DISTANT ACTIVITY OF COMET C/2001 K5 (LINEAR)

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CCD observations of Comet C/2001 K5 (LINEAR) were made at the 60-cm telescope of the Andrushivka Astronomical Observatory on October 27, 2003. Developed codes for simulation of dust environment in distant comets were applied to fit dust tail of the comet. Model runs are successful under assumption that the dust tail is formed by "dirty" ice grains. The trajectories of the cometary particles were calculated taking into account variation of their mass due to sublimation in the solar radiation field. Outflow velocities of the grains out of the collisional zone are very slow and equal, in particular, to 10.7 m s^{-1} for particles having a size of 5 μm at a heliocentric distance of 5.9 AU. The dust size distribution of the ejected particles is significantly different from those in the observed tail. The dust size distributions in different parts of the appeared tail vary widely as well.

INTRODUCTION

Comet C/2001 K5 (LINEAR) was discovered as an asteroid on May 17, 2001 [8]. Its cometary nature was recognized at the Klet Observatory ten days later. Additionally, the prediscovered images with the object have been found at the archived data obtained at the end of April 2001. The heliocentric and geocentric distances of the comet were 6.425 AU and 5.418 AU, respectively. Its perihelion was occurred at a heliocentric distance of 5.19 AU on October 11, 2002. Water does not sublimate at such heliocentric distances, however a well developed dust tail was seen.

OBSERVATIONS AND DATA REDUCTION

We observed the comet at heliocentric and geocentric distances of 5.90 AU and 5.91 AU, respectively, on October 27, 2003, after its perihelion passage. The observations were made with the use of the S1C CCD chip attached to the Zeiss-600 telescope at the Andrushivka Astronomical Observatory. More details on the observed data one can find in Table 1.

Table 1. Observations of Comet C/2001 K5 (LINEAR) at the Andrushivka Astronomical Observatory

Date	Start, UT	End, UT	r	Δ	Aperture, arcmin	Pixel, arcsec	Effective exposure, s
October 27, 2003	27.7122	27.7543	5.90	5.91	23.0×23.0	1.35×1.35	2400

Obtained CCD images were processed in a standard manner. Particular attention was given to careful control and followed substraction of the dark signal. Original frames were flat-fielded and cleaned from cosmic events and star trails as well. During observing set we obtained 20 exposures on the comet each of them being of 2 min. The exposures were summed and, as a result, we have one CCD image to be analyzed with an effective exposure time of 40 min.

No filters were used in our observations. Nevertheless, we consider detected emission as reflected from the dust cometary atmosphere only. A few cases of detection of any molecular emissions in optics are known so far at such heliocentric distances in cometary history [6]. However, measured emissions of CN were very weak and could not distorted measurably appeared dust atmospheres.

Appearance of the tail prepared for a model analysis one can see in Fig. 1. It is typical for distant comet activity, namely, narrow, slightly curved with well defined boundaries.

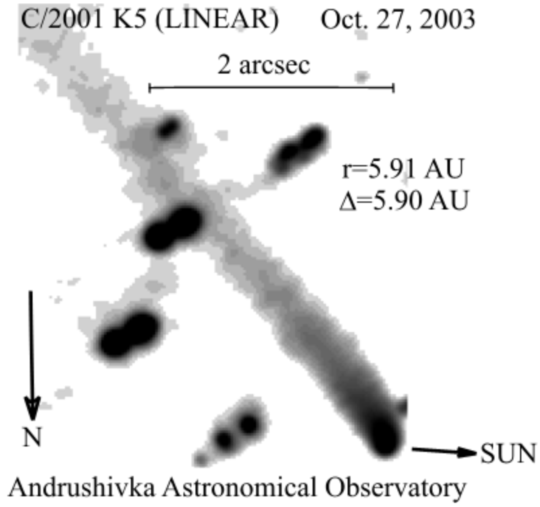

Figure 1. Observed tail of Comet C/2001 K5 (LINEAR). Intensity scale is logarithmic. North is down

MODEL

We already have experience in model analysis of distant comet tails. For this purpose, a model combining a Monte Carlo statistical and Finson–Probstein numerical approaches was developed [14]. The tail of distant Comet C/1999 J2 (Skiff) was fitted in the framework of the model under assumption of "dirty" ice particles forming the tail. Serious restrictions of the model are two-dimensional orbital plane limitation and nonevaporated particles.

Here we propose developed codes of the model where the above-mentioned limitations are overcome. Monte Carlo algorithm remains unmodified. As to the motion of the dust particles, equations of their trajectories with variable mass are now used in the model.

The trajectories of cometary particles are calculated in a non-inertial cometocentric reference system $\{x'_1,\, x'_2,\, x'_3\}$ using the equations derived by Chörny [4]:

$$\begin{aligned}
\ddot{x}'_1 &= -\mu_\mathrm{s}(1-\beta)\frac{r+x'_1}{y^3} - \mu_\mathrm{c}\frac{x'_1}{x^3} + \ddot{\theta}x'_2 + \dot{\theta}^2 x'_1 + 2\dot{\theta}\dot{x}'_2 + \mu_\mathrm{s}\frac{1}{r^2},\\
\ddot{x}'_2 &= -\mu_\mathrm{s}(1-\beta)\frac{x'_2}{y^3} - \mu_\mathrm{c}\frac{x'_2}{x^3} - \ddot{\theta}x'_1 + \dot{\theta}^2 x'_2 - 2\dot{\theta}\dot{x}'_1,\\
\ddot{x}'_3 &= -\mu_\mathrm{s}(1-\beta)\frac{x'_3}{y^3} - \mu_\mathrm{c}\frac{x'_3}{x^3},
\end{aligned} \tag{1}$$

where $\mu_\mathrm{s} = Gm_\mathrm{s}$ is the Sun gravitational parameter, $\mu_\mathrm{c} = Gm_\mathrm{c}$ is the gravitational parameter of the comet; r, $\dot{\theta}$, $\ddot{\theta}$ are comet's heliocentric distance, the angular rate, and the angular acceleration about the Sun, respectively. The components x'_1, x'_2, x'_3 are related to the ξ, η, ζ components of the traditional cometocentric reference system $\{\xi,\, \eta,\, \zeta\}$ as $x'_1 = \xi$, $x'_2 = -\eta$, $x'_3 = -\zeta$.

The equation which determines rate of the particle size decrease $|da/dt|$ due to sublimation is added as well [22]:

$$\frac{da}{dt} = \frac{\mu m_p}{\rho} p_v(T) \frac{1}{\sqrt{2\pi\mu m_p kT}}, \tag{2}$$

where μ is the molecular weight of the evaporated molecules, m_p is the atomic mass unit, k is the Boltzmann constant, and T is the grain temperature.

Since it is expected that water is a major component of dust particles at large heliocentric distances, we consider $p_v(T)$ as the saturated vapor pressure of the water ice. There are two the most used empirical formulae for the saturated vapor pressure of the water ice being valid at low temperatures [15]. We use those covered expected temperature range, namely, below 173 K:

$$\log_{10} p_v(T) = -2461/T + 3.857\log_{10} T + 3.41\cdot 10^{-3}\, T + 4.875\cdot 10^{-8}\, T^2 + 4.332. \tag{3}$$

The temperature T of a grain can be derived by solving the balance between the energy received from the Sun and energy reradiated in the infrared:

$$\pi \left(\frac{R_\bullet}{r}\right)^2 \int_0^\infty \pi a^2 B_\bullet(\lambda) Q_{abs}(a,\lambda,m) d\lambda = 4\pi \int_0^\infty \pi a^2 B(\lambda, T_g) Q_{abs}(a,\lambda,m) d\lambda, \tag{4}$$

where λ is a wavelength, $R_\bullet$ and $B_\bullet(\lambda)$ are the radius of the Sun and the solar brightness, respectively, and r is the solar distance of the dust grain with radius a. $B_\bullet(\lambda)$ is the solar surface brightness and we use the actual one reported by Makarova *et al.* [18]. The Planck function $B(\lambda, T_g)$ for the dust grain at the temperature T_g is defined by

$$B(\lambda, T) = 2hc^2\lambda^{-5}[\exp(\mathrm{hc}/\lambda \mathrm{kT}) - 1]^{-1}, \tag{5}$$

where h, k, and c are the Planck constant, the Boltzmann constant, and the speed of light, respectively.

$Q_{abs}(a, \lambda, m)$ is the absorption efficiency of the grains. We assume the grains chemical composition and structure as being proposed by Greenberg and Hage [9]. They extrapolate their model of interstellar dust to the protosolar nebular cloud stage taking into account solar chemical abundance. According to their model the cometary dust consists of the coremantle (silicates and organics) grains with an additional outer mantle of volatile ices dominated by H_2O with carbon inclusions. Such grains having submicron sizes form aggregates of porous particles with radius a.

Wavelength dependent refractive indices for the silicates, organics and H_2O ice are taken from Henning & Stognienko [13] and for amorphous carbon from Rouleau & Martin [23]. For the above-mentioned composite particle we determine the effective index m_{grain} using the Maxwell–Garnett effective medium theory [9]:

$$(m_{grain})^2 = m_m^2 \left(1 + 3q^3 \left(\frac{m_c^2 - m_m^2}{m_c^2 + 2m_m^2}\right) \left[1 - q^3 \left(\frac{m_c^2 - m_m^2}{m_c^2 + 2m_m^2}\right)\right]^{-1}\right), \tag{6}$$

where a is the radius of the particle, q and m_c are the fractional radius and refractive index of its core, and m_m is the refractive index of its mantle. The equation was applied three times as the composite particle consists of four components. Following the Maxwell–Garnett effective medium theory [9] for the porous grains, the equation is valid:

$$(m_{av})^2 = 1 + \frac{3(1-P)(m_{grain}^2 - 1)/(m_{grain}^2 + 2)}{1 - (1-P)(m_{grain}^2 - 1)/(m_{grain}^2 + 2)}, \tag{7}$$

where m_{grain} is the refractive index of the basic particle, m_{av} is the refractive index of the porous grain, P is the porosity of the grain. Having resulted refractive indexes of the grains their absorption efficiency Q_{abs} was deduced as a large table that covers the values of a and λ that are of interest. The Mie theory and well-known Bohren–Huffman BHMIE codes [2] were used in our calculations.

The numerical solution of Eqs. (1) and (2) was performed by means of a Runge–Kutta algorithm with automatic error control.

To build a modelled comet tail, we need trace the trajectories of about 10^7 particles. These ones were ejected from the collisional zone of the comet along its orbit starting from the time of the tail's origination and being fixed at the time of the observation. Swarm of the fixed particles is just the modelled tail.

RESULTS AND DISCUSSION

As the model is a trial-and-error procedure many trials have been made varying the model parameters to obtain the most probable fitting of the observed tail. Figure 2 shows the result of our simulations. The related model parameters are listed in Table 2.

There are displayed modelled and observed isophotes and surface profiles in the figure. Surface profiles have been extracted approximately along the tail direction with a corridor covered the tail width. Appearance of the modelled tail is presented as well.

Activity of the comet was detected since the time of its prediscovery on April 27, 2001 ($r = 6.51$ AU) and extended uninterruptedly over three years till its last observation on April 27, 2004 ($r = 6.65$ AU). So, it is reasonable to treat in our model runs the trajectories of all the particles ejected since the time of the detection of the comet activity till the moment of the observations.

Our model simulations failed under above assumption until we took into account evaporation of the particles in the solar radiation field. A result with nonevaporated particles one can see in Fig. 3. It is clearly seen that more light particles being located mainly to the right side of the observed isophotes tend to be outside of them.

Table 2. Model parameters of dust in Comet C/2001 K5 (LINEAR)

Parameter	Value
Particle size distribution	$a^{-3.5}$
Maximum size of the particles, a_{max}	1000. μm
Ejection velocities, v_e	10.7^{a} – 0.8^{b} m s^{-1}
Maximum age of the particles	930 days
Heliocentric dependence of Q_d	r^{-2}
Heliocentric dependence of v_e	$r^{-0.5}$
Angular anisotropy of Q_d	U[c] (50%)+S[d] (50%)

[a] For $a = 5$ μm at $r = 5.90$ AU.
[b] For $a = 1000$ μm at $r = 5.90$ AU.
[c] U is a fraction of the dust particles ejected isotropically.
[d] S is a fraction of the dust particles ejected from sunlit side of the nucleus.

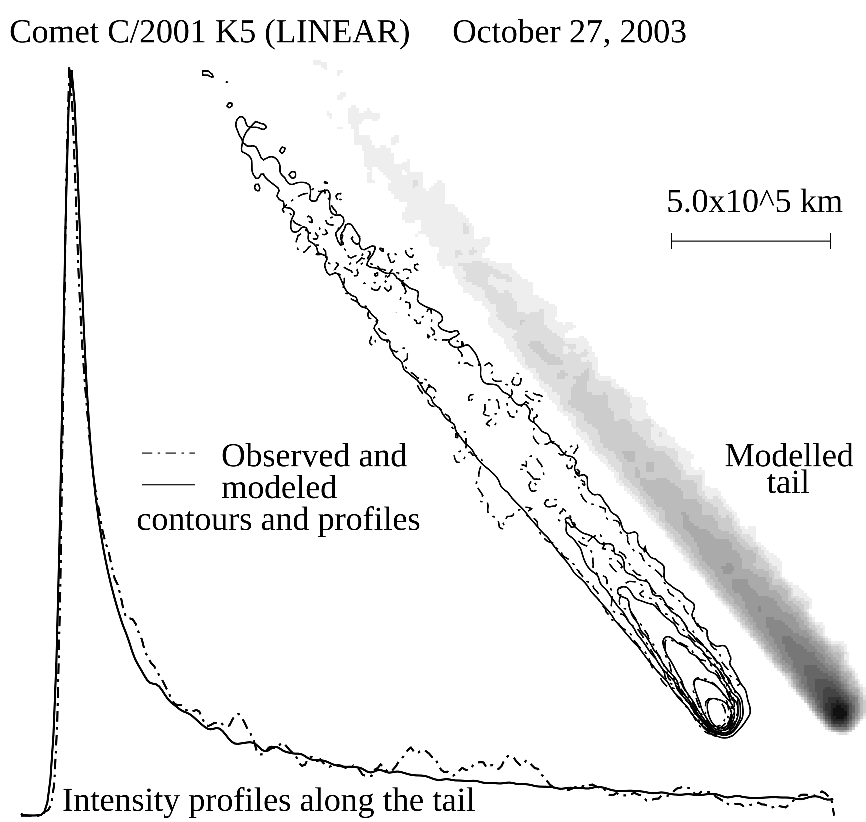

Figure 2. The tail of Comet C/2001 K5 (LINEAR) fitted under assumption of "dirty" ice grains. Observed and modelled isophotes are displayed in the center of the figure. Appearance of the modelled tail, being in the logarithmic scale, is positioned to the right. Intensity profiles are taken along the tail

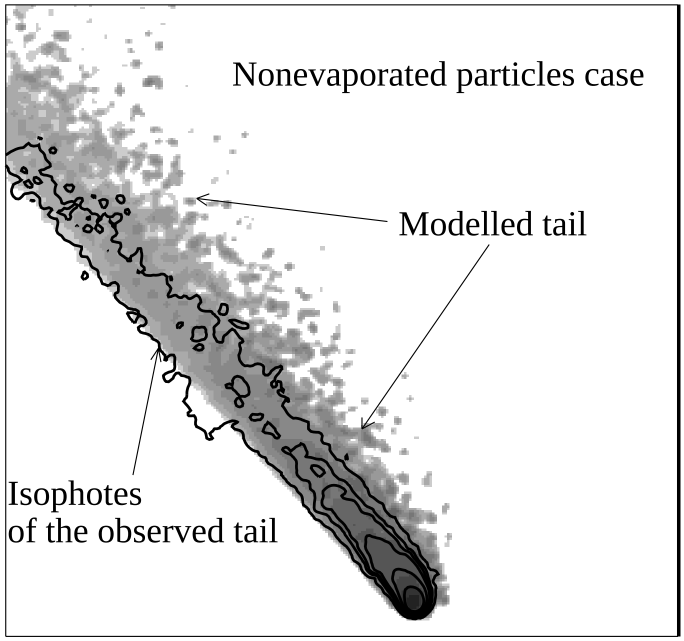

Figure 3. Observed isophotes and modelled tail assuming nonevaporated grains

There are some direct and undirect evidences from study of distant comets that their tails are formed by icy dust particles contaminated by refractory inclusions. The dynamical study of dust particles in distant comets suggests large grains and low dust velocities [14, 19–21]. The strong OH production being observed in Comet C/1980 E1 (Bowell) at $r > 4$ AU has been interpreted by additional evaporation of icy grains [1, 26]. Observing confirmations of water ice grains in the cometary comae at large heliocentric distances were made as well [3, 5, 12, 16]. Observations and theoretical researches strongly state that there are silicate, organic, and graphite inclusions inside the icy grains [9, 11, 22]. Above-mentioned absorbing agents bring "dirty" ice particles to a temperature high enough to expect efficient water ice sublimation from them in the solar radiation field. Details of the sublimation process are influenced by adopting model of an absorbing grain and have been examined by previous investigators [10, 15, 17]. These investigations have a result that lifetimes of the particles, having size smaller than 10 μm, against evaporation in the solar radiation field are dramatically reduced. Just this result resolves the above-mentioned problem of light particles.

Our model simulation was successful with exponential law for dust size distribution with power index equal to –3.5. The dust size distribution is referred to the particles leaving the nucleus, not to the particles occupied the tail and is correlated with results obtained before [7, 14, 24, 25].

Since radiation pressure depends on particle size, dust particles having different size occupy different regions in the cometary tail, which is clearly seen in Fig. 4. Detailed examination of Fig. 4 gives us additional important information. The grains having size less then 10 μm are significantly evaporated and define appearance of the coma surrounding the nucleus. The grains with sizes of 50 μm are exposed by the solar irradiation insignificantly and are extended over the tail appearance range. The grains having sizes about 250 μm and leaving collisional zone at the time of the comet discovery have reached, at last, the outer boundaries of the observed tail. The greater ones are entirely located within the appeared tail.

We fixed in Table 2 that 75% of dust was ejected in sunward direction and 25% in tailward direction. However, it should be remarked that this result is slightly defined. Final note is that dust shows evidence of anisotropic outflow from the nucleus and isotropic outflow case is closer to the fixed result than pure sunlit one.

As to the outflow velocities of the dust grains from the collisional zone they are very slow, namely, 10.7 m s^{-1} for particles having a size of 5 μm and 0.8 m s^{-1} for particles having a size of 1000 μm at a heliocentric distance of 5.9 AU. This is in good agreement with the similar result for Comet C/1999 J2 (Skiff) [14].

Heliocentric variations of the dust production rate and outflow velocities were assumed to be $Q_d \sim r^{-2}$ and $v_e \sim r^{-0.5}$, respectively.

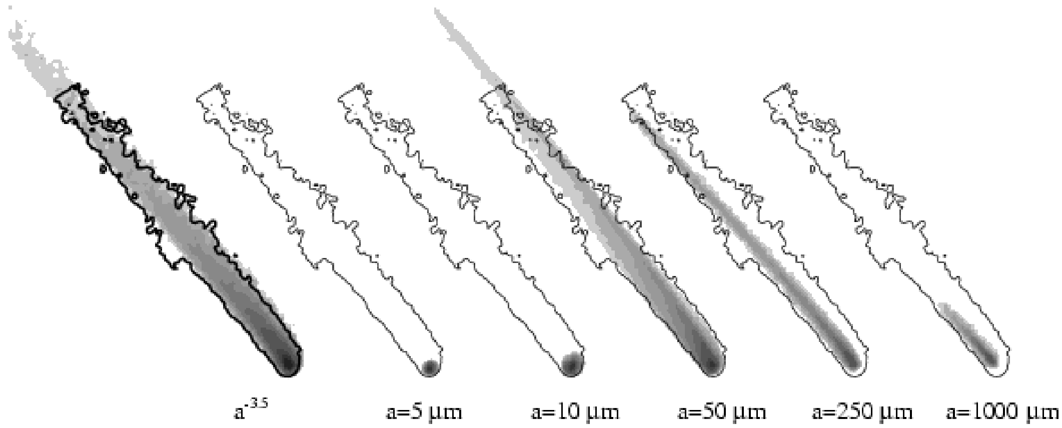

Figure 4. Loci of the modelled particles having various sizes relative to an outer observed isophote

CONCLUSIONS

The main results of our investigation are:

1. The tail has been successfully fitted assuming uninterrupted activity of Comet C/2001 K5 (LINEAR) since the time of its discovery.
2. The tail consists of large "dirty" ice grains evaporating in the solar radiation field. The lifetimes of the grains having sizes less then 10 μm are much shorter then those of the larger ones.
3. The outflow velocities of the grains out of the collisional zone are very slow and equal to 10.7 $\mathrm{m\,s^{-1}}$ for particles having a size of 5 μm and 0.8 $\mathrm{m\,s^{-1}}$ for particles having a size of 1000 μm at a heliocentric distance of 5.9 AU.
4. The dust size distribution of the ejected particles is significantly different from those in the observed tail. Moreover, the dust size distributions in different parts of the appeared tail vary widely as well (see Fig. 4).

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