STRUCTURES IN THE COMA OF COMET C/NEAT (2001 Q4): ANALYSIS AND MONTE CARLO MODELING

Galin B. Borisov and Tanyu R. Bonev

Institute of Astronomy, Bulgarian Academy of Sciences, E-mail: gborisov@astro.bas.bg

Abstract

Comet C/NEAT (2001 Q4) was observed in three consecutive nights in May 2004 (19th, 20th and 21th) with the 2m Ritchey-Chretien-Coude telescope and the 2-Channel Focal Reducer at the Bulgarian National Astronomical Observatory (BNAO) – Rozhen. Narrow-band filters were used, centered on the blue and red comets' continuum at 443 nm and 642 nm, respectively. The images were calibrated to intensities using spectrophotometric standard star observed at the same airmass. The raw images show irregularity of the dust coma in the direction to the Sun. After applying a numerical filter jet-like structures are visible. For the description of these features a Monte-Carlo model, based on Finson-Probstein theory for dust particles dynamics, is developed. The size of the active region, its coordinates on the nucleus surface, and the range of the dust particles' sizes were found by trial and error. Fixed values of the particle size distribution, the rotational period and the orientation of the rotation axis were adopted. The contribution of the structures to the total intensity of the dust coma is 4-5%, which is 10 times more than we expect from the found size of the active region. This suggests that the source region of the observed structures is 10 times more active than the remaining nucleus surface. The images obtained at both continuum wavelengths were used to produce color maps of the dust coma. The color of the structure does not deviate strongly from the color of the ambient dust coma.

Theoretical aspects of the cometary dust particles dynamics

The dust coma consist of solid particles with dimensions from below micrometers to about 1 cm. Bigger particles can not leave the nucleus, because of dynamical reasons, t.e. the gas can not lift a particle bigger than 1 cm.

The forces, which are acting on the dust particles after they leave the nucleus, are expressed as followed (Finson & Probstein 1968):

$$1-\mu=\beta=\frac{F_{rad}}{F_{grav}},\ F_{rad}=\frac{Q_{pr}}{c}\left(\frac{\mathcal{L}_\odot}{4\pi r_h^2}\right)\frac{\pi a^2}{4},\ F_{grav}=\frac{GM_\odot}{r_h^2}\left(\frac{\rho_d\pi a^3}{6}\right)$$
$$\beta=C\left(\rho_d a\right)^{-1},\ C=\frac{3Q_{pr}\mathcal{L}_\odot}{8\pi cGM_\odot}=1.19\times10^{-4}Q_{pr}, g\,cm^{-2} \qquad (1)$$

where $\mathcal{L}_\odot$ is the Solar luminosity , c – the velocity of light, a – particles' radii, ρ_d – their density, r_h – the heliocentric distance, $M_\odot$ – Solar mass, G – gravitational constant, Q_{pr} – the Solar pressure efficiency. From space missions, which collect dust particles in near Earth environment, we know that $\rho_d \in [1,3]$, $g\,cm^{-3}$. Divine *et al.* (1986) propose the following form for dependence of ρ_d with a

$$\rho_d=\rho_{d_0}-\sigma_0\left(\frac{a}{a+a_2}\right), \qquad (2)$$

where $\rho_{d_0}=3\,g\,cm^{-3}$, $\sigma_0=2.2\,g\,cm^{-3}$ and $a_2=2\,\mu m$. Particles from different size contribute differently to the observed brightness of the coma. This different contribution is described by particles size distribution (PSD), which gives the probability, arbitrary selected particle to be in infinity small interval from a to $a+da$. *In situ* measurements of comet Halley, have shown that the PSD can be described with a power low $g(a)\propto a^{-\nu}$, having a different power index ν in different size intervals. Results for power index ν derived from the spacecraft *VEGA2* are presented in table 1.

Table 1. Power index of particles size distributuion law derived from the spacecraft *VEGA2*

ν	$\rightarrow$	a
2.00	$\rightarrow$	$a<0.62\,\mu m$
2.75	$\rightarrow$	$0.62\,\mu m<a<0.62\,\mu m$
3.00	$\rightarrow$	$a>6.2\,\mu m$

Gombosi *et al.* (1985) show that the initial velocity of the dust particles (which is terminal velocity of the gas–dust interaction) follows the $a^{-1/2}$ law (see Eq. 3). Sometimes different value for power index δ shows better results (Fulle 2000).

$$V_d=V_0\left(\frac{a_0}{a}\right)^{-\delta},\ \text{where}\ V_0=500\frac{m}{s},\ a_0=1\,\mu m,\ \delta=\frac{1}{2} \qquad (3)$$

Different kind of structures in the comets' dust coma: jets, fans & shells

Different kind of structures are observed in the comets' coma. These structures are caused by an anisotropic emission from active region over the rotating nucleus. Their shape depends on the orientation of the spin axes, the coordinates of the active region over the nucleus and the aspect of the observations. The three different shapes (jets, fans and shells) are presented in fig. 1 taken from Larson & Sekanina (1984).

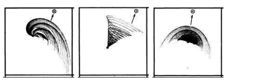

Figure 1. Different kind of structures in the comets' dust coma: left panel - jets, central panel - fans & right panel - shells

Instrumentation and data for the observations

The observational material was obtained with the 2m RCC telescope at BNAO–Rozhen. The focal length of the RC–focus is 16 000 mm. The 2-channel focal reducer (*FoReRo2*) was used to transfore the focal length to 5 600 mm (fig. 2). The *FoReRo2* gives opportunity for observations at two different wavelengths simultaneously (*red* and *blue* channel).

Two filters for comet observation centered at clean continuum windows (*BC* and *RC*) were used in both channels. *BC* is centered at 443 *nm* and has equivalent width of 3.9 *nm* and *RC* is centered at 642 *nm* and has equivalent width of 1.6 *nm*.

A CCD – cameras Photometrics, CE200A-SITe, comprising 1024×1024 px^2 and VersArray 512B, comprising 512 × 512 px^2 were used respectively on blue and red channel. The both CCD cameras have pixel size of 24 μm With this cameras and the described optical system the spatial scale is 0.89″/px. A mean seeing of about 2″ (which is usual for BNAO – Rozhen) is distributed on about two pixels, i.e. the optical system works with optimal sampling (Theorem of Nyquist or Shannon (Lèna 1988)).

The comet was observed in three consecutive nights near the perihelion and in table 2 the heliocentric and geocentric distances, apparent phase angle, the position angles of the extended Sun–target radius vector (PsAng) and the negative of the target's heliocentric velocity vector (PsAMV) orientations are presented.

Figure 2. *FoReRo2*

Table 2. Conditions during the observations.

Date	r	Δ	S-T-O	PsAng	PsAMV
19 May 2004	0.964	0.525	79.69	101.8	190.8
20 May 2004	0.966	0.549	78.60	101.4	190.4
21 May 2004	0.968	0.577	77.38	100.9	189.9

Absolute calibration

The CCD devices are linear detectors (Howell 2000). Therefore the conversion from registered signal to absolute values, fluxes, is made with linear transformation:

$$F_{com}=\frac{F_*}{S_*}S_{com}, \qquad (4)$$

where F_{com} and S_{com} are cometary flux and intensity respectively, but F_* and S_* are the flux and intensity of spectrophotometric standard star. The $\frac{F_*}{S_*}$ is linear coefficient, Q_λ, where F_* is taken from (Hamyu *et al.* 1992, 1994). Relation 4 is true only if the signal, S_*, is corrected for atmospheric extinction or the star is at the same airmass as the comet if the conditions are photometric. The coefficients for transformation from ADU/s to fluxes, measured in erg cm^{-2}sec^{-1}Å^{-1} for both continuums are $Q_{443}=1.35\times10^{-14}$ and $Q_{642}=6.03\times10^{-15}$. After that the images are calibrated to mean solar disk intensity and Af described by A'Hearn *et al.* (1984).

$$Af=\frac{F_{com}}{F_\odot}\left(\frac{r_h}{1AU}\right)^2\left(\frac{2\Delta}{\rho}\right)^2 \qquad (5)$$

where A is the Bond albedo and f is the filling factor.

One of the ways for setting up restrictions over determining the sizes of the particles in the cometary dust coma is to obtain the "colour" of the dust coma. This colour is defined as *the normalized gradient of the scattering efficiently of the dust coma in the weavelength interval* $[\lambda_1,\lambda_2]$ and has the following form (Jewit & Meech 1986):

$$F'_{(\lambda_1,\lambda_2)}=\frac{\partial F/\partial\lambda}{F_{mean}} \qquad (6)$$

Results

Mean radial flux, intensity distribution and color maps

Close to the nucleus the brightness of the dust coma decrease $1/\rho$. Therefore the product of Af and ρ should be constant ($Af\rho=const$). Mean radial profiles calibrated in terms of Af and $Af\rho$ values are presented in left panel on fig. 3 and table 3.

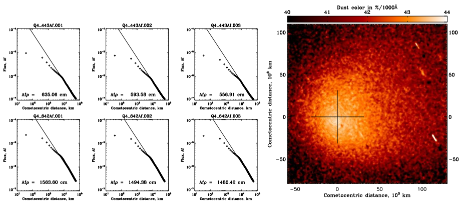

Figure 3. Af vs ρ plots and calculated $Af\rho$ values – left panel, and color map – right panel, for 21 May 2006

Table 3. $Af\rho$ values for all images and all days.

Date	$Af\rho_{443}$, [cm]	$Af\rho_{642}$, [cm]	Date	$Af\rho_{443}$, [cm]	$Af\rho_{642}$, [cm]
19 May 2004	620.63	1963.73	20 May 2004	923.18	1892.65
19 May 2004	484.31	1465.99	20 May 2004	915.71	1810.64
19 May 2004	-	1587.64	21 May 2004	635.06	1563.60
19 May 2004	-	1767.62	21 May 2004	593.58	1494.38
20 May 2004	1065.13	1988.65	21 May 2004	556.91	1480.42

From Af calibrated images the color maps are prepared. They show that the mean color of the dust coma is 43%. There is an indication of slightly reddening in the region of the jet-like structures (see right panel on fig. 3).

Image processing techniques enhancing structures in the coma

Using the theoretical expected surface brightness distribution we produce an synthetic image which follows the $\frac{1}{\rho}$ law and in which $\rho=0$ at the position of the comet in the observed images (see fig. 4).

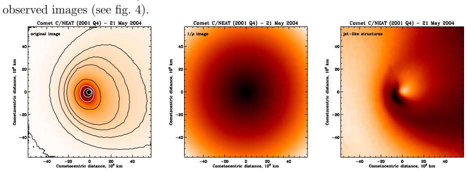

Figure 4. Left: raw image, middle: synthetic $\frac{1}{\rho}$ image, right: ratio *left* by *middle* to enhance the jet-like structures

With this image we divide the raw data (left panel of fig.4) to remove the mean comet's coma and obtain the image with enhanced coma structures (fig. 4 right panel).

Monte–Carlo simulations

For the description of these jet-like features a Monte-Carlo model, based on Finson-Probstein theory for dust particles dynamics, is developed. The size of the active region, its coordinates on the nucleus surface, and the range of the dust particles' sizes were found by trial and error. Fixed values of the particle size distribution, the rotational period and the orientation of the rotation axis were adopted. The model is calculated in a coordinate system centered on the comet's nucleus, x axes orientated to the Sun, y axes is perpendicular to x in clockwise direction in the plane of comet orbit and z axes completes rectangular coordinate system. By trail and errors we found that when comet spin axes coincide with a z axes then the model best reproduce the observations. If on the nucleus surface exist small active region at a coordinates θ and φ and a dust particles escape this active region, its position after time interval t will be described by:

$$x=V_d t\sin\varphi\cos\theta-\tfrac{1}{2}\alpha t^2$$
$$y=V_d t\sin\varphi\sin\theta \qquad (7)$$
$$z=V_d t\cos\varphi,$$

where α is the accelerations of the particles. Our model work with constant acceleration in inertial coordinate system. This model works because the consideration that the structures are short living. The dust particels should be uniformly distributed in this region. The initial coordinates are described by:

$$\varphi=\varphi_0-\tfrac{\mathrm{d}\varphi}{2}+R_i\mathrm{d}\varphi$$
$$\cos\theta=\cos\left(\theta_0-2\pi\tfrac{t}{P}-\tfrac{\mathrm{d}\varphi}{2}\right)+R_i\mathrm{d}\cos\theta, \qquad (8)$$

where R_i is a set of uniform random numbers ($R\in[0,1]$).

In fig. 5 one can see example of simulated jet produced from active region with latitude on the nucleus 45°. The shown structures are produced by particles emitted during a half comet day.

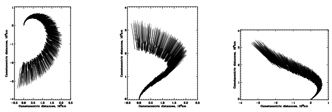

Figure 5. From left to right: projections of a modeled jets onto the $X-Y$, $X-Z$ and $Y-Z$ planes, respectively

The observation of comet C/NEAT (2001 Q4) on 21 May 2004 is shown in left panel of fig. 6. The simulation of this image is presented in right panel of fig. 6. We calculate that the biggest emitted particles in our model need more than 9 days to leave the region of interest. In this case we run the model at least for 10 comet days to reach stationary model. This simulation is created by ejecting 101 particles logarithmic distributed in size interval from 40 to 90 μm every 12 second over the time interval of 10 comet days (rotation period of the comet is P=22h (Lecacheux & Frappa 2004)). The spin axes orientation which best reproduce the observation is perpendicular to the sun position (x axes) and tilted on about 35° from z axes. Using orbit elements ($i=99.64°$) it gives tilt of 45° from ecliptic plane. The next step will be to vary slightly this orientation until the best coincidence will be obtained. In Table 4 are given the parameters of this simulation which roughly reproduces the observed structures.

The obtained 3D data array is integrated along the line of sight (see Eq. 9) to obtain an image, which can be compared with the observed image containing jet-like structures.

$$B_{xy}=C\int_{a_{min}}^{a_{max}}Ng(a)\pi a^2\mathrm{d}a,\ C=\frac{1}{\int_{a_{min}}^{a_{max}}g(a)da} \qquad (9)$$

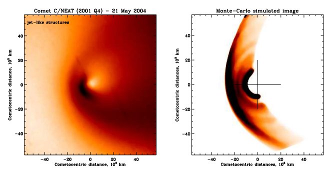

Figure 6. Observed (left panel) and simulated (right panel) jet-like structures

Table 4. Monte-Carlo model parameters.

θ	φ	dφ	a	Δt	P
90	90	5	40–90 μm	12 sec	22 h

The total brightness of jet-like structure is 4-5% from the ambient dust coma. But the area of the active region used in simulations, which well represent the original data, is only 0.15% of the whole surface. The space missions to comet Halley have shown that dust is released from about 30% of the nucleus surface. Using this numbers we can conclude that the active region is about 10 times more active then the ambient nucleus surface.

Conclusions

1. Observations of the dust coma of comet C/NEAT (2001 Q4) are obtained.
2. The dust coma is characterized with presence of discrete structures.
3. The images are absolutely calibrated and $Af\rho$ values and dust color are calculated.
4. The observed structures are enhanced from the ambient dust coma with application of suitable numerical radial filter.
5. A Monte-Carlo model is prepared and the structures are modeled and roughly compared with original data.
6. The contribution of the structure to the brightness of dust coma is evaluated.

Future work

Our future work will be in the direction of the best description of observed features with our model, varying different parameters and better estimations for how active is the active region.

Acknowledgements

The authors thanks the the organisers of the **"XVIIIèmes Rencontres de Blois** – *Planetary Science: challenges and discoveries"* and to the Central Administration of Bulgarian Academy of Sciences for the financial support which gives opportunity to present this work.

References

A'Hearn, M. F. *et al.* 1984, *AJ*, **89(4)**, 579
Divine, N. *et al.* 1986, *SpSciRev*, **43**, 1
Farnham, T. *et al.*, 2001 *SCIENCE*, **292**, p.1348
Finson, M. & Probstein, R., (1968) *AJ*, **154**, p.327
Fulle, M., 2000, *Icarus*, **145**, p.239
Gombosi, T., Cravens, T., & Nagy, A., 1985, *ApJ*, **293**, p.328
Jewitt, D & Meech, K.J. 1986, *AJ*, **310**, 973
Lecacheux, J. & Frappa, E., 2004, *IAUC*, **8349**
Mario Hamuy *et al.*, 1992, *PASP*, **104**, p.533
Mario Hamuy *et al.*, 1994, *PASP*, **106**, p.566
Howell, S. 2000, Handbook of CCD Astronomy, Cambridge University Press
Larson, S. & Sekanina, Z., 1984, *AJ*, **89**, p.571
Pierre Lèna, 1988, *Observational Astrophysics*, Springer-Verlag Berlin Heidelberg

Table 1:

Table 2:

Table 3:

Table 4:

Fig. 1.—

Fig. 2.—

Fig. 3.—

Fig. 4.—

Fig. 5.—