The influence of individual stars on the long-term dynamics of comets C/2014 UN$_{271}$ and C/2017 K2.

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ABSTRACT

Context. In June 2021 the discovery of an unusual comet C/2014 UN$_{271}$ (Bernardinelli-Bernstein) was announced. Its cometary activity beyond Uranus orbit has also refreshed interest in similar objects, including C/2017 K2 (PANSTARRS). Another peculiarity of these objects is the long interval of positional data, taken at large heliocentric distances.

Aims. These two comets are suitable candidates for a detailed investigation of their long-term motion outside the planetary zone. Using the carefully selected orbital solutions, we aim to estimate the orbital parameters of their orbits at the previous perihelion passage. This might allow us discriminating between dynamically old and new comets.

Methods. To follow the dynamical evolution of long-period comets far outside the planetary zone, it is necessary to take into account both the perturbation caused by the overall Galactic gravitational potential and the actions of individual stars appearing in the solar neighborhood. To this aim, we applied the recently published methods based on stellar perturbers ephemerides.

Results. For C/2014 UN$_{271}$, we obtained a precise orbital solution that can be propagated to the past and to the future. For C/2017 K2 we have to limit ourselves to study only the past motion since some signs of nongravitational effects can be found in recent positional observations. Therefore, we use a specially selected orbital solution suitable for past motion studies. Using these starting orbits, we propagated both comets to their previous perihelia. We also investigated the future motion of C/2014 UN$_{271}$.

Conclusions. Orbital evolution of these two comets appears to be sensitive to perturbations from several stars that closely approach the Sun. Unfortunately, some of these stars have 6D data with the uncertainties too large to obtain definitive results for the studied comets; however, it appears that both comets were probably outside the planetary zone in the previous perihelion.

Key words. comets: individual: C/2017 K2 (PANSTARRS), C/2014 UN$_{271}$ (Bernardinelli-Bernstein) – Oort Cloud – celestial mechanics – stars: kinematics and dynamics – (Galaxy:) solar neighborhood

1. Introduction

We present the long-term dynamical evolution of two unusual long-period comets (hereafter LPCs): C/2014 UN$_{271}$ (Bernardinelli-Bernstein) and C/2017 K2 (PANSTARRS). We follow the abbreviation convention proposed by Bernardinelli et al. (2021) and for the brevity call these comets BB and K2, respectively. In both cases, the first observations were taken at extremely large heliocentric distances. In addition, both comets attracted scientific attention because of their pronounced cometary activity well beyond Saturn’s orbit.

The discovery of BB was announced in June 2021 by Bernardinelli & Bernstein (2021) on the basis of astrometric observations spanning 20 nights from 2014 Oct. 20 – 2018 Nov. 8 (29.0 au – 23.7 au from the Sun). A little later, at a distance of over 20 au from the Sun, observers reported the cometary activity of BB (Farnham et al. 2021; Kokotanekova et al. 2021; Bernardinelli et al. 2021). In all these papers, the authors estimate that BB might be one of the largest comets ever observed. Bernardinelli et al. (2021) backward integration of the BB orbit under their assumed Galactic tidal model, and including perturbations from 8 stars taken from a list of Sun–star encounters published by Baier-Jones et al. (2018), yields a perihelion distance of ~18 au during its previous perihelion passage 3.5 Myr ago.

The comet K2 observational campaigns have been conducted from the moment of its discovery in May 2017. Undoubtedly, its activity, most of all related to the existence of CO ice, was found at heliocentric distances well beyond 20 au (Meech et al. 2017; Jewitt et al. 2021; Yang et al. 2021).

BB will pass through perihelion (10.95 au from the Sun) on January 22, 2031, whereas K2 will reach its perihelion on December 19, 2022, at 1.80 au from the Sun. Therefore, both have been observed for many years on their pre-perihelion orbital leg, and in addition, at great distances from the Sun. As a result, they are favorable candidates for studying their past motion and their origin. Moreover, such a large perihelion distance of BB allows us to make some statements on the future orbital evolution of this comet on the basis of pre-perihelion data because we can assume that nongravitational (hereafter NG) forces will be negligible in the context of the orbital motion of this comet.

Both comets have an original barycentric semimajor axis greater than 10 000 au, so they belong to the so-called Oort spike. It is widely accepted that it is necessary to take into account both Galactic and stellar perturbations when investigating the long-term dynamical evolution of so much elongated orbits, far outside our planetary system. A new, reliable, precise, and fast method of calculating the effect of these perturbations on LPC motion has recently been proposed by Dybczyński & Breiter (2022). We use these methods in what follows.

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After applying the methods quoted above, we realized that increasing knowledge on stars visiting the solar neighborhood becomes more important in LPCs long-term dynamical studies. In recent years we have benefited from the Gaia astrometric mission (Gaia Collaboration et al. 2016). Using its latest third data release (Gaia Collaboration et al. 2021), we show the effect of some particularly important stars passing near the Sun on BB and K2 motion. We also present the impact of the stellar data uncertainty on our results.

In the abstract of their paper on K2, Jewitt et al. (2021) wrote: Nongravitational acceleration in C/2017 K2 and similarly distant comets, while presently unmeasured, may limit the accuracy with which we can infer the properties of the Oort cloud from the orbits of long-period comets. However, as we discussed in Królikowska et al. (2013), uncertainties related to the NG acceleration in the comet’s motion can be eliminated or substantially minimized by using the pre-perihelion part of the data to calculate the osculating orbit. An even better effect will be when the pre-perihelion part of data is limited to large heliocentric distances. Then the original orbits will also not be burdened by the uncertainty related to the subsequent orbital change under the influence of increasing NG forces as the comet approaches the Sun.

Comets BB and K2 are ideal for such research based on distant data before perihelion. Astrometric measurements starting from distances exceeding 20 au are available for both. It guarantees that their distant parts of data arcs are long enough to determine orbits of the highest quality class (Królikowska & Dybczyński 2018c). One of the goals of this study is to show how good quality orbits we can deal with by limiting the data arcs for orbit determination to the properly selected part of pre-perihelion orbit. Another goal is to verify how a particular comet’s past motion fits the general picture of cometary reservoir evolution; see Vokrouhlický et al. (2019) and Donet et al. (2015) for the extensive reviews.

The structure of this paper is as follows. In Sect. 2 we discuss the choice of appropriate data arcs to obtain the starting orbits to study the origin of both comets. Our current state of knowledge on the potential stellar perturbers of LPCs motion is briefly described in Sect. 3 while Sect. 4 shows the methods of dealing with the orbital parameter uncertainties of comets and stars in our long-term dynamical studies. We also present data on all particular stars mentioned in this paper. Section 5 describes BB past orbit evolution and its parameters at the previous perihelion, while Sect. 6 offers the same for the future BB dynamics. K2 past orbit changes, we discuss in detail in Sect. 7. Section 8 contains a summary and our conclusions.

2. Orbit determination for both comets

We present a detailed description of the positional data used in this paper for both comets in Table 1. This table also includes values of an original 1/au. The model of motion and the methods used for osculating orbit determination are described in Królikowska & Dybczyński (2017) and references therein.

2.1. The orbit of BB

At the end of September 2021, comet BB was about 20 au from the Sun, and we took the entire set of astrometric data available at the IAU Minor Planet Centre. We supplemented this data with the single precovery positional detection found by Bernardinelli et al. (2021). Due to this single precovery measurement, the data arc of BB has extended by about 3.7 yr, going back to 2010 November 15. Additionally, Bernardinelli et al. (2021) suggested some corrections of positional data, and we applied them according to Table 2 in their paper. It turned out that the precovery measurement and the corrections to other positions resulted in only a slight change in the orbital elements; for example, the value of original 1/au changed at a level below 1%. We conclude that the orbit of BB is now quite well constrained.

As expected, we found no evidence of NG effects in the motion of BB, which is still beyond the orbit of Saturn. Table 1 also shows the solution ‘i1’ based on a 3-month shorter data arc and almost two times smaller number of positional measurements than the data arc used in the case of the ‘b8’ solution. Both 1/au, values do not differ in statistical terms (at one sigma level). Furthermore, based on the data arc almost a year shorter than that used for solution ‘i1’ Bernardinelli et al. (2021) obtained the value of 4.95x10^-6 au^-1 for 1/au, which indicates the high compatibility of the 1/au as a function of the increasing data arc taken for the orbit determination.

2.2. The orbit of K2 for the backward dynamical evolution

For K2, the situation is more interesting regarding the NG effects and is, therefore, more complex from the perspective of the past dynamical evolution study. Our first published attempt to study the past dynamics of K2 was based on the 4.6-yr data arc (Królikowska & Dybczyński 2018a, hereafter KD18a). Almost a year later, we updated our calculations based on a longer interval of observations and published our results as an addendum to our preprint available at arXiv Królikowska & Dybczyński (2018b, hereafter KD18b). These two orbital solutions were presented as Solution A1 in KD18a and Solution A1-new in the addendum of KD18b. In the present paper we call them ‘a8’ and ‘a9’, respectively, see Table 1. Here, we analyze whether a longer observational arc will improve the reliability of the original K2 orbit. We decided to include in Table 1 three additional solutions, ‘a6’, ‘c5’, and ‘b5’, based on longer data arcs.

It turned out that currently some traces of NG effects can be seen in the longer data arcs considered here; see solution ‘c5’. For this orbit, we obtained the following NG parameters: A1 = 28.414 ± 4.968, A2 = 11.610 ± 1.089, and A3 = 4.5795 ± 0.7221, in units of 10^-6 day au^-2, where g(r)-like function reflects CO-driven sublimation and was applied as described in Królikowska (2020). Fortunately, we found that this NG orbit gives a very similar original 1/au as in the purely gravitational case ‘a6’, based on the same interval. In addition, the NG solution for the longest data arc (the same as in the case of the GR solution marked as ‘b5’) results in a small and uncertain radial component of NG acceleration (using the CO-driven formula) and allowing for NG effects does not eliminate some trends visible in [O-C], so it is not considered here. By the analysis of many NG and GR orbits, we finally concluded that the best solution for studying long-term past dynamics of K2 is the solution a9. Thus, solutions based on longer data arcs (‘a6’, ‘c5’, and ‘b5’) are only used here as a check to which extent longer data arcs will change our inference about the dynamical status of K2. Choosing ‘a9’ solution is a rather cautious approach, because the uncertainty of 1/au is two times greater than for the case of ‘c5’ solution.
Table 1. Characteristics of the positional data for both comets analyzed in this paper and the original $1/a$ obtained using an osculating orbit determined from this data arc.

| Comet       | $q$ [au] | first obs. [yyyy mm dd] | last obs. [yyyy mm dd] | $T$ [yr] | data arc range of helio-dist. [au] | No. of obs. | Model of motion | $1/a_{ori}$ [10$^{-6}$au$^{-1}$] | Ref | Model name |
|-------------|----------|--------------------------|-------------------------|----------|-----------------------------------|-------------|-----------------|---------------------------------|-----|------------|
| C/2014 UN$^{271}$ | 10.9 | 2010 11 15 | 2021 06 22 | | 11.6 | 34.1 – 20.2 | 59 | GR | 50.17 ± 0.75 | here | i1 |
|              |         | 2021 09 19 | 2031 01 22 | | 11.8 | 34.1 – 19.9 | 114 | GR | 51.15 ± 0.56 | here | b8 |
| C/2017 K2 | 1.81 | 2013 05 12 | 2018 01 23 | 2022 12 20 | 4.64 | 23.7 – 14.8 | 450 | GR | 48.48 ± 0.73 | KD18a | a8 |
|            |         | 2018 10 13 | | | 5.42 | 23.7 – 13.0 | 996 | GR | 35.49 ± 0.23 | KD18b | a9 |
|            |         | 2020 11 13 | | | 7.51 | 23.7 – 7.81 | 3757 | GR | 33.02 ± 0.45 | here | a6 |
|            |         | 2020 11 13 | | | 7.51 | 23.7 – 7.81 | 3757 | NG | 35.97 ± 0.91 | here | c5 |
|            |         | 2021 09 18 | | | 8.35 | 23.7 – 5.31 | 6634 | GR | 42.78 ± 0.23 | here | b5 |

Notes. The first two rows regarding K2 relate to the solutions discussed in Królicka & Dybczyński (2018a, KD18a) and Królicka & Dybczyński (2018b, KD18b, see Addendum), respectively.

2.3. Future orbital evolution predictions

Today we do not know how the NG acceleration will change the current orbit of K2 when a comet pass the perihelion at a distance of 1.8 au from the Sun in December 2022. Therefore, its future dynamics can only be discussed when the comet will be on its post-perihelion trajectory. The situation is different in the case of BB, because its perihelion distance equals almost 11 au. Thus, it seems that today’s predictions will be correct also in the aspect of a future dynamical evolution for this comet.

3. Stellar perturbers

Our knowledge on stars that can perturb LPCs motion has expanded in the last years. In Wysoczań et al. (2020) they have introduced a publicly available StePPeD database containing data on potential stellar perturbers of LPCs motion. This database has been revised several times in 2020, which finally led to StePPeD release 2.3, mostly based on the Gaia DR2 catalog (Gaia Collaboration et al. 2018). However, after the Gaia Early Data Release 3 has been made available (Gaia Collaboration et al. 2021) it became clear that the next substantial update of the StePPeD database was necessary.

The first step of this upgrade has been finished in September 2021, and a new StePPeD release 3.0 was announced. This first step was limited to the same list of stars as in version 2.3, but for almost all of them, the new data from the Gaia EDR3 catalog have been incorporated. This work is in progress to add new stellar perturber candidates.

We note here that a comparison of the data between DR2 and EDR3 sometimes revealed substantial changes. Almost 25% of the stars in our list have a new parallax that differs by more that 100% when compared to its previous (i.e., DR2) value; nine of them have a negative parallax in EDR3. Over one-third of the stars in our list have a new parallax that differs by more than that 100% when compared to its previous (i.e., DR2) value; nine of them have a negative parallax in EDR3.

During the study of the long-term dynamical evolution of BB and K2, we recognized very strong perturbations caused by stars HD 7977 and Gliese 710 (named P0230 and P0107 in the StePPeD database, respectively) and weaker but potentially important perturbations from five other stars. The details for all seven stars are shown in Table 2, including their identifiers, parameters of the closest approach to the Sun, and mass estimates. We describe the minimal Sun–star distance in two different ways. The value presented in the fourth column, ‘mindist’, is calculated in a special way: this is the distance from the Sun to the centroid of a cloud of 10 000 star clones drawn according to the data uncertainties, using the respective covariance matrix. As the uncertainty of the mindist parameter, we present here a radius of a sphere around that centroid, which includes 90 percent of star clones. Uncertainties greater than the mindist directly indi-
cate that the clone cloud surrounds the Sun (see Col. 4 for P0230 star). In the fifth column, we present a formal statistical description of the Sun-star distance set for all stellar clones using three percentiles: 5% (p05), the median and 95% (p95). They are also expressed in parsecs.

The comparison of the stellar data uncertainties and their minimal distances to the Sun, we present graphically in Fig. 1. For each star listed in Table 2, we plot positions of its 10 000 clones at their closest approach to the Sun, projected on the plane of the maximum scatter; for details of such calculations, see Dybczyński & Berski (2015). The seven different plots of the spread of star clones were then merged into a single image. Centroids of all clouds, are aligned along the horizontal line keeping the correct distance from the Sun and maintaining the same scale in clone clouds spread. The whole clone cloud of P0107 (C in Fig. 1) is hidden under its centroid black dot due to extremely precise data for this star. It should be stressed that the seven stellar close approaches to the Sun presented in Fig. 1 happened or will happen in different epochs spread over 6 Myr interval; see the sixth column of Table 2.

There is an important qualitative difference between the perturbative action of P0230 and P0107 and the remaining five stars mentioned above. According to the most recent data, approaches of these two stars to the Sun are so close that they noticeably perturb the solar galactic trajectory. As a result, these perturbations impart all Solar System bodies’ motion. The resulting heliocentric orbit changes depend at most on a body’s heliocentric velocity. LPCs, when far from their perihelion and therefore moving very slowly, are the best candidates for the largest change in their perihelion distance. We show this effect in the following sections.

4. Dealing with the uncertainties

In the next three sections, we describe in detail the past and future motion of BB and the past motion of K2. For both comets, we also estimated the influence of their orbital uncertainty on a previous or next orbit for all solutions presented in Table 1. In addition, for the preferred solutions, we performed simulations to observe the effects of stellar uncertainties in various cases. To this purpose, we extensively use the methods proposed recently by Dybczyński & Breiter (2022) and the stellar data from the latest release 3.1 of the StePPeD database.

In determining an osculating orbit, we obtain the covariance matrix that allows us to construct comet orbit clones satisfying the observational constraints.

Dealing with the cometary orbit uncertainty is fairly straightforward. During an osculating orbit determination we obtain the covariance matrix that allows us to draw comet orbit clones satisfying the observational constraints, details of this procedure can be found in Sitarski (1998). In all simulations presented in this paper, we use 5000 comet clones plus a nominal orbit. Each clone in this set, we numerically propagated back and forth to obtain original and future swarms of barycentric orbit clones. Investigating the previous (or next) orbit, we repeat the backward (or forward) numerical integration for each comet clone exactly as described in Dybczyński & Breiter (2022), using the latest stellar ephemerides from the StePPeD site. In all cases, we take into account both the overall Galactic gravitational potential and stellar perturbations from a set of 407 potential perturbers. Due to the usage of advanced algorithms, this calculation is precise and very fast, for 5001 comet orbits, we obtain the results in 15–20 minutes on a standard PC. For the sake of comparison, we also present the results of calculations for comet clones with all stellar perturbations excluded.

Analyzing the effect of stellar data uncertainties requires a more complicated and much more time-consuming approach. Each individual calculation consists of two stages. First, we generate a tailored stellar ephemeris and then use a standard code (described above) for a comet motion propagation, using this individualized stellar ephemeris. To obtain this special ephemeris, we replace the nominal data for the studied star with its clone drawn from the respective 6-dimensional covariance matrix from Gaia EDR3. Then we generate the stellar ephemeris using nominal data for the remaining stars. In this way, we still take into account all possible star–star interactions, which are very rare but happen. In all simulations presented in this paper, we use 10 000 star clones for the star in question plus the nominal star tracks for the rest of them. The tailored stellar ephemeris can be produced for a shorter time than the publicly available one (30 Myr

| Star identification | Parameters of the approach to the Sun | Notes |
|---------------------|--------------------------------------|-------|
| StePPeD | Common | Gaia EDR3 | Distance statistics | relvel | Mass |
| ID | name | ID | mindist [pc] | p05 - median - p95 | mintime [Myr] | [kms⁻¹] | [M☉] |
| P0107 | Gliese 710 | 4270814637616488064 | 0.052 ± 0.005 | 0.048–0.052–0.056 | +1.290 ± 0.001 | 14.8 | 0.65 |
| P0111 | HIP 94512 | 4306481867124380672 | 1.037 ± 0.084 | 0.969–1.037–1.108 | +3.30 ± 0.04 | 31.1 | 1.69 |
| P0230 | HD 7977 | 510911618569239040 | 0.014 ± 0.057 | 0.008–0.032–0.071 | −2.47 ± 0.03 | 30.7 | 1.08 |
| P0417 | Ton 214 | 1281410781322153216 | 0.514 ± 0.025 | 0.492–0.514–0.535 | −1.47 ± 0.01 | 32.7 | 0.85 |
| P0506 | 5571232118090082816 | 0.199 ± 0.012 | 0.189–0.199–0.208 | −1.08 ± 0.01 | 90.2 | 0.77 |
| P0508 | 2946037094762449664 | 0.263 ± 0.546 | 0.113–0.382–0.755 | −0.98 ±0.21–0.18 | 39.9 | 0.25 |
| P0509 | 52952720512121856 | 0.318 ± 0.223 | 0.176–0.333–0.501 | −0.67 ±0.05–0.06 | 31.3 | 1.46 |

Notes. The first three columns show the star identifiers, the four next columns present parameters of the closest approach to the Sun, and the last column contains a star mass estimate.
potential was taken into account. K2 orbit. Simulation K2-prev-A describes the results obtained when all stellar perturbations were excluded, while K2-prev-B reflects the results with uncertainties and we used these values. These data are taken from a database, there are mass estimates included together with their uncertainties and we used these values. These data are taken in Table 1; each value is a median or mean of a set of thousands of clones used in a particular simulation with an uncertainty resulting from the obtained distribution. In all cases, perturbations by full Galactic tides are included, while the stellar perturbations are included as follows. For the past motion – BB-prev-A: swarm of 5001 clones of BB, without stellar perturbation; BB-prev-B: swarm of 5001 clones of BB, perturbations by all stars included (using nominal orbits); BB-prev-C: nominal orbit of BB and 10 000 clones of star P0230; BB-next-D: 10 000 pairs: comet clone and P0230 clone. For the future motion – BB-next-A: swarm of 5001 clones of BB, without stellar perturbation; BB-next-B: swarm of 5001 clones of BB, perturbations by all stars included (using nominal orbits); BB-next-C: nominal orbit of BB and 10 000 clones of star P0107; BB-next-D: 10 000 pairs: comet clone and P0107 clone.

Table 3. Orbital parameters of BB at the previous and next perihelia for different types of simulations based on BB orbit solutions ‘i1’ and ‘b8’ given in Table 1; each value is a median or mean of a set of thousands of clones used in a particular simulation with an uncertainty resulting from the obtained distribution. In all cases, perturbations by full Galactic tides are included, while the stellar perturbations are included as follows. For the past motion – BB-prev-A: swarm of 5001 clones of BB, without stellar perturbation; BB-prev-B: swarm of 5001 clones of BB, perturbations by all stars included (using nominal orbits); BB-prev-C: nominal orbit of BB and 10 000 clones of star P0230; BB-next-D: 10 000 pairs: comet clone and P0230 clone. For the future motion – BB-next-A: swarm of 5001 clones of BB, without stellar perturbation; BB-next-B: swarm of 5001 clones of BB, perturbations by all stars included (using nominal orbits); BB-next-C: nominal orbit of BB and 10 000 clones of star P0107; BB-next-D: 10 000 pairs: comet clone and P0107 clone.

| simulation series | solution il | q<sub>prev</sub> [au] | 1/q<sub>prev</sub> [10<sup>-6</sup>au<sup>-1</sup>] | P<sub>prev</sub> [Myr] | solution b8 | q<sub>prev</sub> [au] | 1/q<sub>prev</sub> [10<sup>-6</sup>au<sup>-1</sup>] | P<sub>prev</sub> [Myr] |
|------------------|--------------|------------------------|-------------------------|------------------|--------------|------------------------|-------------------------|------------------|
| BB at previous perihelion | BB-prev-A | 14.99–15.29–15.62 | 50.15 ± 0.75 | 2.81 | 14.77–14.98–15.20 | 51.15 ± 0.56 | 2.73 |
| | BB-prev-B | 294.7 ± 43.0 | 44.65–44.88–44.94 | 3.32 | 237.6 ± 32.9 | 44.36–44.81–44.93 | 3.33 |
| | BB-prev-C | – | – | – | 12.28–50.15–254.1 | 43.97–49.92–52.34 | 2.83 |
| | BB-prev-D | – | – | – | 12.50–49.62–252.4 | 44.10–49.84–52.46 | 2.84 |
| BB at next perihelion | BB-next-A | 2.264–2.619–3.004 | 36.07 ± 0.75 | 4.61 | 2.727–3.015–3.317 | 37.06 ± 0.56 | 4.43 |
| | BB-next-B | 10.33 ± 0.60 | 35.12 ± 0.78 | 4.80 | 11.11 ± 0.42 | 36.16 ± 0.59 | 4.60 |
| | BB-next-C | – | – | – | 9.23–11.08–13.45 | 36.09–36.17–36.23 | 4.59 |
| | BB-next-D | – | – | – | 9.13–11.06–13.50 | 35.40–36.16–36.90 | 4.60 |

Table 4. Influence of the K2 orbit uncertainties on the elements at the previous perihelion. For each orbital solution, we use 5001 clones of K2 orbit. Simulation K2-prev-A describes the results obtained when all stellar perturbations were excluded, while K2-prev-B reflects the results obtained from the full dynamical model with 232 potential stellar perturbers included, using their nominal tracks. In both variants the full Galactic potential was taken into account.

| solution | a8 | a9 | a6 | c5 | b5 |
|----------|----|----|----|----|----|
| q<sub>prev</sub> [au] | 2.751–3.999-8.755 | 8.449–12.00–18.13 | 15.47–16.87–18.48 | 9.815–11.24–13.06 | 5.691 ± 0.101 |
| 1/q<sub>prev</sub> [10<sup>-6</sup>au<sup>-1</sup>] | 48.26 ± 7.93 | 35.48 ± 2.33 | 33.01 ± 0.46 | 35.96 ± 0.91 | 42.77 ± 0.23 |
| P<sub>prev</sub> [Myr] | 2.98 | 4.73 | 5.27 | 4.63 | 3.57 |

Table 5. Impact of uncertainties on the previous K2 orbit elements obtained from three different simulations. For K2-prev-C we used the nominal K2 orbit and 10 000 clones of P0509. In K2-prev-D, a similar model was used but with 10 000 clones of P0230. K2-prev-E consisted of 10 000 pairs: one P0230 clone and a random K2 clone from our set of 5001 ones. Full Galactic potential and all remaining stars on their nominal tracks were taken into account. All these numerical experiments were based on the ‘a9’ orbital solution of K2.

| simulation series | K2-prev-C | K2-prev-D | K2-prev-E |
|------------------|----------|----------|----------|
| q<sub>prev</sub> [au] | 407.1–447.6–489.1 | 5.299–147.3–1064. | 5.163–144.0–1065. |
| 1/q<sub>prev</sub> [10<sup>-6</sup>au<sup>-1</sup>] | 34.69–35.03–35.27 | 34.42–35.07–35.16 | 31.65–34.82–38.0 |
| P<sub>prev</sub> [Myr] | 4.82 | 4.81 | 4.86 |

back and forth), but it still takes a considerable CPU time, typically about 20 secs. At the second stage, the subsequent comet motion integration takes only milliseconds, but a whole investigation consisting of 10 000 cases takes over 50 hours on a single CPU core.

For calculating the effect of the stellar perturbation on a comet motion, we have to know the star mass. In the StePPeD database, there are mass estimates included together with their uncertainties and we used these values. These data are taken from numerous different sources. However, the uncertainties in the mass estimate were obtained by various considerably different methods. Their nature is highly non-linear, often asymmetric, and with unknown error distribution. Therefore, the statistical interpretation of the mass estimate uncertainties is difficult, and we decided not to draw random mass values from these data, and in all calculations we utilize the nominal mass estimate.

However, we should keep in mind that the mass uncertainty is an additional source of the approximate nature of our results.
Fig. 2. Past and future dynamical evolution of C/2014 UN$_{271}$ nominal orbit (b8 solution). Changes in a perihelion distance (green), an inclination (fuchsia) and an argument of perihelion (red) are shown. The thick lines depict the result of the full dynamical model while thin lines show the evolution of elements in the absence of any stellar perturbations, i.e., only the Galactic perturbations are taken into account. Angular elements are expressed in a Galactic frame. We show also names of stars that make significant impart on this dynamical evolution.

For example, the mass estimate for the most important star, P0230, is taken from Stassun et al. (2019) and is described as $1.080 \, M_\odot$ with a symmetric uncertainty of $\pm 0.136 \, M_\odot$. The nominal value of the previous perihelion distance of K2 is 441 au (for the ‘a9’ solution) but if we use a lower limit mass for P0230, that is, $0.944 \, M_\odot$, we will obtain a lower value of $q_{\text{prev}} = 331$ au.

Using the above procedure, we can theoretically investigate the simultaneous effect of two or more star uncertainties without additional computational cost, since the drawing a star clone is very fast. However, the spread of the results considerably grows. Therefore, it is necessary to calculate a much larger number of cases to achieve a statistically valuable result. Fortunately, in all cases described in the following sections, only one star strongly perturbs a comet motion during the previous or next orbital period.

5. C/2014 UN$_{271}$ past orbit evolution

Starting from the up-to-date osculating orbit of BB (solution b8 in Table 1 we calculated the original and future orbits at a distance well outside the planetary perturbation zone (as usual, we used a distance of 250 au from the Sun). The elements of these orbits are presented in Appendix A in Tables A.1 and A.2. Using these original and future orbital elements, we calculated the dynamical evolution of the nominal BB orbit for one orbital period to the past and to the future. This is presented in Fig. 2. In the past motion, we see several small perturbations from passing stars and one very strong orbit change. The two small interactions were with P0509 at $-0.67$ Myr and P0506 at $-1.08$ Myr, see Table 2 for more information on these stars. However, the most prominent perturbation was caused 2.47 Myr ago by the star P0230. As shown in Fig. 2, the nominal previous perihelion distance equals 438 au and BB was at the previous perihelion nominally 2.71 Myr ago. If we exclude all stellar perturbations (the thin lines in Fig. 2), then the previous perihelion distance will be much smaller, only 15 au.

It should be stressed that the dynamical evolution depicted in Fig. 2 is based on the nominal BB data and nominal data for all 232 stars included in the dynamical model of the past comet motion. To obtain a more realistic picture, we should estimate the influence of the cometary and stellar data uncertainties and add the results to the above discussion. In the first step, we calculated the effect of the BB orbit uncertainty using the methods described in Sect. 4. The result of this numerical experiment is summarized in Fig. 3. The previous perihelion distance appears to be very close to the nominal value and can be described as $237.6 \pm 3.9$ au since its distribution can be quite well approximated with the Gaussian one, see also the BB-prev-B row in Tab. 3.
As is clearly shown in Fig. 2 apart from a series of weak stellar perturbations, the strongest one is caused by P0230. Its importance comes additionally from the fact that it is a perturbation of the Sun motion, so it acts on the comet indirectly and independently on the star–comet distance. Instead, it strongly depends on the minimal distance of the Sun–star encounter and its geometry. In Fig. 1 we present the effect of P0230 uncertainties (Star B) on these parameters, drawing 10 000 clones of this star and stopping their motion at the closest approach to the Sun. From this picture, it is obvious that both the minimum distance can be arbitrary small and the direction of the impulse imparted on the Sun is unknown.

To observe the possible effect of P0230 uncertainties on the past BB motion, we performed the calculation in which we used 10 000 pairs: a P0230 clone and a BB clone as described in Sect. 4. The result is shown in Fig. 4. The spread of the previous orbit parameters is considerable, and to make this plot readable, we have to omit a very long tail of points placed to the right. This omitted set of points consists of 27 cases of negative 1/\( q_{\text{prev}} \) and 87 large values for elliptic orbits. For the sake of comparison, we overprinted the main plot with the swarm of blue dots showing the distribution of the previous BB orbit when only the nominal star P0230 acts on 5001 comet clones. This blue set of points is the same as that shown in black in Fig. 3.

The smallest 1/\( q_{\text{prev}} \) value obtained in this numerical experiment equals \(-558.7\) in the same units as in the plot. The interval of \( q_{\text{prev}} \) spreads from 0.021 to 20908.3 au. The distribution of \( q_{\text{prev}} \) is strongly non-Gaussian and we can describe it with three deciles, 10\(^{\text{th}}\), 50\(^{\text{th}}\) (median), and 90\(^{\text{th}}\): 12.5–49.6–252.4 au.

In Fig. 4 it can be seen that the nominal \( q_{\text{prev}} = 237.74 \) au is far from the maximum of the \( q_{\text{prev}} \) distribution. The reason for this comes from the geometry of the cloud of P0230 clones with respect to the Sun (star B in Fig. 1). The nominal minimum distance between P0230 and the Sun is 0.014 pc. However, if we ignore the geometry and analyze one-dimensional minimal distance distribution, the resulting median equals 0.032 au (see the fifth column in Table 2), and over 87% of the values are greater than the nominal one. As a result, the much weaker perturbation producing a smaller \( q_{\text{prev}} \) is much more probable.

The conclusion from this section is rather obvious: before much more precise data for P0230 are provided, we will not be able to describe the BB orbit at its previous perihelion in a definitive manner. We look forward to the next Gaia data release, which is announced to happen in June 2022.

6. C/2014 UN\(_{271}\) future orbit evolution

In the future BB motion part of Fig. 2 we can observe a strong perturbation caused by P0107 and a barely visible, weaker one by P0111. Similarily to the past BB motion, the strongest perturbation is an indirect one, since it results from a very close passage of P0107 near the Sun in 1.29 Myr. However, in this favorable case, the prediction of the future is much easier than the prediction of the past. This comes from the very precise data available for P0107. As was already mentioned, in Fig. 1 all the P0107 cloud of 10 000 clones are hidden under the black dot which marks the star’s nominal position at the closest encounter with the Sun.

Using the methods described in Sect. 4 we performed three numerical simulations to observe the effect of cometary and stellar data uncertainties on the BB next orbit parameters: BB-next-B – all stars on their nominal tracks acting on each of the 5001 BB clones, BB-next-C – the same star set but in each run P0107 is replaced by one of 10 000 clones, acting on the nominal BB orbit, and BB-next-D – 10 000 pairs: a P0107 clone and a BB clone. The numerical results are presented in Table 3. Since the influence of cometary orbit uncertainties appeared comparable to that of stellar data, we summarized all three simulations in one composite plot shown in Fig. 5. We plotted the results of simulation BB-next-D as black dots overprinted with orange dots from BB-next-C, and the results of simulation BB-next-B as blue dots on top of the previous two sets. As it is clearly shown in Fig. 5, stellar perturbations only slightly enlarge the interval of \( q_{\text{prev}} \) values resulting from the BB orbital uncertainty. As was stated at the end of sect. 3 the perturbation of P0107 on BB is only indirect, resulting from an impulse gained by the Sun. It is well illustrated by the fact that in our BB-next-D simulation the smallest distance between BB clone and P0107 clone was over 55 000 au.

For the future BB motion, our conclusion is that its next perihelion could be described by deciles (9.13–11.06–13.50) au that is with a median value almost identical to the nominal one (11.11 au). The semi-major axis of the next BB orbit is larger than for the current apparition, mainly due to the planetary perturbations. Our simulation BB-next-D gives 1/\( q_{\text{next}} \) = (35.40–36.16–36.90) \times 10^{-6} \text{au}^{-1} which corresponds to the semimajor axis of about 27 700 au and an orbital period of 4.6 Myr.

If one compares the original and future BB orbits (see Tables A1 and A2) it can be noticed that while planetary perturbations will change the semi-major axis of this comet orbit by almost 30\%, its perihelion distance will remain almost unchanged. After passing the planetary zone, the orbital period of BB will increase to 4.6 Myr, and, consequently, this comet will reappear among planets.

7. Past dynamical evolution of C/2017 K2 orbit

As was explained in detail in Sect. 2 we study only the past long-term dynamical evolution of K2 and base our calculations on the original orbit obtained using the solution ‘a9’. We present the nominal past K2 orbit evolution in Fig. 6. One can notice a series of moderate stellar perturbations and a very strong per-
The perturbation caused by P0230 2.47 Myr ago. This solution gives the $1/\alpha_{\text{net}} = 35.48 \pm 2.33 \times 10^{-6} \text{au}^{-1}$, which corresponds to the previous orbital period of 4.73 Myr. As a result, the indirect perturbation from P0230 happened almost exactly when the comet was at its aphelion and moved very slowly.

In Fig. 6 local orbit changes due to the action of P0509 at −0.55 Myr and P0506 at −1.08 Myr are visible, as in the case of BB. In addition, small orbit changes resulting from a passage of P0508, 0.98 Myr ago, and P0417, 1.47 Myr ago, can also be observed. More information about these stellar perturbers can be found in Table 2. The accumulated stellar perturbations increased the nominal K2 previous perihelion distance from 12 au obtained when only Galactic potential is taken into account (thin lines in Fig. 6) up to 441 au. We have checked numerically that in the absence of P0230 all other stellar perturbations cancel each other and the resulting previous perihelion distance would almost not be affected by stars.

As was already shown, the nominal previous perihelion is only a highly approximate qualitative result. It must be checked what is the possible influence of cometary and stellar data uncertainties on the final result. The influence of the uncertainty of the K2 orbit (for the solution ‘a9’) on our results is presented in Fig. 7. We used the methods described in Sect. 4. The numerical results of this calculation are included in Table 4. In Fig. 7 we also present marginal distributions of $1/\alpha_{\text{prev}}$ (blue) and $q_{\text{prev}}$ (red). As the best estimate, we obtained from these calculations: $1/\alpha_{\text{prev}} = (34.88 \pm 2.61) \times 10^{-6} \text{au}^{-1}$ and $q_{\text{prev}} = (373.5 \pm 441.6 \pm 490.0) \text{au}$. The latter is in the form of three deciles, since its distribution is not Gaussian. It is easy to note that the range of the previous perihelion distance is well defined here, and its nominal and median values are close to each other. The similar numerical experiments we performed for the remaining orbital solutions and the results can be reviewed in Table 4.

From Fig. 8 one can read that during the K2 backward numerical integration, from the listed stars, we first meet P0509 (star A in Fig. 1). This star data uncertainties are rather large. It has no parallax and proper motion data in Gaia EDR3, probably making some trouble in the observational data reduction, so we use all the astrometry for this star from DR2. We decided to check how important this star might be in our calculations. We draw 10,000 clones of P0509 to observe the spread of the result when calculating past K2 orbit parameters at the previous perihelion. The smallest star–comet distance in this experiment was 765 au. Results of this simulation are presented in Fig. 8 and Table 5 as K2-prev-C. Since this stellar perturbation is direct, that is, P0509 acts on a comet strongly because it passes relatively close to it, we also analyzed a star–comet distance distribution. We use two different colors for dots representing the individual clone results: orange dots for clones with a minimal distance from K2 smaller than 20,000 au and black for more distant ones. It can be noticed in Fig. 8 that the dependence between the strength of the perturbation and the star–comet distance is not obvious because it also strongly depends on the star–comet–Sun geometry. Moreover, some P0509 clones passed much closer to the Sun than the nominal one, therefore, an indirect perturbation is also possible. We omitted 15 cases as the extreme outliers. The smallest $q_{\text{prev}}$ equals 3.6 au while the omitted largest one equals 9510 au. Despite such a large spread, the $q_{\text{prev}}$ distribution shown as a red histogram in Fig. 8 is quite compact. It can be described...
by three deciles as: (407.1–447.6–489.1) au. Still, we are close to the nominal value of $q_{\text{prev}}$.

The situation is quite different when we investigate the impact of the uncertainties of P0230 on our results. We performed two additional simulations using the techniques presented in Sect. 4 – K2-prev-D: a comet in nominal orbit and 10 000 clones of P0230, and K2-prev-E: 10 000 pairs of a star clone and a comet clone. Numerical results of all simulations performed for K2, also for orbital solutions other than ‘a9’, are presented in Tabs. 4 and 5. The results based on the ‘a9’ solution are summarized in a composite plot shown in Fig. 9. We plotted the results of K2-prev-E as black dots overprinted with orange dots from K2-prev-D. For the sake of comparison, we added the results of K2-prev-C (the same as presented in Fig. 7) as blue dots on top of the previous two sets.

In Fig. 9 several interesting features can be seen. The K2 orbit uncertainties are responsible mainly for the spread in $1/q_{\text{prev}}$ (blue dots). The swarm of P0230 clones, when acting on a nominal K2 orbit, causes mainly the spread in $q_{\text{prev}}$ (orange dots) across a wide range of values from 0.0005 au to 19 350.4 au. The third simulation, K2-prev-E (black dots), spread results in both elements. We observe here a similar effect to that in Fig. 4 – the maximum of the $q_{\text{prev}}$ distribution occurs for a substantially smaller value of the previous perihelion distance than that for the nominal orbit. The reason is also the same: due to the geometry of the P0230 swarm of random clones, the nominal star–Sun distance is much smaller than the most probable value. As a result, the weaker perturbation is more frequent than that for the nominal orbit of K2 and a star track.

Despite the general indirect nature of the the influence of P0230 on K2, there are several star clones in K2-prev-E that pass close to K2. The minimum star–comet distance in this numerical experiment is 7707 au. Such close passages produce outlier results with negative $1/q_{\text{prev}}$ values; the smallest value is ~621 in the units used in the plot. When preparing Fig. 9 we omitted 226 points, 27 of them with negative $1/q_{\text{prev}}$. The largest value of the right tail of the black swarm is $q_{\text{prev}} = 59 312.6$ au.

Based on the ‘a9’ solution, the K2-prev-E simulation presents the best we can say on the previous K2 orbit at the time of this writing. We obtained $q_{\text{prev}}$ described by deciles: (5.163–144.0–1065) au, which suggests that, contrary to our previous opinion, K2 is probably a dynamically new comet. However, taking into account how sensitive this result is to the P0230 data change, we should wait for much more precise measurements for this star before any definitive statements can be formulated.

8. Summary and Conclusions

We performed an extensive study of the past and future motion of comet C/2014 UN271 (Bernardinelli-Bernstein) and the past motion of C/2017 K2 (PANSTARRS). For each comet, we obtain a series of osculating orbits based on data arcs of different lengths. In the case of BB, we did not find detectable effects related to the NG acceleration caused by the sublimation of ices from the comet surface. In K2 motion, measurable effects of NG acceleration have now been noticed for the data arc covering large heliocentric distances down to the 7.8 au (solution c5 in Table 1). From all orbits listed in the above-quoted table, we have selected the most appropriate ones for a dynamical study of each comet motion outside the planetary zone. In the case of BB, it is the solution ‘b8’, based on all observations available at the time of calculation (October 2021), for K2 – the solution ‘a9’ based on the data arc shorter than the currently available. However, we also performed simulations for all remaining solutions given in Table 1 for comparison purposes.

The analysis of a series of K2 orbital solutions based on different data arcs clearly shows that in the case of LPCs discovered at large heliocentric distances, the starting orbits for the study of their origin should be determined from the pre-perihelion leg of the orbit and limited to large distances from the Sun. Moreover, in cases such as K2, it is necessary to individually balance the benefits of limiting the action of NG acceleration (the farther from the Sun the better) and the quality of the obtained orbit (the longer the data are the better). This approach, extended to LPCs discovered at very large heliocentric distances, confirms our previous published conclusions [Królikowska et al. 2012, Królikowska 2020].

Based on the selected preferred orbit solutions, we obtained a nominal previous perihelion distance value. For K2, nominal $q_{\text{prev}} = 441$ au and for BB nominal $q_{\text{prev}} = 237$ au, taking into account the perturbing effect of the full Galactic tidal field and all currently known potential stellar perturbers. The influence of orbital uncertainties of the preferred comet orbital solutions is quite small in both cases and resulted in $q_{\text{prev}} = (373.5–441.6–490.0)$ au for K2 (deciles 10th, median, and 90th are used here) and $q_{\text{prev}} = 237.6 ± 32.9$ au for BB. At this stage, we could conclude that both K2 and BB are dynamically new comets. However, as was shown above, the influence of the stellar data uncertainties on our results must be considered. For the K2 past motion, we separately analyze the effects caused by stars P0509 and P0230. In the case of BB past motion, we also experiment with P0230 and for the BB future motion, we analyzed the effect of P0107 uncertainties. Details of the above-mentioned results and several numerical experiments with the stellar perturbations can be found in Tables 5, 2 and 5 and the corresponding figures.

The list of stars that noticeably change BB or K2 orbit evolution is presented in Table 2 together with their parameters of the close Sun–star approaches and their mass estimates, based on the released 3.1 of the StePPeD database. The past motion of both studied comets is dominated by a perturbation caused by
the star P0230 (HD 7977). Our most advanced simulations K2-
prev-E and BB-prev-D resulted in significant changes in the pre-
vious perihelion distance values obtained: $q_{\text{prev}} = (5.163–144.0–1065.)$ au for K2 and $q_{\text{prev}} = (12.50–49.62–252.4)$ au for BB.
Looking at the median values, we can still classify both comets as dynamically new. However, the observed high sensitivity of these results to the uncertainty of the P0230 data causes this conclusion to be preliminary and uncertain. We hope to receive more precise data for P0230.

It is worth mentioning that due to the specific nature of perturbations caused by P0107 and P0230, they can be the significant perturbers of many LPCs. It is worth mentioning that due to the specific nature of perturbations caused by P0107 and P0230 they can be the significant perturbers of many LPCs. This effect comes from their very close passage near the Sun, which generates a strong velocity impulse indirectly affecting all Solar System bodies. As a result, many heliocentric small body orbits have been or will be changed. The strength of this perturbation depends mainly on the small body heliocentric velocity. Therefore, LPCs at their aphelia are the best candidates to track important changes in their orbits.

Our numerical Monte Carlo simulations of the impact of stellar data uncertainties on the long-term evolution of comet orbits clearly show that the accuracy of the stellar data is still insufficient in many cases.

Our numerical Monte Carlo simulations of the impact of stellar data uncertainties on a long-term evolution of comet orbits clearly show that the accuracy of the stellar data is still insufficient in many cases. On the contrary, the accuracy of the orbits of the contemporary observed comets seems to be satisfactory. From a list of seven stars that significantly perturb motion of the two comets studied here, only for two we have satisfying 6D data. We hope that future observational attempts, for example, next Gaia data release, will improve the situation.

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Appendix A: Orbital data for C/2014 UN$_{271}$ (Bernardinelli-Bernstein)

Table A.1. Original barycentric orbits of C/2014 UN$_{271}$ at 250 au from the Sun, which was used as the starting orbit for the dynamical evolution discussed in this paper:

| solution | i1 | b8 |
|----------|----|----|
| time of the perihelion passage [TT] | 2031 01 21.46447114 ± 0.018088 | 2031 01 21.48844110 ± 0.012463 |
| perihelion distance [au] | 10.94876759 ± .00010670 | 10.94877654 ± .00007315 |
| eccentricity | 0.99945070 ± .00000821 | 0.99943996 ± .00000616 |
| inverse of the semimajor axis [10$^{-6}$ au$^{-1}$] | 50.17 ± 0.75 | 51.15 ± 0.56 |
| inclination [deg] | 95.466167 ± 0.000035 | 95.466152 ± 0.000023 |
| argument of perihelion [deg] | 326.280703 ± 0.000015 | 326.280949 ± 0.000036 |
| longitude of the ascending node [deg] | 190.002743 ± 0.000038 | 190.002732 ± 0.000025 |
| epoch of osculation [TT] | 1715 03 12 | 1715 03 12 |

Table A.2. Future barycentric orbits of C/2014 UN$_{271}$ at 250 au from the Sun, which was used as the starting orbit for the future dynamical evolution discussed in this paper.

| solution | i1 | b8 |
|----------|----|----|
| time of the perihelion passage [TT] | 2031 01 21.43420845 ± 0.018081 | 2031 01 21.45818806 ± 0.012461 |
| perihelion distance [au] | 10.94853286 ± .00010668 | 10.94854181 ± .00007313 |
| eccentricity | 0.99960500 ± .00000821 | 0.99959425 ± .00000615 |
| inverse of the semimajor axis [10$^{-6}$ au$^{-1}$] | 36.08 ± 0.75 | 37.06 ± 0.56 |
| inclination [deg] | 95.460461 ± 0.000035 | 95.460446 ± 0.000023 |
| argument of perihelion [deg] | 326.246713 ± 0.000014 | 326.246959 ± 0.000036 |
| longitude of the ascending node [deg] | 190.009262 ± 0.000038 | 190.009251 ± 0.000025 |
| epoch of osculation [TT] | 2346 08 31 | 2346 10 10 |

Appendix B: Orbital data for C/2017 K2 (PANSTARRS)

Table B.1. Original barycentric orbits of C/2017 K2 at 250 au from the Sun, which were used as the starting orbit for the dynamical evolution discussed in this paper.

| solution | a6 | c5 | b5 |
|----------|----|----|----|
| time of perihelion passage TT = 2022 | 12.18803948 ± 0.000814 | 12.18793820 ± 0.002840 | 12.18814958 ± 0.000210 |
| perihelion distance [au] | 1.79565692 ± 0.00000240 | 1.79558257 ± 0.00000609 | 1.79561076 ± 0.00000124 |
| eccentricity | 0.99994071 ± .00000082 | 0.99993541 ± 0.00000163 | 0.99992319 ± 0.00000041 |
| inverse of the semimajor axis [10$^{-6}$ au$^{-1}$] | 33.02 ± 0.45 | 35.97 ± 0.97 | 42.78 ± 0.23 |
| inclination [deg] | 87.573120 ± 0.000005 | 87.573189 ± 0.000077 | 87.573070 ± 0.000003 |
| argument of perihelion [deg] | 236.210369 ± 0.000072 | 236.211575 ± 0.0000161 | 236.212047 ± 0.000035 |
| longitude of the ascending node [deg] | 88.086766 ± 0.000017 | 88.086242 ± 0.000051 | 88.086682 ± 0.000008 |
| epoch of osculation [TT] | 1723 01 29 | 1722 12 20 | 1722 12 20 |

Notes. Original orbits representing solutions a8 and a9 were published in KD18a and KD18b, respectively.