed in Part I of these studies (see also Fig. 10). Now, after calculating its past motion under the influence of Galactic tides and all known potential stellar perturbers, we can confirm that this comet seems to be of interstellar origin. Its osculating perihelion distance and the inverse semimajor axis distributions are

![Figure 10](image1.png)

**Figure 10.** Upper panel: dark green/gold histograms show the distribution of dynamically old VCs for the samples of 108/22 comets, where the dashed parts represent the dynamically uncertain VCs. Lower panel: Histograms filled in violet/magenta ink present the distributions for the dynamically new VCs for the same samples. The overall distribution of the entire sample of 108 comets is given by histogram shown in black ink in both panels.

![Figure 11](image2.png)

**Figure 11.** Joint and marginal distributions of the osculating 1/\(a\) and \(q\) of C/2007 W1 at a heliocentric distance of 120,000 au before entering our planetary system. The centre of the green circle points to the nominal values.
Tables 6. The percentage contributions of dynamically new/old/uncertain parts of VCs to individual bins of \(1/a_{\text{orig}}\)-distribution for all 108 comets studied by us. The range of \(1/a_{\text{orig}}\) corresponds to the area of histograms given on a grey background in both panels of Fig. [10]. Numbers in the upper part of the table are compatible with histograms in Fig. [10]. In the lower part of this table, we show only rows where the numbers were changed as a result of another definition of uncertain VCs.

| Range of \(1/a_{\text{orig}}\) in units of \(10^{-6}\) au\(^{-1}\) | Per cent (in a bin) of dynamically new VCs of all VCs | Per cent (in a bin) of dynamically old VCs of all VCs | Per cent (in a bin) of dynamically uncertain VCs of all VCs |
|---|---|---|---|
| 0–10 | 100 | 0 | 0 | 4.7 |
| 10–20 | 100 | 0 | 0 | 14.1 |
| 20–30 | 88.5 | 2.9 | 8.6 | 11.5 | 14.7 |
| 30–40 | 39.2 | 25.7 | 35.1 | 60.8 | 15.5 |
| 40–50 | 3.4 | 75.5 | 17.5 | 93.0 | 17.5 |
| 50–60 | 0 | 94.8 | 5.2 | 100 | 12.1 |
| 60–70 | 0 | 96.6 | 3.4 | 100 | 6.9 |
| 70–80 | 0 | 100 | 0 | 100 | 3.4 |
| 80–90 | 0 | 100 | 0 | 100 | 1.3 |
| 90–100 | 0 | 100 | 0 | 100 | 1.6 |

For the range of 'uncertain' VCs: \(10 \text{ au} \leq q_{\text{prev}} \leq 20 \text{ au}\):

| Range of \(1/a_{\text{orig}}\) in units of \(10^{-6}\) au\(^{-1}\) | Per cent (in a bin) of dynamically new VCs of all VCs | Per cent (in a bin) of dynamically old VCs of all VCs | Per cent (in a bin) of dynamically uncertain VCs of all VCs |
|---|---|---|---|
| 20–30 | 93.3 | 2.9 | 3.8 | 6.7 | 14.7 |
| 30–40 | 57.7 | 25.7 | 16.6 | 42.3 | 15.5 |
| 40–50 | 7.0 | 75.5 | 17.5 | 93.0 | 17.5 |

For narrower range of 'uncertain' VCs: \(10 \text{ au} \leq q_{\text{prev}} \leq 15 \text{ au}\):

| Range of \(1/a_{\text{orig}}\) in units of \(10^{-6}\) au\(^{-1}\) | Per cent (in a bin) of dynamically new VCs of all VCs | Per cent (in a bin) of dynamically old VCs of all VCs | Per cent (in a bin) of dynamically uncertain VCs of all VCs |
|---|---|---|---|
| 0–10 | 100 | 0 | 0 | 4.7 |
| 10–20 | 100 | 0 | 0 | 14.1 |
| 20–30 | 88.5 | 2.9 | 8.6 | 11.5 | 14.7 |
| 30–40 | 39.2 | 25.7 | 35.1 | 60.8 | 15.5 |
| 40–50 | 3.4 | 75.5 | 17.5 | 93.0 | 17.5 |
| 50–60 | 0 | 94.8 | 5.2 | 100 | 12.1 |
| 60–70 | 0 | 96.6 | 3.4 | 100 | 6.9 |
| 70–80 | 0 | 100 | 0 | 100 | 3.4 |
| 80–90 | 0 | 100 | 0 | 100 | 1.3 |
| 90–100 | 0 | 100 | 0 | 100 | 1.6 |

Presented in Fig. [11] for the heliocentric distance of about 120,000 au before the observed perihelion passage (i.e. almost 2 Myr ago). It is worth to mention that the presented \(1/a\)-distribution is almost identical to the distribution of the original orbit (at 250 au from the Sun) and it is not changed by any means by stellar perturbations. The mean of the \(1/a_{\text{prev}}\)-distribution for this comet is very close to the nominal value and equals \((-42.75 \pm 2.34) \times 10^{-6} \text{ au}^{-1}\). It should be stressed that using all available data we obtained hyperbolic original orbit for this comet in all investigated models, taking into account all uncertainties, also those resulting from strange nongravitational forces behaviour. Remembering that this comet reaches the 120,000 au escape limit in about 2 million years (going backward) it seems really improbable that we missed an important stellar perturber in this case. But if such a perturber will be discovered in future, our conclusion might appear inappropriate.

Comet C/2010 H1 Garradd have \(1/a_{\text{orig}} = -3.17 \pm 10.71 \text{ au}^{-1}\) in units of \(10^{-6} \text{ au}^{-1}\), and, in our opinion should be rather classified as related to the Solar system through interstellar origin can not be ruled out (see also Table 2). In the sample of the remaining 86 comets, we did not record similar cases to C/2010 W1; there were two cases (C/1952 W1 and C/1978 G2, see Table 4 in Paper 1 and Table 7 in Paper 2, respectively) similar to C/2010 H1 with formally negative value of \(1/a_{\text{orig}}\) for the nominal osculating orbit but highly dispersed swarm with high per cent of elliptical orbits. These four comets form the majority of the negative tail of the global \(1/a_{\text{orig}}\)-distribution given in Fig. [10]. Some of the other comets provide quite insignificant contribution to this negative tail.

8 SUMMARY AND CONCLUSIONS

This paper is a continuation of our pending effort to study past and future motion of all observed LPCs for which a reliable osculating orbit can be determined. During a few last years, we focus our attention on so called Oort spike comets, i.e. actual comets with the largest semimajor axes in the whole population of observed LPCs. Thus, the investigated here dynamical population of the sample of 22 near-parabolic comets with small perihelion distance and discovered in 2006-2010 is a continuation of our long-standing studies. A detailed description and statistics concerning osculating, original and future orbits of these comets may be found in the first part of this paper (Królikowska & Dybczyński 2013). There is also a separate paper by Królikowska (2014) describing in detail a publicly available catalogue of nearly-parabolic comets, which offer osculating, original and future orbits, augmented with their uncertainties and the overall quality assessments already introduced in Part I.

Our main conclusions raised from this investigation of 22 comets recently discovered are following:

- Small perihelion comets discovered in 2006-2010 appear rather typical when comparing with many other LPCs studied by us earlier. The only exception is C/2007 W1 which seems to be the first serious candidate for interstellar provenience.

- Studying the past motion of these 22 comets, we found nine of them to be dynamically new, eight dynamically old and five for which we cannot determine their dynamical status according to the adopted criteria. Among dynamically old comets, we found only one (C/2007 Q3) to have a previous perihelion distance close to 10 au, the rest have this parameter smaller than 5 au. One comet in the group investigated here, C/2007 Q1 (very short data-arc span of 24 days) has such an uncertain osculating orbit that any conclusions about its provenience seems impossible.

- The future motion of these comets exhibits various dynamical behaviour. C/2010 X1 disintegrated during the observed perihelion passage, maybe two other also disintegrated after perihelion passage, or split, however, there is nothing for sure (for more details see Part I). Six comets will escape from the Solar system along hyperbolic orbits and fifteen will return to the solar neighbourhood along much more tighten orbits than their original ones. Again, for C/2007 Q1 we cannot make any definitive conclusion due to a large uncertainty of its future orbit.

If we compare this sample of 22 comets with 86 LPCs studied by us earlier we can observe that:

- The percentage of dynamically old comets in the investigated here sample of small-perihelion comets is comparable to the remaining sample of 86 comets analysed in Paper I-II, where we found 38 comets (44 per cent) which are dynamically old and several with uncertain status. The same is true for dynamically new comets. For the entire sample of 108 comets we have 42 per cent of dynamically new old and the same per cent of dynamically new comets, about 16 per cent have uncertain status.

- It seems that we have here no more than 30 per cent of comets which leave the Solar system on hyperbolic orbits. The ambiguity associated with the future of a few comets mentioned above, does not change this picture. Thus, this sample seems to be quite different than the group of small-perihelion comets analyses in Paper I where we found the opposite tendency – there 60 per cent of comets will be lost on hyperbolic orbits. However, for the sample of 108 comets we have 54 per cent of escaping comets on hyperbolic future orbits. But this is effect of planetary perturbations (with some additional influence of nongravitational effects) as it was described in Part I and here we can only add that neither Galactic nor stellar perturbations change the fate of any of LPCs studied by us.

- The dependence of perihelion distance change during the last
orbital period on the original semimajor axis seems to be similar in all samples we studied, as it is shown in Fig.1.

- It is worth to mention here, that for large percentage of small perihelion distance LPCs (50 per cent in this paper, all comets from Paper I) and significant number of large perihelion distance comets (over 20 per cent from Paper II) we used nongravitational orbits. As we already shown original and future semimajor axes of LPCs are often highly influenced by nongravitational forces. This makes our results for previous and next orbits much more reliable for this objects.

Since the total number of near-parabolic comets studied by us so far (108 objects) is quite large we can formulate some more general conclusions:

- This paper again confirms our previous results that not all comets from the Oort spike are dynamically new (see Fig.10). We observed that the significant percentage of near-parabolic in this investigation as well as in our earlier studies have their previous perihelia deep in the planetary region. As a result, one cannot treat them as new comets since they experienced both planetary perturbations and solar radiation heating at least during their previous perihelion passage.

- The second key conclusion is that the widely used concept of the Jupiter-Saturn barrier should be revised since significant number of near-parabolic comets (about 15 per cent) can migrate through it without any significant orbital changes. As a result obtaining small previous perihelion distance do not necessarily make a comet dynamically new, while its thermal interaction with the Sun is obvious. This might be an important factor since one can imagine several consecutive perihelion passages of near-parabolic comets close to the Sun what complicates our understanding of dynamical and physical ageing of LPCs.

For the first time in our calculations we fully account for perturbations from all known stars therefore the second aim of this paper was to test their significance. We have extended our test for all samples we studied, as it is shown in Fig.1. The perturbations from all known stars are weak and often compensate each other. There is only one star, Giese 710 (HIP 89825) which can make arbitrarily close encounter with LPCs in the future. We found the extreme case for comet C/1999 F1 which nominally will approach Gliese 710 as close as 11 000 au.

Our computer codes are fully prepared to use more potential stellar perturbers so if the ongoing GAIA mission reveal stars or stellar systems we missed so far, we can easily check their importance for any particular near-parabolic comet.

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