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Towards a better understanding of the apparent source/sources of long period comets

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ABSTRACT

We report the current status of the on-going project aimed at advancing our understanding of a source or sources of the actual long-period comets (LPCs). For the last several years we have developed several new methods and numerical packages to study in detail well-observed LPCs motion. Our main goal is to increase the thoroughness and precision of each step, starting from a sophisticated astrometric observation treatment through osculating orbit determination with different dynamical models, including different formulations of non-gravitational (NG) forces and, if necessary, adjusting the observational interval to obtain the most accurate past (original) and future orbits. Then we trace LPCs motion for one orbital period backward and forward. In this last step, we fully take into account Galactic perturbations as well as the gravitational influence of all known potential stellar perturbers acting during the relevant time interval around present time. At each step, we carefully propagate observational uncertainties by means of replacing each comet with a swarm of thousands of randomly generated virtual comets, all fully satisfying observational constraints.

At the current stage of the project, we have determined osculating orbits for over 100 LPCs, some of them in several different variants. We carefully chose an appropriate osculating orbit variant for past and future motion studies and follow numerically LPCs motion up to a distance of 250 au from the Sun, obtaining original and future orbits. To study their motion further, we selected over 90 stars as potential perturbers and included their influence during the numerical integration of cometary motion. Our computer tools are fully prepared to use more stellar data, e.g. from the Gaia mission. We already noticed several important facts: (1) Including NG effects in the process of osculating orbit determination improves significantly our knowledge on cometary past and future motion. (2) In the case of well-observed comets with long periods covered with astrometric data it can be fruitful to obtain original or future orbits not from the whole set of observations but from shorter arcs, e.g. to exclude observations close to the perihelion, where violent NG effects can disturb a comet motion. (3) Taking into account the observational uncertainties for 1/a-distribution of original/future orbits, we produce a detailed shape of the famous 'Oort spike' that fully reflects observational constraints. (4) We found that the significant percentage of LPCs 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. (5) The widely used concept of the Jupiter–Saturn barrier should be revised since significant number of LPCs can migrate through it without any significant orbital changes. (6) None of the known stars have changed dynamical status of any of studied orbits of LPCs significantly.

1. Introduction

In Oort (1950) completed a list of 19 original orbits of well observed long-period comets as an argument for the existence of a cometary cloud. He showed, that their inverse of semimajor axis $1/a_{ori}$ have the distribution apparently peeked near zero, at the positive side. He concluded that long-period comets come from distances from 50 000 to 150 000 au. He also showed, that perturbations by passing stars can change a cometary orbit significantly, making it observable as "dynamically new"[1] long-period

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[1] I.e. making their first passage through the inner Solar System, experiencing both gravitational planetary perturbations and solar heating.

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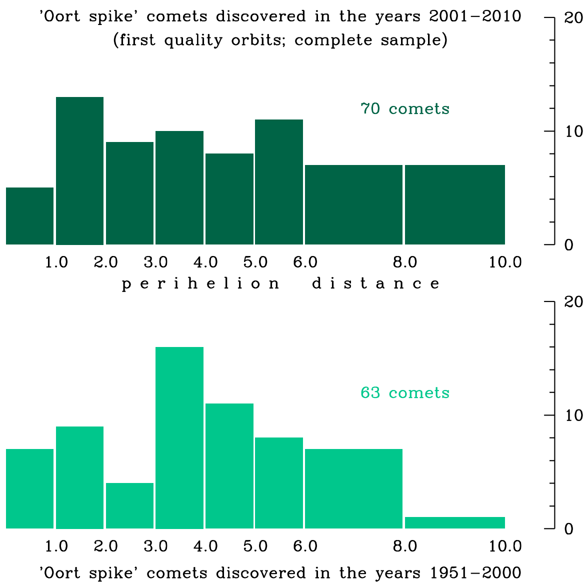

Fig. 1. Dynamics in discoveries of Oort spike comets after famous Oort's paper. Upper panel shows number of cometary discoveries in ten years in the perihelion distance bins, whereas the lower panel presents the number of discoveries in the same bins, however, in five times longer period.

comet. During the last 65 years several new important factors have been revealed in this field.

- The population of precise original cometary orbits has increased from 19 to several hundreds. Today we know that more than 40 comets with $1/a_{ori} \leq 0.000100\,au^{-1}$ (Oort spike LPCs) were discovered prior to 1950. In the last issue of Marsden and Williams Catalogue (Marsden and Williams, 2008, hereafter MWC08), we can find 11 comets satisfying this condition and discovered before 1901 (all of which have first-class-quality orbits), and other 32 comets discovered in the early part of the last century (1901–1950). However, many of them have negative original 1/a in the MWC08 catalogue. Fig. 1 shows the growth in the discovery rate of Oort spike comets between the years 2001–2010 (upper panel) and 1951–2000 (lower panel). This figure also illustrates a significant improvement in the completeness of the Oort spike sample in terms of perihelion distance. After 2010, a number of discoveries in subsequent years is still growing.
- In contrast to the Oort concept, the second and dominating perturbing force must be included in the model: the gravitational action of our Galaxy. It constantly changes cometary orbits. Historically, it was first noted by Byl (1983), then elaborated by Heisler and Tremaine (1986), for a review see for example Fouchard et al. (2005). Our way of incorporating Galactic perturbations in the dynamical model of cometary motion is described and discussed in detail in Królikowska and Dybczyński (2010, hereafter Paper 1).
- There is also a new perspective in understanding stellar perturbations, see Dybczyński (2002) for a historical review. While many authors confirm their importance in the long term Oort cloud evolution, comparable with the age of the Solar System (Rickman et al., 2008; Fouchard et al., 2011b, 2011a), it is still very difficult to point out recent stellar perturbers, responsible for changing orbits of the observed LPCs (García-Sánchez et al. (2001); Dybczyński (2006); Bailer-Jones (2015); Dybczyński and Berski (2015)).
- We learned how to investigate and in many cases we can successfully determine NG forces in the motion of long-period comets. When these forces are included in the process of orbit determination it significantly increases our knowledge on original and future orbits. In the case of well-observed comets with long intervals covered by astrometric data it can be fruitful to obtain original or future orbits not from the whole set of observations but from shorter arcs, e.g. to exclude observations close to the perihelion, where violent NG effects can disturb a comet motion.
- All the above, combined with a growing computing power allows us to study in detail the propagation of observational uncertainties thoroughly during the whole studied dynamical evolution of cometary motion. This has an important consequences in statistical analysis, for example in the Oort Spike shape reconstruction as presented later in this text.

2. Brief description of our approach

Our efforts on developing effective and accurate computer codes for astrometric data processing, orbit determination, dynamical evolution studies and results for well over a hundred LPCs are so far described in a series of papers: Paper 1, Dybczyński and Królikowska (2011), hereafter Paper 2, Królikowska et al. (2012), hereafter Paper 3, Królikowska and Dybczyński (2013), hereafter Paper 4 and Dybczyński and Królikowska (2015), hereafter Paper 5. Additional information, especially on osculating, original and future orbits of selected LPCs can be also found in two other, closely related papers: Królikowska (2014); Królikowska et al. (2014), increasing the sample of studied near-parabolic comets to about 160.

In our studies, the propagation of an uncertainty of cometary orbit (resulting from the positional data set used for orbit determination) during the dynamical evolution is crucial. Therefore, our analysis consists of four basic elements:

1. At the beginning an osculating orbit and its uncertainty in means of orbital element errors is determined from the available set of astrometric measurements. At this point, we focus on the estimation of the cometary NG accelerations from the positional data. Using standard NG model of cometary motion introduced by Marsden et al. (1973), hereafter MSY), next developed by Yeomans and Chodas (1989) and Sitarski (1994), we determined NG parameters for 44% of 108 comets investigated by us so far. In some cases, we use a dedicated approach to NG orbit determination, for example excluding some data intervals where violent non-gravitational phenomena can disturb the comet motion, for an extensive discussion of this idea see Paper 3. We also developed the modified method of orbit quality assessment (Paper 4) useful for purely gravitational (GR) orbits as well NG orbits.
2. Next, each comet is replaced with a swarm of 5001 virtual comets (hereafter VCs), where each clone properly represents the observational set of astrometric observations. For this purpose we applied the method described by Sitarski (2002). These osculating swarms of VCs follow the normal distribution in the space of orbital elements and eventually NG parameters (i.e. the 6–10 dimensional normal statistics).
3. In the third step, each swarm is propagated numerically back and forth up to a heliocentric distance of 250 au, constituting sets of original and future barycentric orbits together with their uncertainties. In this stage, the dynamical model includes the perturbations by all the planets, the relativistic effects and NG effects in the comet's motion if they were determinable from the outset. The orbital element errors are calculated numerically by fitting the Gaussians to a given swarm of VCs. We checked in practice that the adopted number of 5001 VCs (including a nominal orbit), guarantees a very good fitting to normal