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Surface structure and assessment of dust productivity of the cometary nucleus $C/2017\ K2\ (PANSTARRS)$

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$C/2017\ K2\ (PANSTARRS)$ is a dynamically new hyperbolic comet that has exhibited activity at an extremely large heliocentric distance of 23.75 au. Observations of comet $C/2017\ K2$ were performed at Mayaki observational station of the Astronomical Observatory of Odesa I. I. Mechnikov National University using the OMT–800 telescope with a $FLI\ MicroLine$ 9000 camera during March–September 2021. Throughout the period of observations, the heliocentric distance of the comet has decreased from 6.8 to 5.4 au amid irregular fluctuations in the absolute magnitude within $5.0 - 6.2^{\mathrm{m}}$. In the meantime, the value $Af\rho$ has varied in the range of $6500 - 9800$ cm. Such high values of the parameters are indicative of significant activity of the comet. Variations in the comet's brightness hardly affect the shape of isophotes, which are nearly spherical in shape. It is only from April onwards that one can observe a slight elongation in the direction opposite to that in which the comet is heading, due to the dust tail being seen as projected onto the coma. Applying simple rotational gradient filter (simple subtraction) to composite images of the comet enabled us to detect the cometary nucleus spinning westward as measured from the North in the plane of projection. The widths of spiral structures in the coma that appear due to the nucleus spinning suggests the presence of a large-scale inhomogeneity in the distribution of volatiles on the nucleus surface. From July onwards, a new feature can be observed in the images processed using digital filters. Its position and shape have barely changed, which suggests that the area of activity responsible for the formation of this feature is likely located near the northern rotational pole of the cometary nucleus.

Keywords: *C/2017 K2 (PANSTARRS), comet, photometry, morphology, coma.*

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1. Introduction

$C/2017\ K2\ (PANSTARRS)$ is a dynamically new Oort cloud comet with a hyperbolic orbit. The comet was discovered on 21 May 2017 at a heliocentric distance of 16.09 au using the first Panoramic Survey Telescope and Rapid Response System $Pan-STARRS1\ PS1$ telescope located at Haleakala in Hawaii. Further investigations enabled to find pre-discovery images of the comet in the observations retrieved from the Canada–France–Hawaii Telescope ($CFHT$) and $Pan-STARRS1\ PS1$ archives. These images have shown the comet exhibiting activity at an extremely large distance of 23.75 au during the period $10 - 13$ May 2013 [1]. This heliocentric distance is beyond all previously known distances whereat other distant comet's exhibit activity. Such distant activity suggests the presence of supervolatile ices, including CO, CO_2, N_2 and O_2. It is the sublimation of these supervolatile ices at such large heliocentric distances that is responsible for ejecting dust, composed primarily of icy

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grains, into the coma. According to derivations by [2], the comet nucleus radius is within the range of $14 - 80$ km. The spectral reflectance of the C/2017 K2 surface is similar to that of the regions of freshly exposed material on the surface of comet $67P/Churyumov–Gerasimenko$ observed with the Optical, Spectroscopic and Infrared Remote Imaging System ($OSIRIS$) camera onboard the Rosetta spacecraft [3]. The comet is of undoubted interest to researchers as its surface contains pristine matter from which the Solar System formed. This is evidenced by the comet's activity at large heliocentric distances, at which the deeper layers of the cometary nucleus have not been subjected to sufficient solar heating. Pristine matter could be preserved as the comet stayed far away from the Sun in the Oort cloud.

2. Observations and data processing

Observations of the comet were performed at Mayaki observational station of the Astronomical Observatory of Odesa I. I. Mechnikov National University using the OMT–800 telescope [4] with the primary mirror diameter $D = 80$ cm and the focal length $F = 214$ cm with a $FLI\ MicroLine$ 9000 camera (the imaging array 3056×3056 pixels; pixel size $12 \times 12\,\mu$m; the image scale $1.16''$ per pixel; the field of view $59' \times 59'$). The observational data are given in Table 1, where the columns represent the observation date, the heliocentric distance (r), the geocentric distance (Δ), the phase angle (α) and the number of frames.

Table 1. The logbook of observations of comet $C/2017\ K2$ ($PANSTARRS$).

#	Data	r (au)	Δ (au)	α (deg)	N
1	2021 Mar 26	6.776	6.754	8.5	15
2	2021 Apr 09	6.663	6.530	8.6	48
3	2021 Apr 10	6.655	6.499	8.6	96
4	2021 Jul 09	5.917	5.472	9.2	32
5	2021 Jul 15	5.866	5.443	9.4	16
6	2021 Aug 09	5.656	5.380	10.1	16
7	2021 Aug 10	5.648	5.380	10.1	62
8	2021 Aug 15	5.605	5.376	10.3	16
9	2021 Sep 08	5.401	5.393	10.7	64

$^*T_{\text{exp}} = 60$ sec

Preliminary processing of the obtained frames was performed using standard methods and techniques. A master dark frame was created using median filtering technique from a set of $9 - 15$ dark frames with an exposure time equivalent to that for light frames. A master flat frame was created in a similar way. The master dark was subtracted from each light frame with subsequent division of the resulting frame by the master flat. Photometric calibrations were made against field stars in each frame with the comet captured. Since the comet images were taken without any filters, it was necessary to choose a photometric system (or combination of such systems) which would best fit the photometric calibrations for the employed camera. It has been found out that the Sloan Digital Sky Survey ($SDSS$) magnitude system, which is widely used in studying galaxies, best matches our instrumental system [5]. Figure 1a illustrates a comparison between the $SDSS$ r-band magnitudes of the captured comet's stellar neighbours and instrumental magnitudes. The root-mean-square error is 0.04^m in the range of magnitudes 11.4–15.0^m, but it subsequently increases due to errors in determination of brightness of the faint stars captured, as well as the $SDSS$ catalogue errors.

Unfortunately, the $SDSS$ standard stars were not available for all the regions of the sky with the comet captured. This is why, apart from the $SDSS$ r-band stellar magnitude system, the $Pan - STARRS1(PS1)$ catalogue data were used for the regions wherein the $SDSS$ data were not available [6]. In order to analyse all observational data in a single internally-consistent photometric magnitude system, coefficients of transformation of the $PS1$ catalogue magnitudes into the Cousins

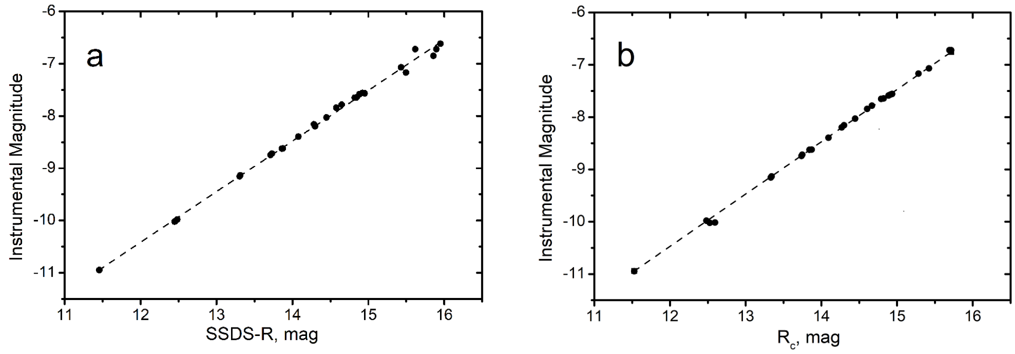

Fig. 1. A comparison of measured instrumental magnitudes with the $SDSS$ r-band (a) and R_c magnitudes (b) of the captured comet's stellar neighbours. The dotted line represents a linear relationship between instrumental and catalogue magnitudes.

r-band (R_c) magnitudes, approximately corresponding to the $SDSS$ r-band system, were defined by the following equation:

$$R_c = -0.134 + r - 0.329(r - i),$$

where r is the mean r-band magnitude; i is the mean i-band magnitude. For comparison, Fig. 1 b presents R_c magnitudes compared with instrumental magnitudes of the same stars as in Figure 1a. For the calculated R_c magnitudes, the root-mean-square error is slightly increasing in the range of $11.4-16.0^{\mathrm{m}}$, being about 0.05^{m}. In order to estimate photometric parameters, each frame was processed separately. To this end, $6-8$ stars with no near neighbours were selected at a distance of $50-100$ pixels around the comet. The sky background level in the comet image was measured from the sky background in the vicinity of standard stars. Then, all comet shots taken in one night were stacked into one single image to enhance the image quality and reduce the signal-to-noise ratio. In so doing, the possible change in the camera sensitivity, defined through standard stars, was taken into account. For correct image stacking, the precise position of the comet in each frame was determined from all pixels of the comet image using the following formulae:

$$x_c = \frac{\sum_n x\, I_n(x,y)}{\sum_n I_n(x,y)}, \quad y_c = \frac{\sum_n y\, I_n(x,y)}{\sum_n I_n(x,y)},$$

where x_c and y_c are co-ordinates defining the comet's location to an accuracy of a fraction of a pixel; $I_n(x, y)$ is the pixel intensity of the comet image. The comet image was shifted to a fraction of a pixel when stacking. The final photometric parameters were estimated from the composite image that resulted from stacking all frames obtained in one observation night. Images taken on different dates had different apparent sizes. However, the coma appears to be noticeably denser towards the central concentration around the nucleus. In order to normalize the comet's magnitudes, one and the same aperture size of $13.9''$ covering the central concentration in all images was chosen for all the dates. Table 2 presents the comet‘s magnitudes and respective errors estimated for the relevant parameters in each frame. These values depend strongly on the heliocentric and geocentric distance of the comet. This is why the absolute magnitude that enables to compare the activity of different comets has been commonly used. The absolute magnitude, H, is derived from integral magnitudes as follows:

$$H = m - 5\cdot \log_{10}(r\cdot\Delta) - g(\alpha),$$

where m is the integral magnitude measured from the entire comet image; r and Δ are the heliocentric and geocentric distances of the comet, respectively; $g(\alpha)$ is a term of the equation that factors in the dependence on the phase angle α. According to [7], $g(\alpha) = 0.02 - 0.04\cdot\alpha$, where the phase angle is expressed in degrees. We adopted the mean coefficient value of 0.03. The calculated absolute magnitudes are listed in Table 2. The obtained magnitudes of comet $C/2017$ $K2$ ($PANSTARRS$) are employed to calculate the parameter $Af\rho$ that characterises the relative cometary dust production rate and is the product of the albedo of the cometary dust grains (A), the filling factor of grains within the aperture (f), which is the total cross-section of dust grains within the field of view, and the linear aperture radius at the comet (ρ) expressed in centimetres [8]. Such calculations are feasible since the emission lines in the comet's spectra are very weak [2,9], so that the total flux from the comet is mainly contributed by the solar radiation scattered by the dust in the coma. To calculate the quantity $Af\rho$, we adopt the formula from [10]:

$$Af\rho = \frac{4 \cdot r^2 \cdot \Delta^2 \cdot 10^{0.4} \cdot (m_s - m_c)}{\rho},$$

where both the linear aperture radius at the comet (ρ) and the geocentric distance (Δ) are measured in centimeters, and m_s is the Sun's magnitude for the $SDSS$ r-band filter adopted from [11]. The heliocentric distance (r) is expressed in astronomical units. As there is a correlation between the value $Af\rho$ and the linear aperture radius (ρ), the standard circular aperture of physical radius 20000 km has been chosen to estimate parameters at all the dates of observation. Table 2 presents all the values required.

Table 2. Photometric parameters of comet $C/2017$ $K2$ ($PANSTARRS$).

#	Data	r (au)	mag*	$Error$ (mag)	H (mag)	$Error$ (H)	$Af\rho$**, cm	$Error(Af\rho)$, cm
1	2021 Mar 26	6.776	14.10	0.17	5.54	0.17	8160	500
2	2021 Apr 09	6.663	14.65	0.15	6.20	0.15	7370	320
3	2021 Apr 10	6.655	14.48	0.12	6.04	0.12	6580	400
4	2021 Jul 09	5.917	13.62	0.13	5.79	0.13	9040	510
5	2021 Jul 15	5.866	13.47	0.07	5.30	0.10	9830	610
6	2021 Aug 09	5.656	13.44	0.06	5.30	0.09	9300	430
7	2021 Aug 10	5.648	13.28	0.05	5.00	0.07	9610	360
8	2021 Aug 15	5.605	13.42	0.04	5.31	0.06	9420	300
9	2021 Sep 08	5.401	13.26	0.09	5.17	0.13	9490	810

*The integrated magnitude in the 13.9″ aperture.

**$Af\rho$ values within the circular aperture of physical radius 20000 km.

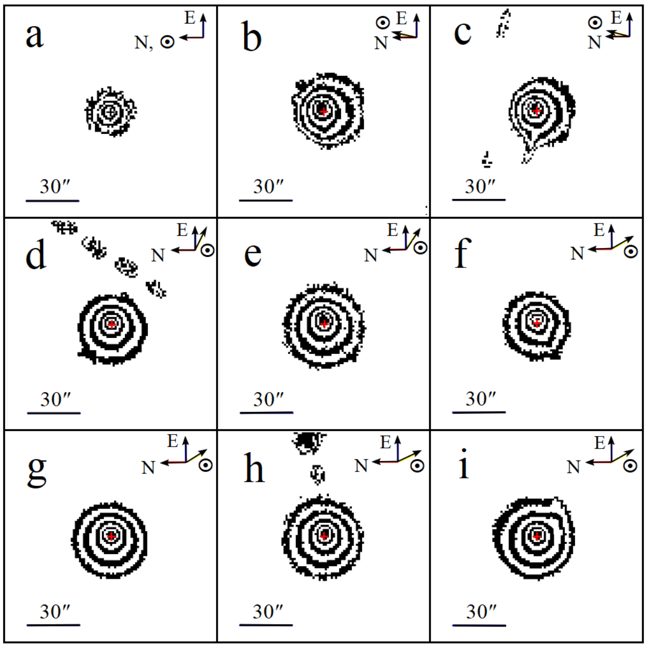

Fig. 2. The plotted isophotes of comet $C/2017$ $K2$ ($PANSTARRS$) at the following dates: a — Mar 26, b — Apr 09, c — Apr 10, d — Jul 09, e — Jul 15, f — Aug 09, g — Aug 10, h — Aug 15, i — Sep 08. The direction arrows denoted by N, E and ⊙ represent the North, East and the Sun, respectively.

The following step is the morphological analysis of composite images. The comet's appearance has barely changed throughout all the observation dates. The comet images show the structure nearly spherical in shape featuring a central concentration with faint halo. The obtained isophotes (Fig. 2) confirm the afore-described features. As the comet nears the Sun, its apparent size increases gradually. Starting from April, a slight asymmetry with respect to the photometric centre of the coma can be observed in the comet images. The photometric centre has been shifting in the direction of the apparent motion of the comet. Such a shift may be due to the cometary dust tail whose projection is directed along the line of sight. It is typical for cometary dust tails which point predominantly in the direction opposite to that in which the comet is heading.

The rotational gradient filters are frequently used in morphological studies of cometary comae [12]. The Larson–Sekanina filter enables to create a new image I_{rg} by adding the two original images and subtracting the result from twice the original image, which is calculated using the following formula:

$$I_{rg}(\rho,\varphi) = 2 \cdot I_o(\rho,\varphi) - I_o(\rho,\varphi+\Delta\varphi) - I_o(\rho,\varphi-\Delta\varphi),$$

where ρ is the distance between a pixel and the nucleus (optical centre) of the comet; φ is the position angle of a pixel with respect to the nucleus; $I_o(\rho,\varphi)$ is the original image. Applying the rotational gradient filter has not revealed any specific structural features which may be due to their low contrast. In such a case, better contrast can be achieved using the simple subtraction filter, which creates a new filtered image I_{srg} by taking the difference between two oppositely-rotated copies of the original image from each other:

$$I_{srg}(\rho,\varphi) = I_o(\rho,\varphi+\Delta\varphi) - I_o(\rho,\varphi-\Delta\varphi).$$

The filtered images obtained through simple subtraction work better in the case of a significant noise level and low-contrast features in the coma. Disadvantages of the simple subtraction filter include possible position-angle-wise displacement of the marked features. Fig. 3 shows the results of applying the simple subtraction filter for the composite images of the comet.

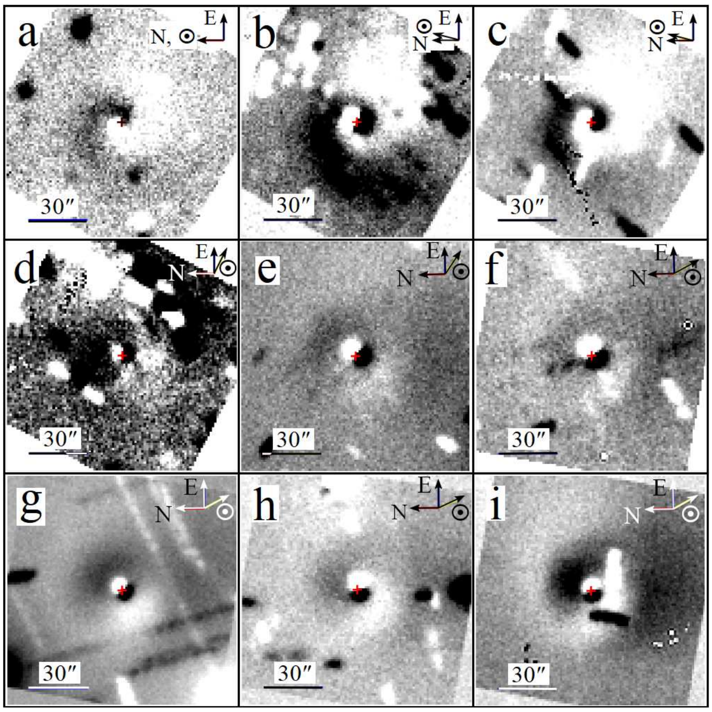

Fig. 3. The results of applying the simple subtraction filter for the images of comet $C/2017\ K2\ (PANSTARRS)$ taken at the following dates: a — Mar 26, b — Apr 09, c — Apr 10, d — Jul 09, e — Jul 15, f — Aug 09, g — Aug 10, h — Aug 15, i — Sep 08. The direction arrows denoted by N, E and ⊙ represent the North, East and the Sun, respectively.

3. Discussion and conclusions

1. The estimated photometric parameters are indicative of significant ejection of dust particles by the comet's nucleus. At large heliocentric distances ($r = 5.4 - 6.7$ au), the value $Af\rho$ ranges within $6 - 9{\cdot}10^3$ cm, which is several orders of magnitude higher than typical values for periodic comets. It corroborates the conclusion that the comet is rich in volatiles, such as CO, CO_2, N_2 and O_2. The sublimation of ices composed of such volatile species results in dragging fine dust particles away from the nucleus at such long distances from the Sun. Moreover, more profound fluctuations in the comet's brightness have been detected at the beginning of the cycle of observations at larger distances from the Sun.
2. The isophotes obtained at different dates have shown that the comet's appearance has barely changed. It suggests the absence of any active processes that may result in noticeable sporadic cometary matter ejections, at least for the indicated dates of observations. Starting from April, a slight asymmetry with respect to the photometric centre of the coma can be observed in the comet images. The photometric centre has been shifting in the direction of the apparent motion of the comet. Such a shift may be due to the cometary dust tail whose projection is directed practically along the line of sight. It is typical for cometary dust tails which point predominantly in the direction opposite to that in which the comet is heading.
3. The filtered images of the comet obtained through simple subtraction show more specific features. Helically-shaped or spiral structures which appear due to spinning of the cometary nucleus, can be seen in Fig. 3 a, b, c, h and i. The nucleus of the comet spins westward as measured from the North in the sky plane. The appearance of spiral structures (in particular, the widths of such spirals) suggests that there are extensive areas with higher emissivity on one side of the nucleus amid a smaller number of such areas on the opposite side. It is possible when the cometary nucleus exhibits large-scale surface inhomogeneities. Interestingly, no spiral structures can be observed at the dates from 09 July to 10 August. It may be associated with the depletion of the most volatile components (e.g. CO and N_2) on the surface of more active part of the nucleus with further switch to other sources of carrying dust particles away from the nucleus (e.g. CO_2). Starting from 09 July, a bright area can be observed in the centre of each of the filtered images. In all the images, processed using digital filters, this feature has barely changed its position being slightly shifted north-eastwards. The detection of this feature supports the conclusion about factoring in a new source of activity on the nucleus surface as the comet approaches the Sun. The steadiness of this feature (that is, its independence on the nucleus spinning), suggests that it is likely to form in circumpolar regions while the spin axis of the comet's nucleus almost coincides with an observer's line of sight.

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Структура поверхні і оцінка пилоутворення ядра комети $C/2017$ $K2$ $(PANSTARRS)$

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Комета $C/2017$ $K2$ $(PANSTARRS)$ — динамічно нова комета з гіперболічною орбітою, яка демонструвала активність на екстремально великій геліоцентричній відстані 23.75 а.о. Ця комета становить значну наукову цікавість для досліджень через таку екстремальну поведінку. Спостереження комети $C/2017$ $K2$ проводилися на спостережній станції Маяки Одеського університету за допомогою телескопа $OMT-800$ з камерою FLI $MicroLine$ 9000 в період березень–вересень 2021 р. Спостереження проводилися без фільтра, тому для отримання фотометричних оцінок паралельно вивчалося питання, яким чином їх можна отримати. З'ясувалось, що з незначними похибками фотометричні оцінки зір поля відповідають системі $SDSS-R$. У випадку, коли опорних зір з величинами в цій системі не було, використовувалася комбінація зоряних величин r та і каталогу $PS1$. За період спостережень геліоцентрична відстань комети зменшувалася від 6.8 до 5.4 а.о., а абсолютна зоряна величина відчувала нерегулярні коливання в межах 5.0–6.2^m. Величина $Af\rho$ в цей час змінювалася в межах $6500-9800$ см. Такі великі значення говорять про значну активність комети. Це підтверджує висновок, що комета має значний вміст летючих компонентам (типу CO, CO_2, N_2 та O_2), які забезпечують викиди пилу на значних відстанях від Сонця. Варіацію блиску практично не впливають на форму ізофот, які показують майже кругову форми. Тільки починаючи з квітня спостерігається невелика витягнутість в протилежному напрямку від переміщення комети, що пояснюється проекцією пилового хвоста на кому. Застосування простого фільтра обертального градієнту до сумарних зображень кометі дозволило виявити обертання ядра комети в напрямку від півночі на захід в картинній площині. Ширина спіралі в комі, яка виникає внаслідок обертання свідчить про наявність значної великомасштабної нерівномірності в розподілі летючої речовини на поверхні ядра. Починаючи з липня, в зображеннях які отримані за допомогою цифрової фільтрації з'являється нова структура. Її положення і форма практично не змінюється, що свідчить про положення активної ділянки, яка формує цю структуру, біля північного полюса ядра.

Ключові слова: *C/2017 K2 (PANSTARRS), комета, фотометрія, морфологія, кома.*