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DUST MORPHOLOGY OF COMET HALE-BOPP (C/1995 O1). II. INTRODUCTION OF A WORKING MODEL

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Abstract. A Monte Carlo image simulation code for dust features in comets is applied to comet Hale-Bopp in order to model the object's persistent porcupine-like appearance on high-resolution images taken between May 11 and Nov. 2, 1996. A self-consistent fan model is proposed, with six isolated sources of dust emission assumed at various locations on the surface of the rotating nucleus and with the spin axis undergoing a complex motion in an inertial coordinate system. In the framework of this model, jet pairs represent boundaries of fan-shaped formations described by dust ejected from isolated sources during periods of time when the Sun is above the local horizon. The spin axis is found to have traveled through a field of 10° by 20° during the examined period of nearly six months. Still more successful is a fan model with large diurnal dust-emission fluctuations, which is consistent with an inertially fixed position of the spin axis and requires only three discrete sources. In this scenario, the dust-emission profile is dominated by several brief flare-ups, or "puffs", in the production of dust from one of the sources. The results are insensitive to the spin rate, but the observed dust coma appearance is more typical of a rapidly rotating comet.

Key words: comet Hale-Bopp, nucleus, active area, dust morphology, computer modelling

1. Introduction

For several months following its discovery in late July 1995, comet Hale-Bopp's appearance was characterized by a prominent, recurring dust feature, modelled by Sekanina (1996). Following conjunction with the Sun in early January 1996, the dust coma morphology changed dramatically: straight or almost straight jets constantly emanated from the nucleus in various directions, giving the object a peculiar porcupine-like appearance. The jet orientations were subjected to only slight variations during 1996. For more information on a dedicated monitoring program, the reader should consult a paper by Boehnhardt et al. (1998), hereafter referred to as Paper I.

The nearly stationary character of the jets in comet Hale-Bopp during 1996 presents an interesting problem in the light of clear evidence for a short rotation period, of ~11.3 hours, established from comprehensive imaging observations of near-nucleus features in early 1997 (Jorda et al. 1997, Sarmecanic et al. 1997). The complex system of dust jets observed during much of 1996 is investigated as a product of ejections from a single rotating nucleus. If there was an active satellite orbiting the main nucleus (Sekanina

1998a), simulation models for activity from two objects should be considered in the future. Computer processed images obtained on seven dates between May 11 and Nov. 2, 1996 are shown in the first row of Fig. 1.

2. The Fan Model

Similarly to our preliminary work on the porcupine-like appearance of comet Hale-Bopp (Sekanina and Boehnhardt 1997; also Paper I), we employ a paradigm proposed by Sekanina (1987) for comets with a fan-shaped coma. According to this *fan model*, the coma is a projected conical surface populated by dust particles ejected nonstop in a collimated fashion from a discrete source located on the sunlit side of a rotating nucleus (a circumpolar-Sun regime). Even when the production of dust is subjected to no diurnal variations, the fan's boundaries should appear sharp (jet-like) because of optical-depth effects in the case of a favorable configuration (the Earth outside the emission cone; Fig. 2, left panel). In this scenario, the model can explain only an even number of boundary jets (one pair per source), unless a source is located at the sunlit rotation pole. The spin-axis orientation coincides with the emission cone's axis, which in projection onto the plane of the sky corresponds to the apparent axis of the emission fan. Sometimes a short jet is embedded in the fan (e.g., Fig. 5 of Sekanina 1989), a signature of incipient dust ejecta from the source. Except when the orientation pattern of such an embedded jet can systematically be followed, the spin rate cannot be established from fan-shaped coma images, even though a rapidly rotating comet is more likely to display this type of morphology.

On the average, only a small fraction of the nucleus surface remains sunlit throughout rotation. An entire polar hemisphere is sunlit during whole rotation only when the spin axis points at the Sun. On the other hand, no part of the surface is permanently sunlit when the Sun is situated in the equatorial plane of the nucleus. It is thus unlikely that several randomly distributed sources should all be sunlit throughout rotation. Sources on the dark side of the nucleus will be dormant, while others will experience sunrise and sunset. When a source is active from sunrise to sunset and its dust production rate jumps up to near maximum shortly after sunrise and remains largely unchanged until sunset, the resulting emission fan may exhibit — like in the circumpolar-Sun regime — two fairly sharp boundaries, with or without an embedded jet (Fig. 2, right panel), depending in this scenario also on the Sun-Earth-comet configuration. However, when activity of a discrete source is gaining slowly in intensity after sunrise and diminishing gradually before sunset (i.e., when the production rate depends strongly on the Sun's local elevation above the horizon), the emission fan may exhibit only one sharp boundary or none at all, again depending on the geometry.

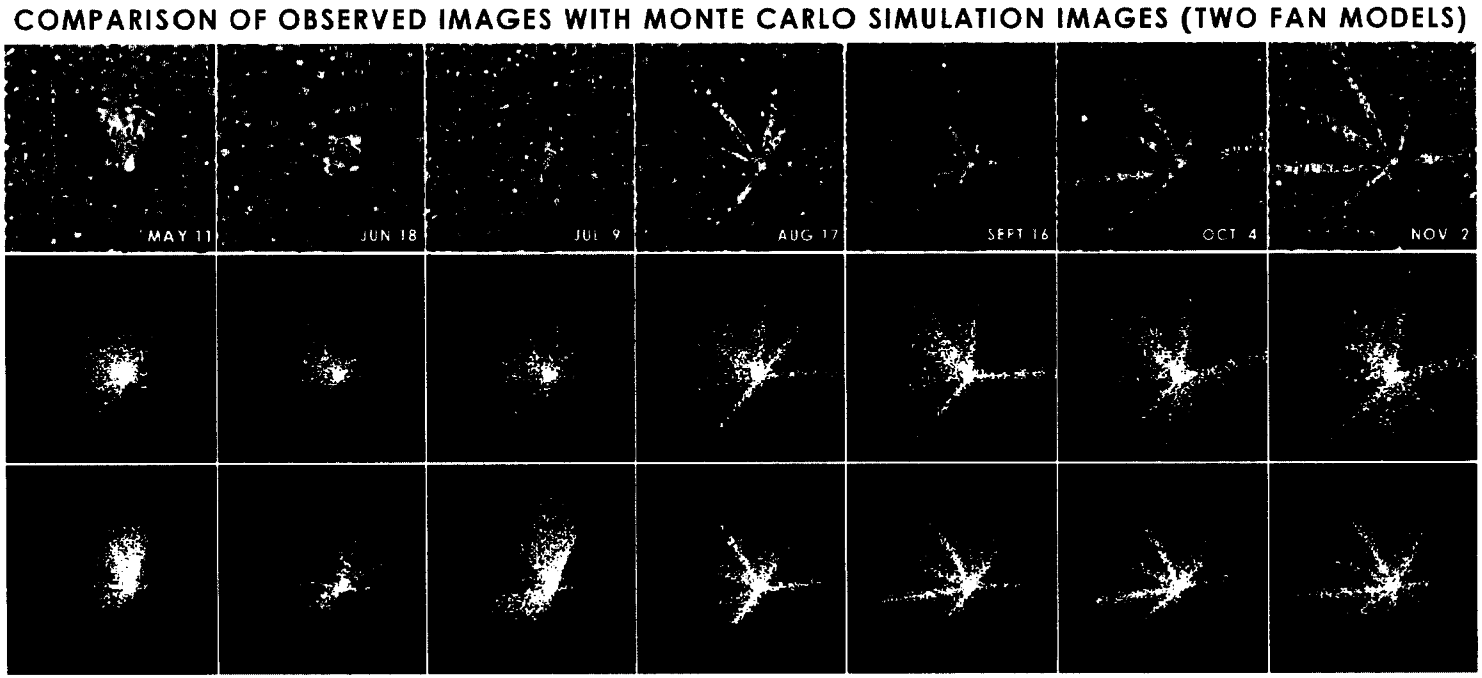
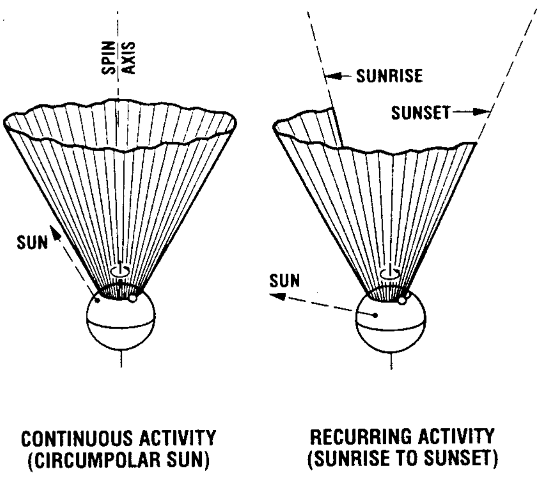


Figure 1. Observed and computer generated images of dust jets that made up the porcupine-like appearance of comet Hale-Bopp before perihelion. Each frame is 100 arcsec on a side. North is up and east to the left. *Top row*: observed images that are computer processed to enhance the jets. Each image is identified with its 1996 UTC observation date; for other relevant information, see Table I of Paper I. *Middle row*: Monte Carlo computer simulation images generated by applying the basic fan model. The jets are sharp boundaries of the ejecta's sectors or fans. The discrete sources at the latitudes of −70°, −35°, and 0° give rise to jets on all seven images; the source at +30° contributes only to the June, July, October, and November images; at +45°, to the May–September images; and at +85°, to the May–July images. *Bottom row*: Monte Carlo computer simulation images generated by applying the fan model with brief flare-ups (Fig. 4) for the source at a latitude of −20°. The sources at the latitudes of −20° and −50° give rise to jets on all seven images; the source at −80°, on the six images from May and July–November. For both models, the rotation period is taken to be 0.47 day (although the images are insensitive to it) and the peak particle ejection velocity is assumed to amount to 450 m/s on May 11 and vary inversely as a square root of heliocentric distance.



CONTINUOUS ACTIVITY (CIRCUMPOLAR SUN)

RECURRING ACTIVITY (SUNRISE TO SUNSET)

Figure 2. A schematic representation of a fan-shaped coma formed by collimated ejection of dust from an isolated source on the rotating nucleus, as viewed by a terrestrial observer. *Left*: continuous activity in a regime of the circumpolar Sun; ejecta populate a conical surface, the spin axis coincides with the cone axis and projects midway between the fan's sharp boundaries, which are due to optical-depth effects. *Right*: recurring activity from sunrise to sunset; the fan's boundaries may or may not be well defined; the spin axis usually does not coincide with the fan axis. (Adapted from Sekanina 1987.)

Refining our early model (Sekanina and Boehnhardt 1997), we allow dust from some of the sources to be ejected during only a limited period of time between sunrise and sunset (e.g., only in the afternoon). The results of our image-simulation experiments with the basic fan model are presented in the second row of Fig. 1. The dust production was assumed to proceed during five rotations prior to the time of observation. By determining, by trial and error, a great circle that represents a line of symmetry for as many jet pairs as possible, we were able to identify a projected direction of all possible loci for the spin axis that satisfy this condition for each of the images. The actual spin-axis position in each case was selected, again by trial and error, to satisfy an additional constraint: to minimize the number of sources needed. The solution represented in the second row of Fig. 1, the best we have been able to come up with but by no means the only one of its kind, involves a total of six sources, at the latitudes of, respectively, −70°, −35°, 0°, +30°, +45°, and +85°, not all of them responsible for the jets on all the seven dates. The derived motion of the northern rotation pole between May and November 1996 is plotted in Fig. 3. Although the general agreement between the observed and computer-generated images in Fig. 1 is relatively satisfactory, numerous discrepancies are apparent. In particular, we found it difficult in several instances to match the observed jet orientation pattern and to control the relative intensities of the boundary jets for some fans.

3. The Role of Brief Flare-Ups in the Production of Dust

These discrepancies, as well as the implied relatively rapid motion of the spin axis between November 1996 and February 1997 (Fig. 3) prompted us to search for scenarios with a fixed spin vector. We submit that a number of

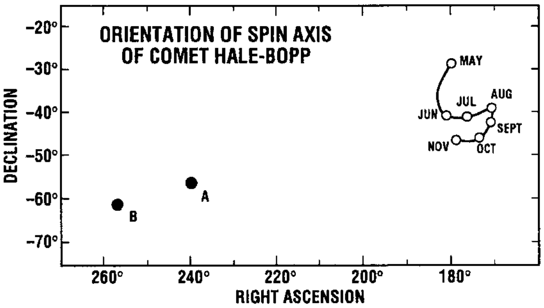


Figure 3. Motion of the nuclear spin vector of comet Hale-Bopp in the period of May–November 1996, as derived from the basic fan model, is compared with its fixed positions determined for the same period of time (A) from the fan model with flare-ups and for the end of February 1997 (B) from the diurnal evolution of a bright jet (Sekanina 1998b).

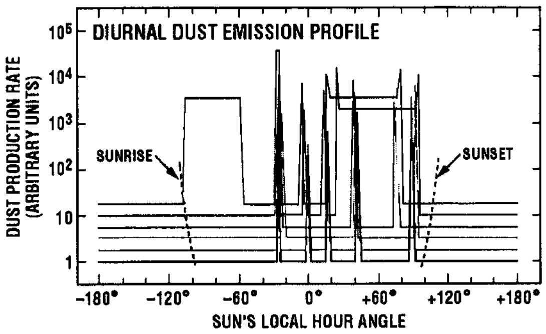


Figure 4. Diurnal dust emission profiles assumed for the source at a latitude of −20° (the fan model with flare-ups). The curves for the individual dates (all in 1996 UTC) are shifted stepwise along the axis. From top down: May 11 (orange), June 18 (blue), July 9 (brown), Aug. 17 (green), Sept. 16 (purple), Oct. 4 (red), and Nov. 2 (black).

distinct jets can be generated by dust ejecta from a single isolated source, if its diurnal activity profile is characterized by a sequence of brief flare-ups, or "puffs", during which the dust production rate increases significantly. In order to satisfy the observed nearly stationary configuration of the jets, the flare-ups should occur, rotation after rotation, at about the same position of the Sun in the sky as seen from the source. This orderly repetition could be controlled by local terrain in the active region itself.

The results of our application of the fan model with brief flare-ups are in the last row of Fig. 1. The derived spin-axis position (Fig. 3) is within 10° of the position established in a study of the diurnal evolution of a bright jet on Feb. 28, 1997 (Sekanina 1998b). For each image, activity is again assumed to proceed from sunrise to sunset for the five preceding rotations. All the jets are explained by ejecta from only three sources, at the latitudes of, respectively, −80°, −50°, and −20°. The first two sources are found to display some diurnal variations in activity, but no brief flare-ups. For the third source, the nearest to the equatorial plane, brief flare-ups are inferred to occur at specific times of the comet's day (Fig. 4). In order to match the temporal variations in jet extent, the peak ejection velocity (for submicron-sized particles) is varied with the Sun's distance r as $950\,r^{-1/2}$ m/s at $4.5 > r > 2.5$ AU before perihelion. If dust ejecta older than ∼2.5 days (five rotations) contribute detectably to the jets, this velocity is likely to be somewhat overestimated.

4. Conclusions from Our Image Simulation Experiments

Our image simulation experimentation shows that the fan model offers more than a satisfactory match to the observed porcupine-like appearance of the dust coma of comet Hale-Bopp. We find that, in details, the model's option with brief flare-ups or puffs is more successful as well as versatile. Also, it satisfies the constraint of an inertially fixed spin axis and does not require as many sources as does the basic model. However, the flare-ups must be very brief indeed. A good fit requires the FWHM duration of the puffs to be only several minutes, with intervals on the order of one hour between two successive events. Most, but not all, of the assumed puffs occurred in the afternoon local time. The propensity for puffing appears to vary strongly from source to source and the process could be controlled by local terrain. The relative prominence of the jets on unprocessed images suggests that the dust production rate during flare-ups must exceed the "quiescent" rate significantly, even though certainly not by as much as the emission profiles in Fig. 4 would indicate. Should the flare-ups be as brief as several minutes, respectably high rates are necessary in order for these events to contribute a moderate fraction of the total amount of dust in the atmosphere.

5. Acknowledgments

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References

Boehnhardt, H., Birkle, K., Colas, F., Fiedler, A., Jorda. L., Peschke, S., Rauer, H., Schulz, R., Schwehm, G., Thomas, N., Tozzi, G., and West, R. M.: 1998, this volume. (Paper I.)
Jorda, L., Lecacheux, J., and Colas, F.: 1997, IAU Circ. No. 6583.
Sarmecanic, J., Osip, D. J., Fomenkova, M., and Jones, B.: 1997, IAU Circ. No. 6600.
Sekanina, Z.: 1987, in E. J. Rolfe and B. Battrick (eds.), *Diversity and Similarity of Comets*, ESA SP-278, ESTEC, Noordwijk, pp. 315–322.
Sekanina, Z.: 1989, Astron. J. 98, 2322–2345, 2377–2382.
Sekanina, Z.: 1996, Astron. Astrophys. 314, 957–965.
Sekanina, Z.: 1998a, this volume; also: JPL Cometary Science Team Preprint Series No. 173.
Sekanina, Z.: 1998b, Astrophys. J. 494, L121–L124.
Sekanina, Z., and Boehnhardt, H.: 1997, IAU Circ. No. 6542.

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