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On mechanisms of the outbursts activity of comets 29P and 174P

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Abstract. We study common features in mechanisms of the outburst activity of comet 29P/Schwassmann–Wachmann 1 and asteroid (60558) Echecles, which also has a cometary designation 174P. These celestial bodies belong to the group of centaurs, whose orbits lie between the orbits of Jupiter and Neptune. An important feature of these comets is the observed brightness outbursts, up to 6 stellar magnitudes, which do not depend on the heliocentric distance. Previously, we explained the outburst activity of comet 29P/Schwassmann–Wachmann 1 by the existence of satellites touching the surface of the comet nucleus at the pericenters of their orbits. In this work, we focused on studying the parameters of 174P outbursts. We calculated the comet's orbital elements based on the available positional observations and analyzed O–C (residuals of the orbit fit) deviations. We found correlations in O–C deviations and comet's apparent magnitude and assume that an explosive emission of dust particles the total brightness of which exceeds the brightness of the nucleus takes place there and leads to deviations in O–C in the positional observations. We determined the parameters of the assumed gas-dust jet during the outbursts using the deviations in O–C. The calculations carried out allow us to conclude that in December 2005, fragments of the comet were ejected, some of which fell on the nucleus between 2006 and 2017. These collisions led to a multiple increase in the brightness of the comet.

Keywords: comets: comet 29P; comet 174P

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1 Introduction

The purpose of this study is to search for common features in the mechanisms of outburst activity of comet 29P/Schwassmann–Wachmann 1 and asteroid (60558) Echeclus, also known as 174P. These celestial bodies belong to the group of centaurs, whose orbits lie between the orbits of Jupiter and Neptune. Members of this group have unstable, usually highly elongated orbits, crossing the orbits of the giant planets, and dynamically represent a transitional stage between main belt and Kuiper belt objects. We estimated the Lyapunov time values, which show the predicted dynamics of these comets. For comet 29P it was about 100 years, and for comet 174P it was about 40 years, which makes it difficult to study their dynamics over long time intervals.

2 Outbursts of the comet 174P

The comets under study have large nuclei, the diameters of which are estimated at approximately 60 km (https://ssd.jpl.nasa.gov). It is assumed that the surfaces of the comet nuclei are covered with a thick layer of dust. The observed brightness outbursts, up to 6 stellar magnitudes, which do not depend on the heliocentric distance, are an important feature of these comets. The velocities of matter near the surfaces of the nuclei during outbursts are low; according to observations made by the Hubble Space Telescope, the dust velocity at distances less than 1200 km from the nucleus of 29P is 17 m/s (Miles et al. 2016) and for comet 174P the dust velocity lies in the interval from 20 to 50 m/s (Rousselot et al. 2021).

To date, many hypotheses have been put forward attempting to explain the causes of the observed outbursts of comets 29P and 174P. The most widely accepted explanation is that the comet has subsurface cavities containing methane and carbon monoxide ices. The ejection of matter in this case is a consequence of the sublimation of volatile ices located on the sunlit side and causing the explosion (Rousselot et al. 2021). Other hypotheses suggest the fragmentation of the comet nucleus as a result of internal stresses (Neslusan 2014). Previously, we explained the anomalous outburst activity of comet 29P/Schwassmann–Wachmann 1 by the existence of satellites touching the surface of the comet nucleus at the pericenters of their orbits (Medvedev & Pavlov 2023). It was assumed that the satellites move in eccentric orbits and as a result of their collisions with the dust layer of the nucleus, a large amount of dust is ejected, the reflection from which causes periodic bursts of brightness. Depending on the depth of penetration of the satellites into the dust layer, the intensity of the outbursts varied.

In this work we focused on studying parameters of the outbursts of the comet 174P. Based on available positional observations, the comet orbit was calculated and the O–C (residuals of the orbit fit) were analyzed. We found systematic deviations in O–C in the positional observations of 174P that correlate with its outbursts.

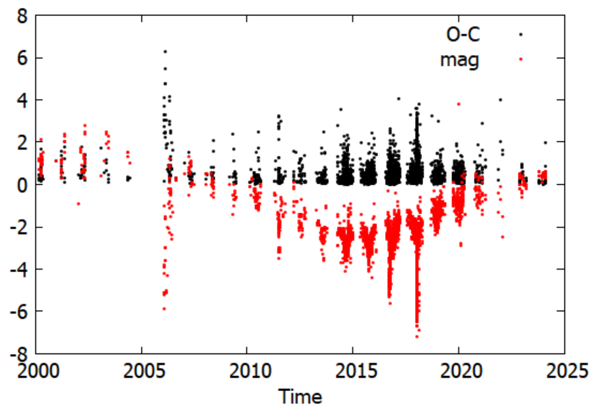

Fig. 1. The values of $\varDelta_{O-C}$ and stellar magnitudes of comet 174P.

In Fig. 1, the red dots denote the magnitude values and the black dots denote $\varDelta_{O-C} = \sqrt{\varDelta\alpha \cos\delta^2 + \varDelta\delta^2}$, where $\varDelta\alpha \cos\delta$ are the O–C values for right ascension and $\varDelta\delta$ for declination. For convenience of presentation of two quantities in Fig. 1 the values of stellar magnitudes are reduced by 20 units. Thus, in Fig. 1, the ordinate axis shows $\varDelta_{O-C}$ in both arcseconds and the stellar magnitude.

The most statistically significant deviations in O–C were obtained for the brightness outbursts that occurred in December 2006 and 2017. We assumed that there was an explosive ejection of dust particles, the total brightness of which exceeds that of the nucleus. The outbursts lead to deviations in O–C in the positional observations, which we use to determine the parameters of the putative gas-dust jet.

2.1 Calculation

When calculating the motion of dust particles, we neglected their mutual interactions and took into account only external forces: gravitational attraction by the cometary nucleus and the Sun, acceleration by the flow of sublimating gas and light pressure. The dust particles were considered spherical. We used the simplest model of brightness distribution in coma, which implies calculating the motion of only one particle, which is considered the center-of-light.

Calculations of particle dynamics were performed in the cometocentric orbital coordinate system XYZ, where the X axis coincides with the direction to the Sun at the moment of ejection; the Y axis lies in the orbit plane perpendicular to X and the Z axis is directed from the plane and complements the coordinate system to the right–handed one. The velocity vector was determined by its absolute value, V, and two angles: λ with the X axis in the XY plane and β with the Z axis.

In the equations of motion of the particle in the comet's head, the accelerations defined by formulas (1-4) (Chernetenko & Medvedev 2020) were included:

1) gravitational attraction from the comet's nucleus

$$W_1 = -GM_n \frac{r}{|r|^3}, \tag{1}$$

where G is the gravitational constant, M_n is the mass of the nucleus, $\mathbf{r}$ is the cometocentric position vector of the particle, $|r|$ is the lenght of r;

2) gravitational attraction from the Sun

$$W_2 = -GM_S \left(\frac{r + r_c}{|r + r_c|^3} - \frac{r_c}{|r_c|^3} \right), \tag{2}$$

where M_S is the mass of the Sun, r_c is the geliocentric position vector of the comet nucleus;

3) acceleration (or deceleration) from the flow of the sublimating gas

$$W_3 = C_d\ \rho\ \frac{s}{m}\,|V_{gas} - \dot{r}|(\,V_{gas} - \dot{r}), \tag{3}$$

where C_d is the aerodynamic drag, ρ is the sublimating gas density, s is the midsection of the particle, m is the mass of the particle, V_{gas} and $\dot{r}$ are the cometocentric velocities of gas and the particle, respectively;

4) disturbing acceleration caused by solar radiation pressure

$$W_4 = -\theta_d\ \frac{s}{m}\ \frac{q_0}{c}\ \frac{r + r_c}{|r + r_c|^3}, \tag{4}$$

where θ_d is a coefficient determining the efficiency of the transmission of the solar radiation to the particle, q_0 is the solar constant, c is the speed of light.

The expansion of the Carbon monoxide (CO) gas in the comet's head was assumed to be spherically symmetric, the production rate Q(CO) to be equal to $(7.7 \pm 3.3) \cdot 10^{26}$ mol/s and the gas velocity $|V_{gas}| = 500$ m/s.

We used the standard values for the solar mass, the speed of light, the gravitational constant, and the solar constant. The particle dynamics is related to a number of parameters considered with comet nucleus. The following values were adopted: density of the nucleus, ρ_n =1.0 g cm^{-3} and radius of the nucleus, R_n = 60.0 km.

We determined the values of three parameters characterizing the movement of an average dust particle: initial velocity, V, and angles, λ and β. We also attempted to determine the average particle diameter, but it turned out to be insensitive to O–C deviations due to the large distance of the comet from the Earth and the Sun and the low density of the gas jet, which led to small non-gravitational accelerations in the motion of dust particles.

The parameters were calculated as follows. Some initial values were specified and the system of differential equations was numerically integrated over the outburst interval, the beginning and the end of which were determined using the change in stellar magnitude. Using these data, the O–C values in the outburst interval were considered as the observed position of the dust particle (i.e. the center-of-light) in the cometocentric coordinate system. The differences between the observed and calculated coordinates of the dust particle formed the right-hand side of the conditional equations. The differential coefficients of the three refined parameters in the conditional equations were calculated using the grid method. The initial values were then corrected using the least squares method (LSM). The values obtained as a result of this procedure were considered as final and no further refinements of the comet's orbital parameters were carried out. The procedure was used to determine the jet parameters during the 2006 and 2017 outbursts.

The obtained solutions are shown in Table 1. The table contains: the moment of the outburst, T_{jet}, the ejection velocity of the particles, V in m/s, the angles λ and β in degrees, the root–mean–square error, rms in arcseconds.

Table 1. Emission parameters and their errors.

T_{jet}	V m/s	λ $^\circ$	β $^\circ$	rms $''$
2005.12.29	36.4±5.6	43±17	42±8	1.1
2017.12.04	17.6±0.1	42±17	15±4	0.5

The obtained results show that a powerful ejection of matter occurred at the end of 2005. We took the ejection moment of December 29. The calculated ejection velocity exceeded the comet's escape velocity. The first ejection occurred almost at the aphelion of the comet's orbit and some of the fragments entered a satellite orbit around the comet nucleus. The probable satellites moved in a plane with a large inclination to the plane of the comet's orbit, thus the ejection occurred mainly perpendicular to the orbital plane. As the comet nucleus moved towards perihelion, the highly inclined orbits of the satellites became unstable, they entered more elongated orbits and collided with the surface of the nucleus. In December 2017, almost at the perihelion of the comet, a collision with a fairly large satellite occurred. This resulted in the ejection of matter; the ejection speed was noticeably lower and this time did not exceed the comet's escape velocity.

3 Summary

Asteroid (60558) Echeclus was discovered active on December 30, 2005, and subsequently renamed to comet 174P/Echeclus. Observations over the next five months showed that the apparent source of activity moved away from the main body to a maximum distance of 7 arcseconds (65,000 km from the comet's nucleus) in late February 2006. The source of activity then moved back towards the main body, passing it by only 2.7 arcseconds in early May 2006 (Weissman et al. 2006). Since then, at least four outbursts have been recorded during 2006–2024.

We assume that as a result of the first ejection, some of the material fell into the orbit of the comet's satellite. Since the ejection occurred almost perpendicular to the orbital plane, their orbits were unstable, therefore, these satellites gradually fell onto the surface of the comet nucleus, causing new brightness bursts. In December 2017, a fairly large fragment probably fell onto the surface of the nucleus, which affected the positional observations of the comet. Using the O–C variations, we obtained the parameters of this ejection of matter. The ejection velocity was significantly lower than during the first ejection, 17 m/s according to our calculations, which is less than the comet's escape velocity for a comet with a 60-kilometer nucleus, and the ejection direction was close to the direction obtained for the first ejection. Therefore, we believe that outburst activity of comet 174P, i.e. the fall of fragments of matter onto the surface - is similar to the one we proposed for comet 29P.

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