Search for the apparent source/sources of near-parabolic comets

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This article is based on a lecture given during the Polish Astronomical Society meeting held in Poznań 7–10.09.2015. It should not be regarded as a systematic review of long-period comets studies. Here, we focus on a few key points from the results of our own research.

1 Introduction

Since in 1950 Oort formulated his hypothesis on the existence of the cometary cloud surrounding our planetary system several new and important circumstances have been revealed in this field of research. While Oort founded his hypothesis on the statistics of 19 precise, original cometary orbits of long-period comets (LPCs) now we have in hand several hundreds of such orbits. If we define Oort spike comets as those having $1/a_{\rm ori} < 0.0001\mathrm{AU}^{-1}$, we can collect from among best determined orbits 11 such comets discovered in the 19th century, 95 comets discovered in the 20th century and 70 comets discovered only in the first decade of the 21st century. This shows that the observed Oort spike comets population grows quickly and additionally it covers larger and larger heliocentric distances.

Oort suggested, that perturbations from the passing stars are responsible for directing comets from their "parking" orbits in the cloud into near-parabolic orbits with a perihelion distance in the sphere of observability. Several decades ago (Byl, 1983; Heisler & Tremaine, 1986; Delsemme, 1987) another and probably dominating perturbing force was recognized: tidal action of the whole mass of our Galaxy which completely changed the overall picture of the long term dynamical evolution of LPCs orbits. Moreover, increasing knowledge on nearby stars allows us to search for particular stellar perturbers of the motion of observed LPCs. In the last decade, we also learned how to include non-gravitational (NG) forces in the dynamical model of one-apparition comet motion, see for example Królikowska 2001, 2006.

Section 2 briefly describes our methods. In section 3 we present several important findings from our still ongoing research and illustrate them with two examples of detailed dynamical evolution of particular LPCs.

2 Methods

In our research we use effective and accurate computer codes for astrometric data processing, orbit determination and dynamical evolution studies under planetary, Galactic and stellar perturbations, well suited for LPCs. We presented results for

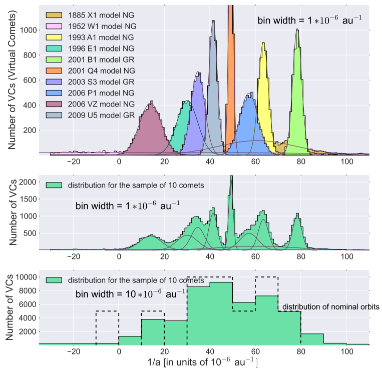

Fig. 1: How do we construct the original 1/a histogram; adapted from Paper 6.

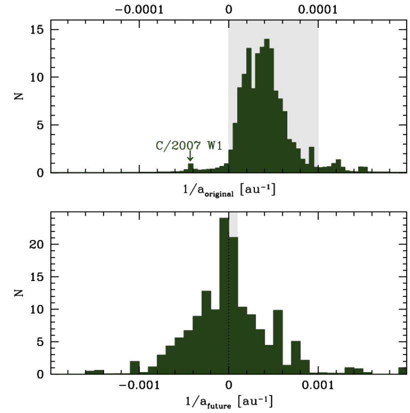

Fig. 2: Distribution of original and future $1/a$ for 157 near-parabolic comets.

over a hundred near-parabolic comets, described in a series of our papers (see the bibliography, Papers 1–6). Two other papers (Królikowska, 2014; Królikowska et al., 2014), are concentrated on osculating, original and future orbits of selected LPCs and increased the sample of studied near-parabolic comets to about 160.

The whole process of studying a particular Oort spike comet starts at the determination of an osculating orbit and its uncertainty determined from the available set of astrometric measurements. At this point, we also try to estimate the NG accelerations from the positional data. Using standard NG model of cometary motion introduced by Marsden et al. (1973), next developed by Yeomans & Chodas (1989) and Sitarski (1994), we determined NG parameters for about 40% of 160 comets investigated by us so far. In some cases, we use a dedicated approach, for example excluding some data intervals where violent non-gravitational phenomena can disturb the comet motion, see Paper 3 for more details. We also developed the modified method of orbit quality assessment (Paper 4) useful for purely gravitational (GR) orbits as well NG orbits.

Propagation of uncertainties of cometary orbit (resulting from the positional data set used for orbit determination) during the whole dynamical evolution is crucial in our approach. For this purpose, we replace a comet with 5001 virtual comets (hereafter VC), i.e. nominal orbit and 5000 of its clones, drawn according to Sitarski (1998) method. Next, each swarm is propagated numerically back and forth up to a heliocentric distance of 250 AU, constituting sets of original and future barycentric orbits. Therefore, we obtain the nominal original and future orbits together with their uncertainties. The dynamical model at this stage includes the perturbations by all planets, the relativistic effects and NG effects in the comet's motion if they were determinable.

At a distance of 250 AU from the Sun we start to ignore planetary perturbations but include Galactic and stellar perturbations. In the Galactic tides both disc and central terms were added. Stellar perturbations on cometary motion are calculated by numerical integration of the influence of 90 potential perturbers selected from all known stars approaching the Sun in the relevant time interval of several Myr. We keep our dynamical model up-to-date, continuously incorporating new results describing our Galactic neighbourhood and most recent data on potential stellar perturbers, see Papers 4 and 5 for more details.

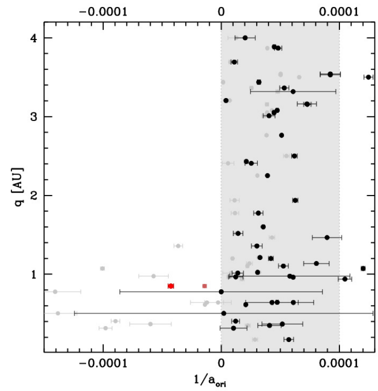

Fig. 3: Original inverse semimajor axis, $1/a_{\mathrm{ori}}$, for 48 comets with determinable NG effects from the positional data.

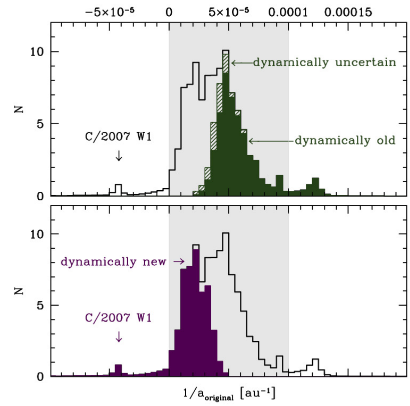

Fig. 4: Oort spike shape for the sample of 108 LPCs; adapted from Paper 6.

The example of constructing $1/a$ distribution for a sample of comets where $1/a$ uncertainties are taken into account is given in Fig. 1. Upper panel displays original $1/a$ distributions for ten different LPCs. Each histogram represents the distribution of 5001 VCs, where the Gaussian function (dark line) gives perfect fit in each case. The vertical axis shows counts in each bin within the sample of 5001 clones considered in each case, it means that counts of 1000 VCs gives probability of 0.2. In this group of ten comets, we have orbits of quality classes from 1a+ (the best, e.g. C/2001 Q4 NEAT) to the 2a (e.g. C/1885 X1 Fabry). Green histograms given in the middle and lower panels show the cumulative histograms of these ten individual distributions aggregated into bins of $10^{-5}\,\mathrm{au}^{-1}$ and $5\times10^{-5}\,\mathrm{au}^{-1}$, respectively. The dashed histogram in the lower panel represents the distribution of nominal orbits of the same ten comets. In Fig. 2 we show the original and future 1/a distributions on the basis of 157 comets studied by us so far. The uncertainties of $1/a$ determinations were incorporated into these histograms by taking the full swarm of VCs for each comet (i.e. its individual, normalized 1/a distributions), as described in the previous example.

3 Key results and examples

Below, we outline a few major findings resulting from our studies aiming at obtaining the most precise orbits of LPCs and studying their dynamical evolution to the previous and next perihelion passages.

(1) The incorporation of NG forces directly in the process of osculating orbit determination changes the result significantly. Fig. 3 presents spectacular trends visible in LPCs $1/a$ values. Values of $1/a_{\mathrm{ori}}$ obtained using full NG model of motion are given by black dots whereas values of $1/a_{\mathrm{ori}}$ obtained in the ballistic model of motion are given by light grey and slightly smaller dots. Three largest uncertainties of $1/a_{\mathrm{ori}}$ (NG solutions), belong to comets of orbital class 2. Red points represent C/2007 W1 Boattini that is the best candidate for interstellar comet in the sample of LPCs investigated by us so far. It is clearly seen that with the one exception of C/2007 W1 all so-called 'hyperbolic' comets (with negative gravitational $1/a_{\mathrm{ori}}$) become elliptical after including NG effects in the model.

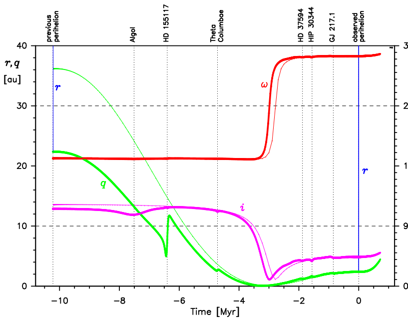

Fig. 5: Past and future evolution of C/2006 OF_2 nominal orbit under the simultaneous Galactic and stellar perturbations, adopted from Paper 5.

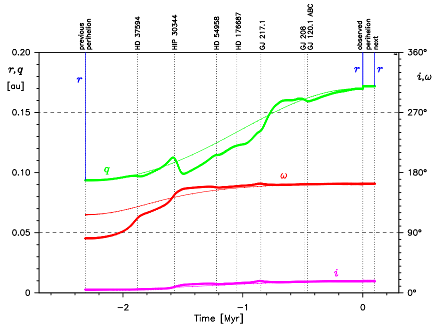

Fig. 6: Past and future evolution of C/2006 P1 nominal orbit under the simultaneous Galactic and stellar perturbations, adopted from Paper 5.

(2) Taking into account all known perturbing agents, we found that about half of LPCs have their previous perihelia deep in the planetary region. As a result one cannot call them 'new comets' since they most probably have experienced planetary perturbations as well as the solar radiation heating at least during their previous perihelion passage. The $1/a_{\rm ori}$ distribution of Oort spike comets consists of almost equal parts of dynamically new and old comets, as depicted in Fig. 4. Green histogram (upper panel) shows the distribution of dynamically old part of VCs of 108 comets, where the dashed part represents the dynamically uncertain VCs. Violet histogram (lower panel) presents the distribution for the dynamically new VCs in the sample. In both panels the black histogram represents the overall distribution of the entire sample of 108 comets. Notice the two-fold narrower bins (0.000005 in $1/a_{\rm ori}$) in comparison to the picture from Paper 6.

(3) Basing on the currently available stellar data, we can conclude that none of the known stars have changed any of the studied LPCs orbit significantly in the sense of discriminating between dynamically old and new comets. Even in extreme case of C/2006 OF_2 (see Fig. 5), where $q_{\rm prev}$ changes on the level of 30% due to known stellar perturbations its dynamical status remains unchanged (it is a dynamically new comet). In this and the next figure we present the time-variation of the nominal osculating perihelion distance (in green) simultaneously with the nominal argument of perihelion (in red) and the nominal inclination (the magenta curve), pointing to some individual stellar perturbations. The horizontal time axis extends from the previous perihelion passage through the observed one up 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). The right vertical axis is expressed in degrees and describes the evolution of the osculating inclination (i, magenta line) and the argument of perihelion (ω, red line) 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. The vertical dashed lines show closest approaches of this comet with several stars or stellar systems, which names are placed near the corresponding line.

(4) The second example of cometary orbit dynamical evolution depicted in Fig. 6

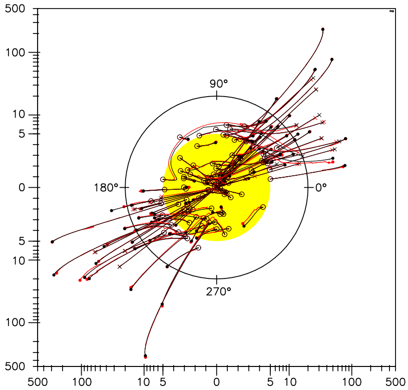

Fig. 7: Last orbital period evolution of the osculating argument of perihelion and the perihelion distance of nominal orbits of 108 comets investigated by us so far; adopted from Paper 6.

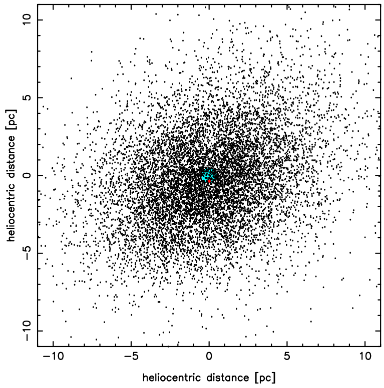

Fig. 8: The spatial distribution of points of the closest Sun-star proximities for 10000 clones of HIP14473 drawn according to the astrometric data uncertainties; adapted from Dybczyński & Berski (2015).

shows that a popular concept of fully opaque Jupiter-Saturn barrier seems to be oversimplified. About 15% of LPCs can migrate through this barrier without any significant orbital changes which is in conflict with the total opacity assumed in many papers, except for the investigation of Fouchard et al. (2013), where a very similar level of the transparency is estimated. Comet C/2006 P1 is an example of such a case. It was observed at a very low perihelion distance of 0.17 AU but its previous perihelion distance was even smaller, about 0.1 AU. Several individual weak stellar perturbations are visible here (Fig.6) but the overall evolution of orbital elements is also affected by a cumulative effect of other numerous weak stellar perturbers. The past evolution of the perihelion distance of this comet is also a good example of a typical feature, when a series of weak stellar perturbations compensate each other.

As stated above none from among known nearby stars has significantly perturbed the motion of studied comets during their previous orbital revolution. This conclusion was carefully checked by testing a large set of potential stellar perturbers against all studied comets. An overall picture of weak stellar action is clearly depicted in Fig. 7. It synthetically presents a comparison of the past dynamical evolution of all 108 LPCs investigated by us, plotted twice for two different models: red one with stellar perturbations (caused by known stars) included and a black one with stellar perturbations ignored. In Fig. 7 the dominance of the decreasing q_{prev} phase due to the Galactic tides is clearly manifested in the argument of perihelion of the observed LPCs when expressed in the Galactic frame.

However, this conclusion must be treated with caution because of many uncertainties in stellar kinematic data. In Fig. 8 we present an extreme example of HIP 14473 that perfectly illustrates this problem. According to the latest estimates of this star astrometric and kinematic parameters (Dybczyński & Berski, 2015) this star passed near the Sun (3.78 ± 0.48 Myr ago) at a nominal heliocentric distance of 0.25 pc (50 000 AU, red dot in Fig. 8). However, when we construct a set of 10 000 clones of this star according to the covariance matrix of the astrometric data, we obtain a widely spread swarm of proximity points (marked with black dots, the blue circle denoted the classical Oort cloud size).

We cannot calculate the influence of nearby stars with high precision in many individual cases but the overall statistical picture in our opinion suggests clearly that for currently observed LPCs the dominating perturbing agent is the Galactic potential. The upcoming results from the Gaia mission will increase both the precision and completeness of available stellar data significantly.

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