ISSN 0884-5913, Kinematics and Physics of Celestial Bodies, 2009, Vol. 25, No. 4, pp. 189–193. © Allerton Press, Inc., 2009.
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DYNAMICS AND PHYSICS OF SOLAR SYSTEM BODIES

Model Analysis of the Dust Tail of Comet Hale-Bopp

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Received September 26, 2008

Abstract—The paper presents the results of dynamic simulation for the dust tail formation of comet C/1995 O1 (Hale-Bopp). To simulate the dust tail, the trajectories of 2×10^6 dust particles were traced. The sizes, ejection moments, outflow directions and velocities of the dust particles were defined by the Monte Carlo algorithm. The obtained three-dimensional tail was projected on the sky plane to compare it with the observed images. The brightness distribution in the comet tail was fitted to similar model parameters for three different dates. According to our model experiments, the observed tails could be formed by particles with sizes from 0.3 to 8.0 μm, ejection velocities from 0.155 to 0.670 km/s, and power index of the exponential size distribution from –3.6 to –3.7. It is shown that the inclusion of the particles fragmentation processes leads to a noticeable improvement of the simulation results.

DOI: 10.3103/S0884591309040035

INTRODUCTION

Comet Hale-Bopp was discovered by Alan Hale and Thomas Bopp on July 23, 1995. The comet's intense activity facilitated its discovery at 7.1 AU from the Sun and on-going monitoring after perihelion passage up to the present. Beyond doubt, Hale-Bopp is one of the most well-studied long-period comets.

Its dust-mass to gas-mass ratio is approximately five [8, 11]. According to various sources, the particles velocities are 0.40–0.67 km/s. Thus, the study [3] focused on images of arc entities in the comet atmosphere covering the distances 4.12–0.9 AU from the Sun yielded the value 0.67 ± 0.07 km/s. The set of light filters covered the range of near ultra-violet, visible, and near infrared radiation. The paper [6] gives the dust particles velocity 0.41 ± 0.05 km/s. This figure was found by expanding arc entities on the images produced by the polarization method. In the research, visible range light filters were used; the comet was at the distance 4.1–1.0 AU from the Sun. The paper [9] gives the estimate 0.45–0.60 km/s; this figure was obtained by analyzing CCD images taken with the help of light filters in the visible and near infrared range, when the comet was near perihelion. Finally, the paper [11] gives the velocity of the expanding dust particles 0.4 km/s. The comet arc structures were studied using infrared and optical images taken in 1996 and 1997.

The greatest contribution to the comet's dust tail is made by amorphous carbon, olivine and pyroxene, and iron sulfide [12]. Based on indirect evidence, we may conclude that comet Hale-Bopp has considerable content of small-sized particles, which, at the beginning of their movement, were part of large, highly porous aggregates [6]. In the paper by Min et al. [12], estimates are given of the dust particles effective radius $r_{ef} = 1.0$ μm and the index of the particle distribution by size $\alpha = -3.0$. The research was based on the spectroscopic observations of the comet, which was then located at 2.8 AU from the Sun. According to the data by Bouwman et al. [2], the radii of the comet tail dust particles vary in the range 0.01–10 μm at $\alpha = -2.8$ (for distances from the Sun 2.8–3.0 AU). These data are based on the analysis of Hale-Bopp's spectrum obtained by the Infrared Space Observatory. In the work by Moreno et al. [13], the particle sizes are within the range 0.1–5 μm at $\alpha = -3.6$ (for distance from the Sun 2.8 AU). The study analyzed the comet's infrared spectrum obtained by the Infrared Space Observatory.

This work is focused on studying the physical properties of the dust in Hale-Bopp's tail based on dynamic simulation of the tail's formation process.

OBSERVATIONS AND OBSERVATION DATA PROCESSING

Observations were conducted at Crni Vrh Observatory, Slovenia, by Herman Mikuz using a Baker-Schmidt camera with an objective diameter of 180 mm and an aperture ratio $f/2.8$ and an ST-6

Table 1. Comet parameters at the observation moments

Date of observations start, 1997	V	Distance fro the Sun, AU	Distance from the earth, AU	Tail position angle	Pixel size, 10^3 km
February 8.199	1.7^m	1.28	1.86	326.1°	34.0 × 34.0
February 18.169	1.0	1.16	1.65	325.3	30.2 × 30.2
March 7.166	0.1	1.02	1.41	335.0	25.8 × 25.8

CCD-detector with the dimensions 578 × 385 pixels. Since the pixel size is 25.2″ × 25.2″, then the field of vision is 3.8° × 2.5°. The images were obtained using a specialized comet filter that passes the light scattered on the particles. Its passage band is maximal on the wavelength $\lambda = 647$ nm with the half-width 10 nm. The exposition period for all the three images was 5 min. Bayes was excluded from the images, dark current was compensated, and plane field correction was performed. Table 1 lists the orbital parameters of comet Hale-Bopp at the three observation moments and pixel size in kilometers.

MODEL

To simulate the dust tail of comet Hale-Bopp, we applied the model developed by P.P. Korsun [10] used to explore distant comets. In this model, to construct the comet's dust neighborhood, trajectories of each individual particle are traced from the collision zone around the nucleus up to the observation moment. For this purpose, the Monte-Carlo algorithm is used to establish the moment and outflow direction of the particle as well as the simulation parameters: radius and outflow velocity from the collision zone. Then, for each particle, an equation system is constructed, namely, a system of equations of motion affected by two forces, i.e., solar gravitation and solar radiation pressure. Solution of this system yields the coordinates of one particle at the observation moment, and the total set of these solutions simulates the comet's dust tail. Finally, the calculated comet-centric coordinates of the particles are projected onto the image plane to compare them with the real observations.

P.P. Korsuns's model simulates motion of big particles in which dust is frozen into ice and which change in their mass with their gradual melting. When constructing a near-Sun model of comet Hale-Bopp, we had to give consideration to the new circumstances: the ice component of the particles had completely evaporated, so we had to analyze the motion of highly porous particles made of a refractory substance very likely to decay. Therefore, it was very important to give consideration to the fragmentation process, which had been emphasized by many researchers [4, 7].

Fragmentation. If we assume fragmentation to occur largely in the comet collision zone, then, to some approximation, one can analyze the simultaneous outflow from the collision zone of the dissolved parent particle fragments. As it is known from the model calculations, particles of different sizes that left the comet nucleus at one and the same point in time, will be on one line in the tail, forming synchrons.

We should treat the positions of a non-fragmented particle and the smallest possible fragment as the boundary conditions for this line. Also, for further calculations we need the masses of these two particles with the aforementioned boundary conditions. The comet dust particles are known to be highly porous, and there is certain dependency between the particle radius and its density. This dependency was studied by many researchers. Here we shall use Combosi's empirical formula [4]:

$$\rho = 2.2 - 1.4r/(r+2),$$

where density ρ is expressed in grams per cub. cm and the radius of particle r is in microns. Then, using the known formula, we can obtain the particle mass:

$$m = 4\pi\rho(r/10000)^3/3.$$

The only limit for the number of the formed fragments is the parameters of the law of conservation of mass, which is controlled by the residual mass parameter m_r.

The position of the fragment of radius r_f on the synchron line is determined from the assumption that the particle location is proportionate to its radius. Then

$$r_f = (1-R_i)r_m + R_i r,$$

where r_f is the fragment radius and r_m is the radius of the minimum possible fragment.

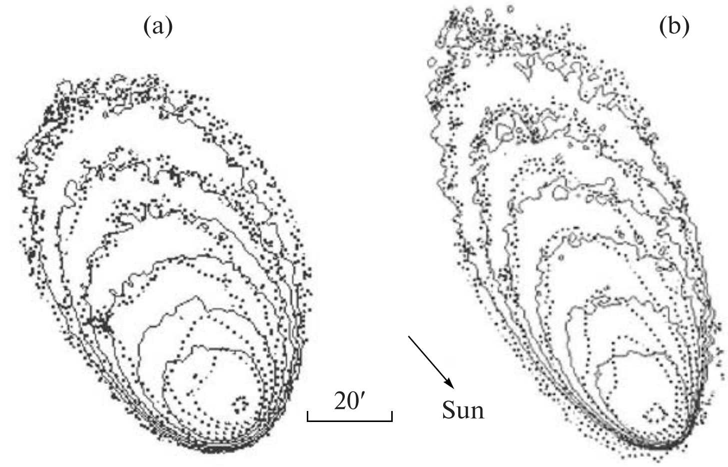

Fig. 1. Simulation results for comet Hale-Bopp for two observation dates: (a) February 8 and (b) February 18, 1997. The solid lines are the model isophotes, the dotted lines are the isophotes obtained from the observations.

If the mass of the fragment m_f turns out to be higher than the residual mass, then a new random number R_i is generated, and a new value m_f is found. In the opposite case, a new value of the residual mass is found: $m_r = m_r - m_f$. Coordinates of the fragment are found by the formulae

$$R_f = (1 - R_i)R_m + R_i R_u,$$

where R_f, R_m, and R_u are coordinates of the given fragment, minimal possible fragment, and non-fragmented particle, respectively.

The fragmentation cycle is viewed as complete if the residual mass is lower than the minimal mass.

SIMULATION PROCESS AND DISCUSSION OF THE RESULTS

The computer program was written in the FORTRAN algorithmic language; the launch and calculations control interfaces were implemented using the IDL software package focused on image analysis. As a criterion of coherence between the observed and simulation data, we chose the match level of isophote sets.

The following values were taken as simulation parameters: maximum age of the particles contributing to the tail formation, minimum and maximum radii of the particles, degree of the distribution law by particle radius under the assumption of exponential distribution, and initial values of the dust particles velocities and fragmentation share (probability). The simulation parameter β determined by the ratio of the forces of the solar radiation pressure and solar gravitation was established by the formula [5]

$$\beta = 0.585 \times 10^{-4} Q_{pr}/\rho a,$$

where a is the particle radius in μm, ρ is the particle density in g/cm^3, and Q_{pr} is the radiation pressure effectiveness factor. This formula is fair for particles with the radius $a \geq 0.2$ μm, Q_{pr} being constant, and β inversely proportionate to the radius. The quantity of particles leaving the collision zone is 2×10^6 for all the dates.

Table 2. Optimal model parameters for different images

Date, 1997	Particle age, days	r, μm	α	V, m/s	Fragmentation share
February 8	56	0.3–8.0	–3.6	168–721	0.1
February 18	66	0.3–8.0	–3.6	143–640	0.1
March 7	59	0.3–7.0	–3.7	155–650	0.2

Fig. 2. Simulation results for comet Hale-Bopp for the observation date March 7, 1997. The solid lines are the model isophotes, the dotted lines are the isophotes obtained from the observations.

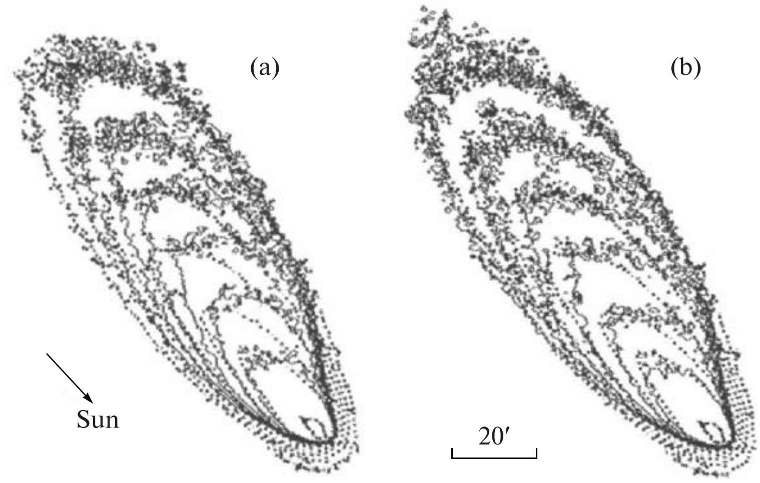

Fig. 3. Simulation results (a) without fragmentation and (b) with the fragmentation process. The simulation was conducted for comet Hale-Bopp; the observation date was March 7, 1997. The solid lines are the model isophotes, the dotted lines are the isophotes obtained from the observations.

The particles outflow velocities were found by the empirical formula proposed by Sekanina [14]:

$$V = Ar_d(B + \beta^{-0.5}).$$

Here V is the velocity of the ejected partciles, A and B are numerical parameters, r_d is the heliocentric distance of the dust particle, and β is the ratio of the solar pressure force to the Sun gravitation.

Table 2 gives numerical values of the simulation parameters. These parameters have enabled us to obtain the best results in reproducing the brightness distribution. We should note that there are no significant differences between the parameter sets for the three different dates. Figure 1 shows the results of modeling Hale-Bopp's dust tail for two dates: February 8 and 18, 1997. The image taken on March 7, 1997 is largely different from the other two. At this time, the comet was practically in perihelion. You can see from Table 2 that the quantity of small-sized particles on March 7, 1997 is also somewhat higher. This is shown by the indicator of the power-series distribution by radius (–3.7 against –3.6 for other dates), deformation share (0.2 against 0.1), and the size of the maximum particle (7.0 against 8.0).

As you can see from Fig. 2, we have not been able to obtain a part of the dust coma in the neighborhood of the nucleus of comet Hale-Bopp. This is related to charge spreading on the CCD-receiver due to high brightness in the comet's near-nucleus area.

We should also point out that inclusion of the particle fragmentation process does improve the simulation results. Figure 3a shows the model isophotes of comet Hale-Bopp obtained without fragmentation, and Fig. 3b shows the isophotes calculated for the fragmentation share 0.2. Other simulation parameters correspond to the optimal ones listed in Table 2.

The obtained values of the dust partciles final velocities correspond, in general, to the data in [3, 6, 9, 11]. Thus, our data of comet tail dynamic simulation are coherent with those obtained by other methods. At the same time, the indicator of the distribution by size (Table 2) is somewhat higher than the one obtained in the works [2, 12] and corresponds to the value obtained in the work [13]. These differences can be explained by the fact that our observations were made at closer distances to the Sun, where smaller particles are expected to occur in the comet tail.

CONCLUSIONS

The three images of comet Hale-Bopp were taken by H. Mikuz using a special filter that passes the light scattered by the comet dust particles. We were able to reproduce the brightness distribution in Hale-Bopp's dust tail using the Monte-Carlo simulation for three different dates with proximate simulation parameters. We obtained estimates of the maximum age of the partciles forming the tail (56–66 days), initial outflow velocities (140–720 m/s), characteristics size (0.3–8 μm), and indicator of the power-series distribution by size ($\alpha = -3.6$ to -3.7). Our simulations show that inclusion of the fragmentation process for dust particles in the comet tail largely improves the simulation results.

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