THE COMET HALE-BOPP NUCLEUS: HOW FAST ITS AXIAL ROTATION WAS?

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After the First International Conference on Comet Hale-Bopp (Canaries, 1998) many astronomers agree with the value of the period of axial rotation of its nucleus, which was obtained by observers by a comparison of the two sequential pattern of the dust arcs. It was noted that the pattern had been repeated each ~12 hours. The value $11^{\mathrm{h}}.35$ was taken as the period of axial rotation. Before the conference on Canaries, just after the first HST observations published by Weaver, Sekanina found a much longer period $\approx 8^{\mathrm{d}}$. Later Shulman obtained from the observation of Kidger *et al.* another value of the period, namely $\approx 4^{\mathrm{d}}$. The possible reasons of this discrepancy are discussed. It is shown that the short period is probably obtained by a misidentification of the same arc on two sequential images and, as a result, a severe overestimation of the radial velocity of dust in the arcs. To obtain the short period (a half of day) one must take the projected velocity of the arc ~ 1.6 km/s. This value can hardly be realistic because it exceeds the gas H_2O expansion velocity by the order. If one takes a more realistic expansion velocity the long period should be automatically obtained.

HOW THE LONG PERIOD WAS OBTAINED

Since 1995 August till October Kidger *et al.* [1, 2, 3, 4] observed three spiral jets. It was the beginning of activity of this comet and it is essential that only a single jet was observed each time. The Spanish astronomers have observed a series of consequent images of the comet. One could see that there was a spiral jet which was moving outward from the nucleus of the comet. The most probable suggestion is that the jet was a dust outflow from the nucleus swept by its axial rotation into a spiral. It means that the projected velocity of expansion could be determined by a simple geometric calculation. Let X and Y are the co-ordinates of a point of the jet in the image plane. Let the jet was produced by a single active region on the rotating nucleus. The circumstances of the dust ejection are defined by the next angles: ϕ is the nucleocentric latitude of the active region; ϕ_o is the nucleocentric latitude of the observer; θ_0 is the positional angle of the central meridian of the comet "disk"; $\lambda(t) = \omega(t - t_0)$ is the longitude of the active region in the moment t, t_0 is the moment when the active region passes the central meridian. It is convenient to choose the coordinate system in the picture plane with its Y-axis directed along the central meridian. If the active region was ejecting dust with the velocity $v(\tau)$ in the moment of ejection τ then an earth observer has to see, in the moment t, the curve whose equation may be written in these coordinates as follows:

$$X(t,\tau) = (t-\tau)v(\tau)\cos\phi\sin(\omega(\tau - t_0)), \tag{1}$$

$$Y(t,\tau) = (t-\tau)v(\tau)\left[\sin\phi\cos\phi_o - \cos\phi\sin\phi_o\cos(\omega(\tau - t_0))\right], \tag{2}$$

where τ is the parameter, which should be excluded to get the $Y(X)$ function on the moment of observation t. The rotational component of the velocity ωr_n as well as the repulsive acceleration by solar radiation are neglected.

This parametric curve can be described in the polar coordinates in the picture plain by the equations:

$$X = \rho\cos\theta, \quad Y = \rho\sin\theta, \tag{3}$$

where $\theta = \theta_{obs} - \theta_0 + \pi/2$ is the polar angle of the point in jet, θ_{obs} is the observed positional angle of the same point, ρ is the projected distance in the picture plain.

It is defined by the relationship

$$\rho(t,\tau) = \sqrt{x^2+y^2} = V_{pr}(\tau)(t-\tau) = (t-\tau)v(\tau)\times$$

$$\left[(\cos\phi+\cos\phi_o)^2 - \frac{1}{2}\sin 2\phi\sin 2\phi_o\cos(\omega(\tau-t_0)) + \cos^2\phi\cos^2\phi_o\sin^2(\omega(\tau-t_0))\right]^{1/2}, \quad (4)$$

where V_{pr} is the projected velocity and

$$\tan\theta(\tau) = Y/X = \frac{\tan\phi\cos\phi_o}{\sin(\omega(\tau-t_0))} - sin\phi_o\cot(\omega(\tau-t_0)). \quad (5)$$

Here x and y are the observed rectangular coordinates which are measured to the East and to the North, respectively. One can see that the ejected dust moved from the nucleus with an approximately constant velocity and the projected velocity can be calculated directly from the measured coordinates of points in the jet.

After the calculation of the $V_{pr}(\theta)$ and $\tau(\theta)$ the next step is to use the Eq. (5) and obtain all the set of parameters: ω, ϕ, ϕ_o, t_0. Two of these parameters, namely ϕ and ϕ_o, control the shape of the jet. One can easy estimate the axial rotation period $P = 2\pi/\omega$ because the nucleocentric angle covered by the jet approximately corresponds to a half of the period. We have obtained the following values.

Parameter of the nucleus and source of dust	quantity	value
The observer passed the central meridian of the nucleus at	t_0	Oct 24.46
Positional angle of the central meridian	θ_0	130°
Nucleocentric latitude of the source	ϕ	68°
Nucleocentric latitude of the observer	ϕ_o	55°
The period of rotation	P	$3^{\mathrm{d}}\!.96$

One can easy calculate the space velocity of ejected dust as a function of time. The result is plotted below in Fig. 1. One can see that we have here a steep invisible increase of the velocity, then the velocity slowly decreases and finally steeply goes to zero after the local sunset in the vicinity of the active region. The maximal

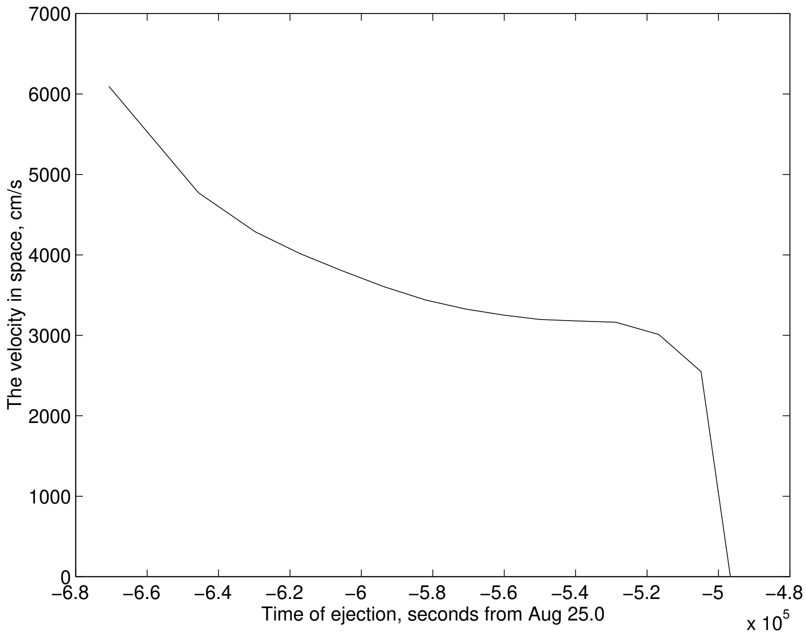

Figure 1: The projected velocity of dust in the August jet

value of the velocity ~60 m/s agrees with the radioastronomical data [8] which gives the CO velocity ~500 m/s. The CO was probably the propellant that dragged the water ice grains which formed the jet. So, the long four day period is in accordance both with the direct observed kinematics of the spiral jet and with the data on the movement of the gas which accelerated the grains. The modelled picture fits well observations as one can see in Fig. 2 below.

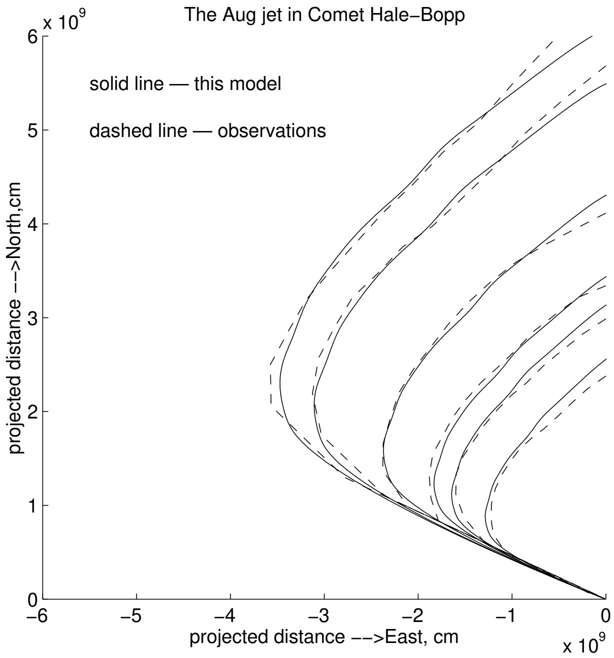

Figure 2: Comparison of this model with observations

HOW TO GET A SHORT PERIOD?

The mentioned short period (half a day) has been obtained much later when the comet approached the Martian orbit. That time it produced many jets and arcs. Several arcs were often observed simultaneously. Farnham *et al.* [5] have found the period 11.35 ± 0.05 hours from the movement of dust arcs from March 25 through April 1, 1997. The same value has been found by Licandro *et al.* [9] from a 16 days series of narrow band near infrared images of this comet obtained during April 1997. Two possible reasons may be proposed to explain this discrepancy. One of them is the spinning up of the nucleus by the angular momentum of ejected matter. Another reason is the existence of more than one active regions on the surface of the nucleus (N_{ar}) which were able to produce dust arcs.

One can expect in this case that the rotation period found from the periodicity of the arcs is only a part of the real period: $P_{obs} = P_{real}/N_{arcs}$. Both the reasons can do together. So, there may be a difference between the periods of 1995 and 1997, *i.e.*, $P_{obs}(1997) = (P_{real}(1995) - \Delta P)/N_{ar}$. The discrepancy disappears if we take $N_{ars}(1997) = 8$ and $\Delta P = P_{real}(1995) - P_{real}(1997) = 4.24$ hours so the angular velocity in 1997 exceeded its 1995 value by 4.5%. Surely, such a small difference may be simply an error of data processing. One can see that in the case of self-spinning up there should be a specific appearance of the arcs. Generally, they would not be approximately equidistant because there is no reason for the active regions to be separated by an equal interval of the nucleocentric longitude. The authors cited above [5, 9] paid their attention to the fact that all the pattern repeated approximately each 12 hours. Hence, the atmosphere of a comet is not rotating with its nucleus as a solid body and, therefore, any periodicity of the pattern cannot be considered as an effect of spinning of the nucleus.

There is the third possible reason to obtain a period of rotation which is many times shorter than the real period. If one have two multi-arc images of a comet it is possible to determine the velocity of their expansion and here is a real possibility to make a mistake. It is necessary to identify the same arc in two subsequent images. There is no individual features which could help to make this identification and, therefore, one can take two different arcs in two images as two positions of the same arc separated approximately by one day. The real velocity of expansion is given by the relationship

$$V_{real} = \frac{R_2 - R_1}{N P_{real}}, \quad (6)$$

where $R_{1,2}$ are two nucleocentric distances of the same arc, N is the number of revolutions between both arcs, P_{real} is the real rotation period. In the case of misidentification one should get a false estimation of the velocity

$$V_{false} = \frac{R_2 - R_1}{\Delta t}, \quad (7)$$

where $\Delta t \approx 86400$ s is approximately one day interval between two images. If the difference between the nucleocentic distances of two opposite edges of the same arc is

$$\Delta R = VP\frac{\psi}{2\pi}, \quad (8)$$

where ψ is the angular size of the arc, then one can get a false period using the relationship (7)

$$P_{false} = \frac{\Delta R \cdot 2\pi\Delta t}{\psi(R_2 - R_1)} = \frac{\Delta t}{N}. \quad (9)$$

So, the misidentification can give a false period which can be equal to an integer part of a day: one day, a half a day, one third of a day and so forth. This consideration does not depend on the conditions of projection because both the distances and velocity are projected and so the function of angles is self-eliminated. May be the authors of [9, 5] implicitly took N = 2 and so got their 11.35 hour period.

Note that this approach cannot give the real period because any real period fits the relationships (6) and (8). So, one has to obtain the velocity in another way, namely from the kinematics of an individual arc. It is important to remember that physical nature of the arcs was different from those observed when the comet was at a heliocentric distance about 7 AU. When the comet crossed the Jovian orbit water vapour became the main constituent of its atmosphere. So, instead of icy grains propelled by CO we had then usual mineral dust dragged outward by water vapour. If we take the half day period of rotation then the arc should expand with a velocity 1–2 km/sec. This value exceeds by the order the possible velocity of dust grains accelerated by gas outflow. Even gas itself cannot have its velocity more than 100–200 m/sec. One can see that the short period of rotation is not real.

The discrepancy between our 4 day and Sekanina's 8 day periods can be explained by the circumstances of the observations. Sekanina [6] used the Hubble Space Telescope data, which were the images of the inner circum-nuclear region, where it was very easy to take the spiral jet produced during two revolutions as that produced in one period. Sekanina simply determined the double period interval as the period.

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