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Modelling two dust features in comet Hale-Bopp (1995 O1)

Z. Sekanina

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109. U. S. A

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Abstract. A Monte Carlo computer simulation code for generating synthetic images of dust features in comets is applied to comet Hale-Bopp to model the diurnal evolution of a bright jet and the appearance of nearly concentric halos. Although both the jet and the halos were under observation for long periods of time in early 1997, they are unrelated, having originated from different discrete emission sources on the nucleus. The comet's complex state of rotation is confirmed, and the major effects of the diurnal regime of dust production and the particle size distribution law on the observed features are exemplified.

Key words: comet Hale-Bopp - diurnal evolution of a dust jet - dust halos - nuclear rotation emission sources

1. Introduction

In early 1997, the impressive list of morphological dust features displayed by comet Hale-Bopp (1995 O1) grew even longer, documenting the complexity of the comet's activity. Unfortunately, one finds much confusion and even plain errors in published attempts to interpret these phenomena. Two features that offer important information both on the comet's state of rotation and on the process of dust emission from the nucleus are discussed below.

One is a short, bright jet of variable direction, which was reported by many observers in the third quadrant. From images taken between January 12 and February 10, 1997, Lecacheux et al. (1997) noticed the jet's orientation to change measurably on a time scale of less than 2 hours, with a recurrence period of 11.47 ± 0.05 hours.

The other morphological feature is a system of nearly concentric halos (also called ripples, shells, rings, waves, etc.), first reported by Hergenrother et al. (1997). In spite of the various terms used, the formation of dust halos in comets is well understood. They are identified with the sharp outer boundaries of conical sheets of particulate material released from a discrete emission area on the nucleus. A successful modelling of halo formations requires that the sizes a of the particles involved have a steep distribution $a^{-s}\,da$, with $s > 5$. These grains must be accelerated to terminal ejection velocities of ~0.5 km/s that are nearly independent of the size and represent the peak particle velocities. The best candidates are grains from ~0.2 to <1 micron in diameter, optically the smallest and the most important particles in comets. They could derive from larger, very fragile parent particles that fragmented precipitously shortly after ejection from the nucleus, if sufficiently large momentum can be acquired by the fragments either during breakup or in the course of interaction with expanding gas near the nucleus.

In addition, it was shown by Sekanina and Larson (1984) that multiple dust halos are diagnostic of a rapidly rotating comet nucleus and that they constrain the orientation of its spin axis at the time (see also Sekanina 1987, 1991). Bond's (1862) description of multiple halos in comet Donati (1858 L1) was employed by Whipple (1978) to argue that they were products of dust emission from a single active area on the nucleus whose rotation period was 4.6 hours, perhaps the shortest on record.

Proposing an early model for comet Hale-Bopp, based solely on the high-resolution images obtained in 1995, I concluded that the nucleus was in a complex state of rotation (Sekanina 1996a). Recent observations appear to corroborate this conclusion (Jorda et al. 1997).

2. Monte Carlo simulation of dust morphology

The morphological features of interest are modelled in this study by applying a Monte Carlo computer simulation code, which generates synthetic images of dust ejects released from discrete sources on a rotating nucleus. Brief descriptions of this technique can be found elsewhere (Sekanina 1996a, b and several references therein).

Dust-morphology models generated in this fashion are defined by their rotation and dust-emission parameters. It is assumed that pure spin approximates satisfactorily the comet's state of rotation during a fraction of a day, a reasonable assumption if significant long-term variations occur over a period of ~20 days (e.g., Sekanina 1996a,

Send offprint requests to: Z. Sekanina

Jorda et al. 1997). The position of the spin axis can then be defined by two Eulerian angles, the argument Φ and the obliquity I (e.g., Sekanina 1981a), or by the coordinates of the north rotation pole (from which the nucleus is seen to spin counterclockwise), while the adopted spin period is based on information by Jorda et al. (1997). It is further assumed that the dust ejects that make up the observed features were released from discrete sources activated only from sunrise to sunset. The locations of the sources and the circumstances of their activity, together with the spin-vector constants, are derived by fitting the observed images of the features by trial and error.

The dust-ejects parameters for the examined features in Hale-Bopp are less well determined. They cannot be tightly constrained because of the unavailability of photometric information. For this reason, a constant rate of dust production was assumed between sunrise and sunset. Limits on the particle acceleration β by solar radiation pressure (a dimensionless quantity expressed in units of the Sun's attraction) are only crudely constrained at this time, based on the recognized properties of the specific features (Sects. 3 and 4). From my experience with other comets, the peak β value should be between 0.5 and 2.5. However, on time scales of a fraction of a day, particle motions are determined primarily by the ejection velocity v_{eject}, whose relation to the acceleration β is given by

$$v_{eject}^{-1} = A + B\beta^{-1/2}, \qquad (1)$$

where A and B are constants whose values are extensively discussed in the investigations of comets 109P/Swift-Tuttle (Sekanina 1981b) and 1P/Halley (Sekanina and Larson 1984, 1986). The values of A and B can be calculated from the adopted limits on β and v_{eject}.

Table 1. Rotation and dust-emission parameters used to model the evolution of the bright jet and the multiple halos

	Bright Jet	Multiple Halos
Rotation Parameters:		
Argument Φ of subsolar meridian at perihelion	60°	35°
Obliquity I of orbital plane to equator	90°	100°
Right ascension of north rotation pole[a]	285°	293°
Declination of north rotation pole[a]	−42°	−16°
Adopted sidereal period of rotation[b]	11^h15^m	11^h28^m
Dust Source Parameters:		
Cometocentric latitude	+60°	−5°
Cometocentric longitude of subsolar meridian at perihelion	207°	174°
Local hour angle of Sun at onset/end of dust emission (sunrise/sunset)	∓116°	∓93°
Sun's elevation at local noon	44°	66°
Duration of emission[c]	7^h15^m	41^h30^m
Dust Ejecta Parameters:		
Power index of differential particle size distribution law	3.5	5.5
Particle acceleration β (units of s.a.)		
lower limit β_{min}	0.00004	0.01
upper limit β_{max}	0.50	0.50
Particle ejection velocity v_{eject} (m/s)		
lower limit $(v_{eject})_{min}$		100
upper limit $(v_{eject})_{max}$	450	500

[a] Equinox 2000.0.
[b] Based on information from Jorda et al. (1997).
[c] One rotation for the jet, seven consecutive rotations for the halos

3. Diurnal evolution of the bright jet

On February 28, 1997, Jorda et al. (1997) were monitoring the diurnal evolution of the bright jet, using a near-infrared filter. In their Pic-du-Midi observing run, from 3:50 until 15:35 UTC (i.e., mostly in broad daylight), they took a total of 1100 images that cover an entire rotation cycle. An animated representation of some 70 co-added frames is available in a referenced electronic report.

At the level of detail seen on the animation sequence (affected by a variable signal-to-noise ratio), the jet first appeared at a position angle of ~240°, growing gradually longer, rotating toward the south (clockwise), and broadening somewhat. A peculiar property is an indication that the jet's rotation stopped near a position angle of 180° about midway through the cycle. The jet then persisted in this direction until it faded away and a new jet appeared at a position angle of ~240° after the onset of the next cycle. I notice no sign of the jet's reversing the sense of its apparent rotation at any time.

The derived rotation and dust-emission parameters for a crudely optimized model of the jet's diurnal evolution are listed in column 2 of Table 1. The observed persisting southerly direction suggests that slower, micron-sized and larger particles were plentiful in these ejects. The lower limit for v_{eject} was therefore taken to amount to 'i m/s, the velocity of escape from the nucleus of an assumed bulk density of $0.2\ g/cm^3$ and 40 km in diameter (Weaver 1995). The modelled diurnal evolution of this jet is displayed in Fig. 1. For the sake of argument, it is assumed that the jet's source was activated exactly at 3:50 UTC (as observed at Earth), which is identified with the time of sunrise at the source. No trace of the jet is predicted to show 10 minutes after activation. The model jet, whose length increases rapidly, remains essentially rectilinear for the first two hours, then its curvature becomes apparent. It broadens strikingly some 5 hours after activation, at which time the persisting bright sub-jet inside the feature already points directly south, faithfully simulating the observed behavior. Dust emission is calculated to have ceased at 11:05 UTC, the time of sunset. No sign of this termination of activity is seen in the synthetic images, which show a perceptible fading of the sub-jet only 2–3 hours later. The next diurnal cycle of activation began at 15:05 UTC, with traces of the new jet seen in the last two frames. For further details, see the caption to Fig. 1. A refined model will be formulated when more information is available on the jet's observed evolution.

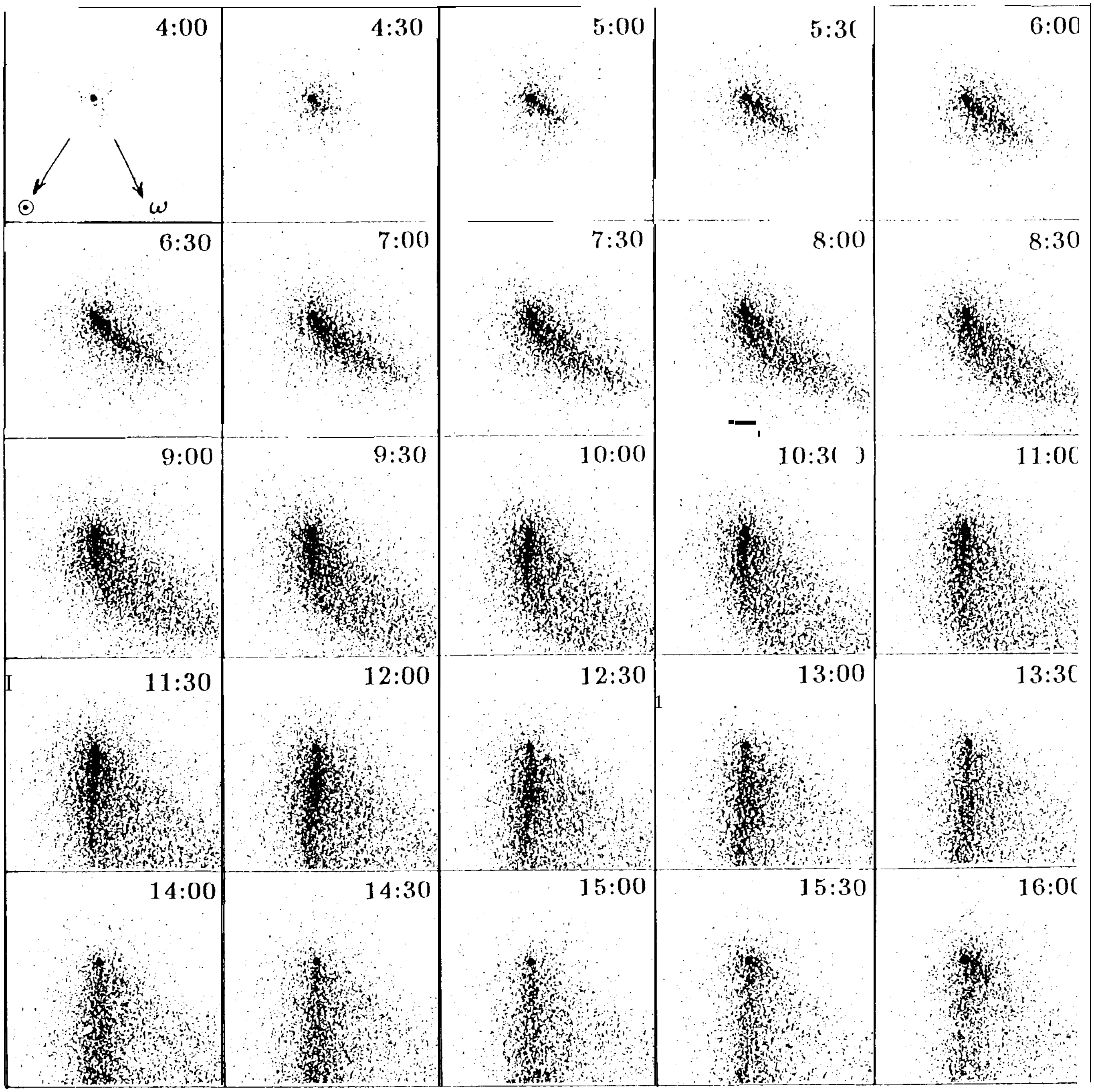

Fig. 1. Synthetic. computer generated images simulating the diurnal evolution of the bright jet of cornet Hale-Bopp observed by Jorda et al. (1997) at Pic du Midi on February 28, 1997. The dot density is proportional to the integrated geometric cross sectional area of the dust ejecta. The neighboring frames show changes in the jet's appearance in 30-minute intervals. The model assumes the emission source to be activated at sunrise. taken to occur at 3:50 UTC (as observed at Earth). and to product dust at a constant rate between sunrise and sunset. The first frame shows no trace of the jet 10 minutes after activation. The transit across the subsolar meridian occurred at 7:28 UTC and the activity Lasted for 7^h15^m, terminating at 11:05 UTC (sunset). Noteworthy is the formation of a bright sub-jet in the broadening feature later in the cycle. The orientation of this suh-jet dicl not change for some 7 hours. during which it was pointing directly to the south. It eventually made up the eastern boundary of the original jet. which in the meantime turned into a fan-shaped feature with a sector angle of 60- 70°. A new jet began to develop at 15:05 UTC; it shows up in the last two frames. The model suggests that remnants of the old jet were surviving even *after* the source's reactivation in the new cycle, In terms of the short jet's evolution, the second frame fits midway between the last two frames. Each frame is 8 arcsec on a side, equivalent to 9160 km at the cornet. North is up and east to the left. Identified are the position of the nucleus (solid circles) and the projected directions of the spin vector (ω) and the Sun (circled dot).

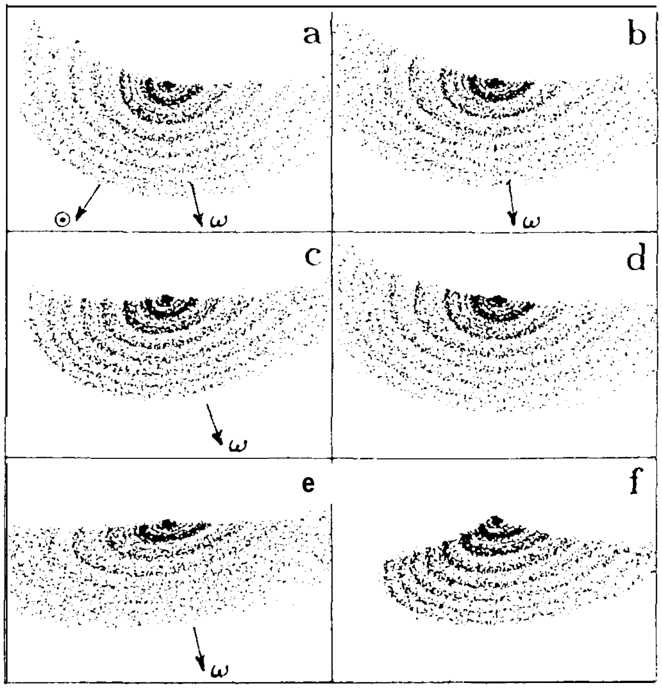

Fig. 2. Synthetic images simulating the system of nearly concentric halos of comet Hale-Bopp, observed by Larson and Hergenrother (1997) at the Steward observatory on February 9, 1997. The dot density is proportional to the integrated geometric cross sectional area of the dust ejects. The individual frames refer to the following combinations of the argument Φ, the obliquity I, and the emission source's cometocentric latitude: (a) 35°, 100°, −5°; (*b*) 45°, 100°, −5°; (c) 45°, 90°, +5°; (d) 45°, 100°, 0°; (*e*) 60°, 90°, +5°; (*f*) 60°, 90°, +25°. Each frame is 180 arcsec wide and 125 arcsec high (240,000 km by 167,000 km at the comet). For the orientation and other information, see the caption to Fig. 1.

4. System of nearly concentric halos

A system of several halos that became visible in early 1997 is exemplified on an image obtained by Larson and Hergenrother (1997) on February 9, 1997. Its computer processed version is presented in the electronic report by the two observers. The separation between two neighboring halos was about 8 arcsec.

Six models of the halos in Fig. 2 cover seven consecutive rotation cycles. If the comet's state of rotation is complex, the assumption of a fixed spin axis is now less safe than it was for the jet. In each cycle, a constant rate of dust production was assumed for the halo-emission source between sunrise (the western end of the halos) and sunset (the eastern end). No attempt was made at this time to match the observed brightness variations along the halos. Since high particle accelerations due to solar radiation pressure would smear the outer halos (in which the ejects are several days old), a constraint $\beta \leq 0.5$ was implemented to make the models compatible with the observed sharp boundaries of all the halos.

The six models in Fig. 2 allow one to examine effects of varying their basic parameters. Comparing *a* and *b* shows that a change in Φ rotates the system of halos in position angle. Comparing *c* with *e* indicates that a change in I varies a tilt of the pattern. Lastly, comparing *b* with *d* and especially *e* with *f* shows that a change in the source's latitude affects the extent of the halos in position angle.

In Fig. 2, the best match to the observed image is probably offered by the case *a* (Φ = 35°, I = 100°), whose parameters are listed in column 3 of Table 1. The spin-axis position derived in Sect. 3 to fit the jet's diurnal evolution fails to offer an acceptable model for the system of halos, as exemplified by the cases *e* and *f*. I am thus compelled to confirm my earlier conclusion (Sekanina 1996a) that *the comet's state of rotation cannot be pure spin.*

Some published images suggest the presence of additional halo systems and/or a possibility that the southeastern and southwestern branches of the halo system considered here to be a single feature were in fact two separate formations. This issue remains to be further examined.

Finally, the results of this study indicate that the jet and the halo system consisted of physically unrelated dust ejects, with different particle size distribution laws and released from different emission sources.

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References

Bond, G. P. 1862, Ann. Harvard Coll Obs 3 1
Hergenrother, C. W., Larson, S. M., and Marsden, B. G. 1997, IAUC 6555
Jorda, L., Lecacheux, J., and Colas, F. 1997, IAUC 6583
Larson, S. M., and Hergenrother, C. W. 1997, Electronic report (URL http://www.lpl.arizona.edu/bss/comets.html)
Lecacheux, J., Jorda, L., and Colas, F. 1997, IAUC 6560
Sekanina, Z. 1981a, Ann. Rev. Earth Planet. Sci. 9, 113
Sekanina, Z. 1981b, AJ 86, 1741
Sekanina, Z. 1987, in: Rolfe, E. J., and Battrick, B. (eds.) Diversity and Similarity of Comets, ESTEC, Noordwijk, the Netherlands p. 315
Sekanina, Z. 1991, AJ 102, 1870
Sekanina, Z. 1996a, A&A 314, 957
Sekanina, Z. 1996b, in: Gustafson, B. Å. S., and Hanner, M. S. (eds.), Physics, Chemistry, and Dynamics of Interplanetary Dust, Astronomical Society of the Pacific, San Francisco, CA, p. 377
Sekanina, Z., and Larson, S. M. 1984, AJ 89, 1408
Sekanina, Z., and Larson, S. M. 1986, AJ 92, 462
Weaver, H. A. 1995, Electronic report dated Dec. 15 (URL http://www.arcorp.com/Hale-Bopp.html)
Whipple, F. L. 1978, Nature 273, 134

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