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Orbital dynamics of the superactive comets 46P/Wirtanen and 103P/Hartley

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Abstract. Comets 46P/Wirtanen and 103P/Hartley are Jupiter-family short-period comets. They passed very close to the Earth in 2018 and 2010, respectively, resulting in radar observations and a large number of positional observations and, thus, they caught our attention. Radar observations have revealed the presence of ice grains in the comas surrounding comets, ejected by streams of more volatile compounds during sublimation, which allowed them to be classified as hyperactive. So far, we have not seen the results of combining positional and radar observations of comet 103P in one orbit. We managed to overcome this assuming the presence of offset between the center-of-light and the center-of-mass in positional observations of the apparition with the radar observations by the value of $S = S_0/r^2$. The components of the vector S_0 (R, T, N) in the orbital coordinate system associated with the comet were: $R = 264 \pm 6$ km, $T = 7 \pm 5$ km, $N = -116 \pm 5$ km. In addition, the residuals, $(O - C)$, of both comets revealed systematic deviations that could not be explained by systematic errors of individual observatories. In addition, the light curves of these comets showed peculiarities matching with $(O - C)$ behavior. To eliminate systematic deviations in the positional observations, they were divided into four intervals according to the light curves. We determined a set of parameters of non-gravitational acceleration A_1, A_2, A_3 at each interval simultaneously with the determination of the orbit from all observations. This approach allowed us to get rid of deviations in $(O - C)$. The results obtained for these comets may indicate a truly complex nature of the non-gravitational acceleration acting on these comets.

Keywords: planetary systems: comets: individual (46P/Wirtanen, 103P/Hartley)

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1 Introduction

Short-period comets 46P and 103P have a fairly long observation history. Comet 103P was studied by the Deep Impact spacecraft, mission EPOXI, which provided us with a lot of diverse information about the comet activity, its shape and rotation parameters (A'Hearn et al. 2011). Radar observations of the comets made during close approaches to the Earth have revealed the presence of ice grains in the comet's coma (Harmon et al. 2011; Kareta et al. 2023). The ice particles are delivered into the coma by streams of supervolatile substances (CO_2) whose evaporation begins at a lower temperature than the evaporation of H_2O. As a result, more H_2O is produced per unit time than it is possible during sublimation from the surface of the nucleus.

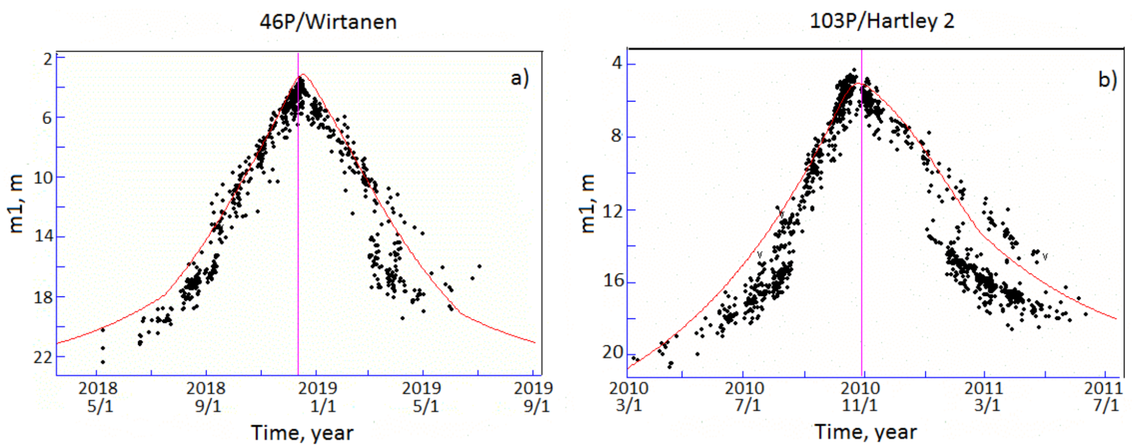

Fig. 1. Light curves of comets 46P – (a) and 103P – (b) created by Seiichi Yoshida: comet total magnitude, m1, versus time.

The light curves of these comets, Figs. 1a, b, are created by Seiichi Yoshida[1]. They demonstrate non-periodic peculiarities which is most likely due to the sublimation activity. By analyzing the comets observations, we revealed systematic deviations in $(O - C)$. Moreover, positional and radar observations of comet 103P could not be combined in one orbit. Therefore, we have set our sights on determining the orbital parameters of these comets using all available observations and identifying the reasons leading to the systematic deviations in residuals.

[1] http://www.aerith.net/

2 Results

Positional observations were taken from the website of the International Minor Planet Center[2], radar observations were taken from the website of NASA's Jet Propulsion Laboratory[3]. The solutions of the systems of normal equations were carried out using the least squares method.

The equations of motion included gravitational perturbations from all eight planets using DE 440 ephemeris (Park et al. 2021) and non-gravitational acceleration according to the Marsden model (Marsden et al. 1973).

To combine the radar and positional observations of 103P, we included an offset in the positional observations of the apparition as 103P approaches the Earth. We assumed that the center-of-light is shifted from the center-of-mass by the value of $S = S_0/r^2$ (r is heliocentric distance of the comet) and we determined the vector S_0 (R, T, N) in the orbital coordinate system along with the orbit improvement. The obtained values were $R = 264{\pm}6$ km, $T = 7{\pm}5$ km, $N = -116{\pm}5$ km. In this case, Root Mean Square Error (RMSE) of the positional observations was about 0.67 arcsec, of time delay observations − 0.48 μs, of Doppler observations − 0.13 Hz. It can be seen that the vector of offset is close to the orbital plane (the angle with the orbital plane is about 23.7°) and directed predominantly away from the Sun. This result does not contradict with the conclusion of the paper A'Hearn et al. (2011).

However, taking offset into account cannot help to remove systematic deviations in the residuals of positional observations, Fig. 2a, the limits of ± 3 RMSE are shown by red lines. These deviations can't be explained by the errors of the individual observatories, since the comet was observed by 168 observatories and the observations were evenly distributed. Therefore, systematic deviations are probably related with the complex rotation of the irregularly shaped nucleus which may include: 1) the seasonal effect of non-gravitational acceleration; 2) tumbling of the axis of rotation; 3) changes in the sublimation rate, approximated in this work by the function $g(r)$ (Marsden et al. 1973).

Since the features in the comet's light curve may indicate changes in the comet's sublimation activity, we used them to divide the observations into four intervals in which particular parameters of non-gravitational acceleration were determined. We used this approach to get rid of systematic deviations in $(O - C)$. We determined the parameters of non-gravitation accelerations separately in each interval together with the orbital parameters common to the entire observation period (Table 1). Since

[2] http://www.minorplanetcenter.net/
[3] https://ssd.jpl.nasa.gov/sb/radar.html

there are about 6000 observations of the comet during this apparition, such approach turned out to be possible. By analyzing the data in Table 1, we can say that the highest value of non-gravitation acceleration was during the first interval. This may be explained by the sublimation of CO_2 during the comet's approach to the Sun. The values of transversal parameter of non-gravitational acceleration, A_2, changed sign after passing perihelion, that may be caused either by tumbling of the comet nucleus or by substantially irregularly shaped nucleus of 103P. Δv in Table 1 shows the changes of the comet's velocity along the orbit due to the action of the transversal acceleration A_2.

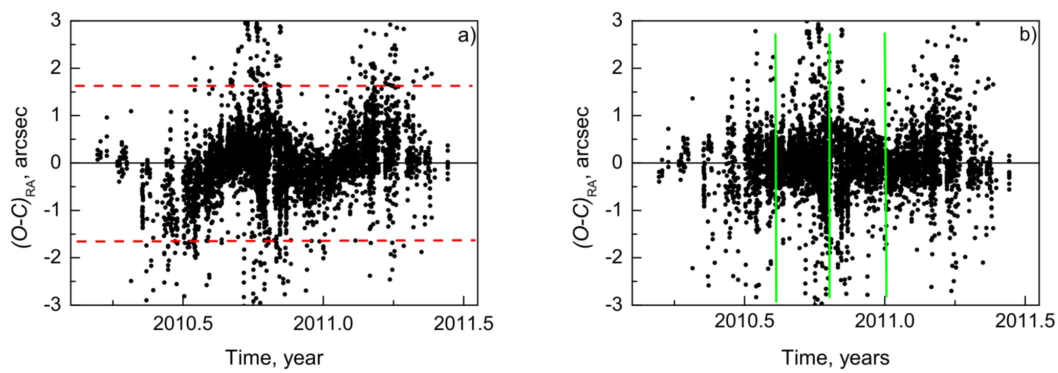

Fig. 2. Residuals in right ascension for comet 103P: (a) – for entire interval, (b) – for four intervals. Red lines on the panel (a) show ±3 RMSE limits, green lines on the panel (b) show individual intervals.

Table 1. Non-gravitational parameters of the comet 103P ($A_1, A_2, A_3 \cdot 10^{-8}$ au/day^{-2}).

Para-meter	Observation interval, year				Entire interval, year
	2010.16-2010.66	2010.66-2010.82	2010.82-2011.00	2011.00-2011.45	2010.16-2011.45
A_1	0.231±0.123	0.518±0.024	0.358±0.020	−0.490±0.060	0.092±0.003
A_2	−0.641±0.046	−0.318±0.018	0.333±0.028	0.227±0.034	0.075±0.003
A_3	−0.234±0.056	0.224±0.019	−0.022±0.021	0.021±0.020	0.004±0.002
Δv, cm/s	−1.10	−0.66	0.53	0.39	0.13
RMSE	0.484 arcsec				0.540 arcsec

It was not necessary to account offset between the center-of-light and the center-of-mass to combine radar and positional observations of comet 46P; however, we evaluated the time delay for the maximum of $g(r)$, which was about 14 days. Figure 3a shows $(O-C)$ after orbit improvement. One can see systematic deviations in the residuals within ± 3 RMSE similar to 103P. As for comet 103P, to get rid of them, we divided the observations into four intervals according to the light curve, Fig. 1a, and determined the parameters of non-gravitational accelerations at each interval separately along with the orbit parameters. Figure 3b shows that this allowed us to significantly reduce systematic deviations; however, the RMSE values for all observations did not change much. Table 2 presents the parameters of non-gravitational accelerations obtained for four intervals and for entire interval of observations.

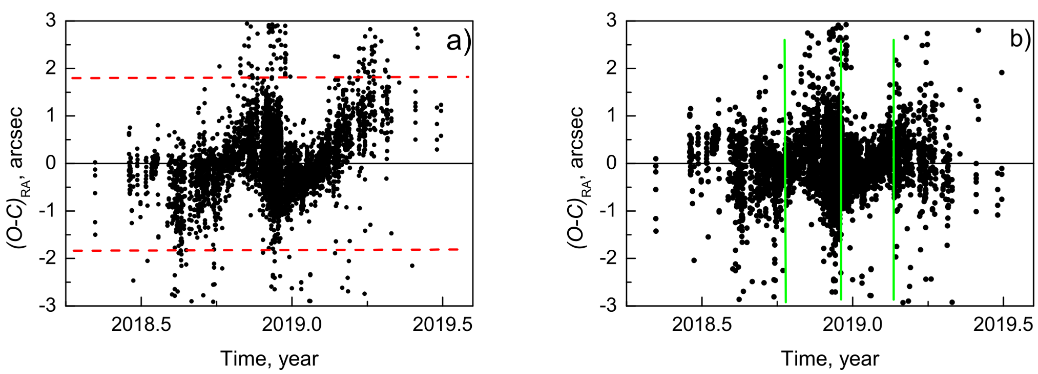

Fig. 3. Residuals in right ascension for comet 46P: (a) – for entire interval, (b) – for four intervals. Red lines on the panel (a) show ±3 RMSE limits, green lines on the panel (b) show individual intervals.

Table 2. Non-gravitational parameters of the comet 46P ($A_1, A_2, A_3 \cdot 10^{-8}$ au/day^{-2}).

Parameter	Observation interval, year				Entire interval, year
	2018.35-2018.81	2018.81-2018.96	2018.96-2019.10	2019.10-2019.50	2018.35-2019.50
A_1	0.823±0.101	0.466±0.008	0.344±0.040	1.566±0.193	0.446±0.002
A_2	−0.463±0.021	−0.231±0.014	−0.295±0.027	0.530±0.040	−0.209±0.003
A_3	0.157±0.027	0.084±0.011	−0.082±0.028	0.499±0.076	0.075±0.002
Δv, cm/s	−0.81	−0.40	−0.51	0.92	−0.31
RMSE, optic.	0.535 arcsec				0.601 arcsec
RMSE, delay	0.680 μs				0.691 μs
RMSE, Dopp.	0.003 Hz				0.004 Hz

3 Summary

In this research, we obtained the orbits of hyperactive comets 46P and 103P, and considered in more detail their apparitions during which they came close to the Earth. Combining radar and positional observations of comet 103P was possible only by taking into account the offset between the center-of-light and the center-of-mass in positional observations. The total offset was ~ 300 km at a distance of 1 au.

We also noticed systematic deviations in $(O - C)$ in the positional observations of both comets. Dividing the entire observation interval into several intervals in accordance with the light curves and determining the parameters of non-gravitational acceleration in each interval helped to get rid of them. This allowed us to reveal the irregular nature of the change in non-gravitational acceleration within one apparition, which is probably a consequence of the complex rotation of the comet nuclei.

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