DUST MORPHOLOGY OF COMET HALE–BOPP (C/1995 O1): I. PRE-PERIHELION COMA STRUCTURES IN 1996*

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Abstract. In 1996 comet Hale–Bopp exhibited a porcupine-like coma with straight jets of dust emission from several active regions on the nucleus. The multi-jet coma geometry developed during the first half of 1996. While the jet orientation remained almost constant over months, the relative intensity of the jets changed with time. By using the embedded fan model of Sekanina and Boehnhardt (1997a) the jet pattern of comet Hale–Bopp in 1996 can be interpreted as boundaries of dust emission cones (fans) from four – possibly five – active regions on the nucleus (for a numerical modelling see part II of the paper by Sekanina and Boehnhardt, 1997b).

Keywords: Hale–Bopp, dust coma, jets, fans

1. Introduction

From its discovery until perihelion comet C/1995 O1 Hale–Bopp had a well developed coma of sometimes stable, sometimes rapidly varying morphology. A description of the fan-shaped coma in 1995 is given by Kidger et al. (1996) (see Sekanina, 1996, for a first modelling of this phenomenon), the evolving jet and shell structures around perihelion passage are nicely seen in many published pictures (see also these conference proceedings). Here, we present an analysis of the persistent coma structures observed from April until November 1996. The results are interpreted in the framework of the embedded fan model (Sekanina and Boehnhardt, 1997a, b). This model assumes that the jets are produced by active regions on a rotating nucleus.

* Based on observations collected at the European Southern Observatory in La Silla/Chile.

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TABLE I
Observing geometry and equipment for C/1995 O1 Hale–Bopp at ESO La Silla

Date	Sun dist. / Earth dist. (AU)	Phase / Elongation (deg)	Telescope / Instrument	CCD size (pix × pix) / Pixel size (arcsec/pix)	Observers
25/4/96	4.61	12	Danish 1.5 m	2k × 2k	Boehnhardt,
	4.33	98	DFOSC	0.41	Rauer
11/5/96	4.45	12	2.2 mMPG/ESO	1k × 1k	West
	3.91	116	EFOSC2	0.32	
18/6/96	4.06	5	Danish 1.5 m	2k × 2k	Jorda,
	3.10	158	DFOSC	0.41	Schwehm
9/7/96	3.83	4	2.2 mMPG/ESO	1k × 1k	Peschke
	2.84	167	EFOSC2	0.32	
19/8/96	3.38	15	Danish 1.5 m	2k × 2k	Boehnhardt,
	2.76	120	DFOSC	0.41	Rauer, Thomas
16/9/96	3.06	19	2.2 mMPG/ESO	2k × 2k	Schulz, Tozzi
	2.31	89	EFOSC2	0.27	
4/10/96	2.85	19	Danish 1.5 m	2k × 2k	Rauer
	3.00	78	DFOSC	0.41	
2/11/96	2.50	17	Danish 1.5 m	2k × 2k	Boehnhardt
	3.05	48	DFOSC	0.41	

2. Observations and Basic Data Reduction

The observations of the comet were performed at the European Southern Observatory (ESO) in La Silla/Chile. The input data for our analysis are selected Bessel BVR filter exposures from our image collection of the comet obtained between late April and early November 1996 (pre-perihelion). A summary of the observing geometry and equipment is given in Table I. The images were bias subtracted and flatfielded.

3. Coma Structure Analysis

For the enhancement of coma structures we applied a Laplacian adaptive filter technique in a very similar way as described in Boehnhardt and Birkle (1994) and references therein. Selection criteria for the images were a high signal-to-noise (over 70–100) in the inner coma region of the comet and the avoidance of star-rich background fields with bright objects. A Laplace filter width of 15 or 23 pixels

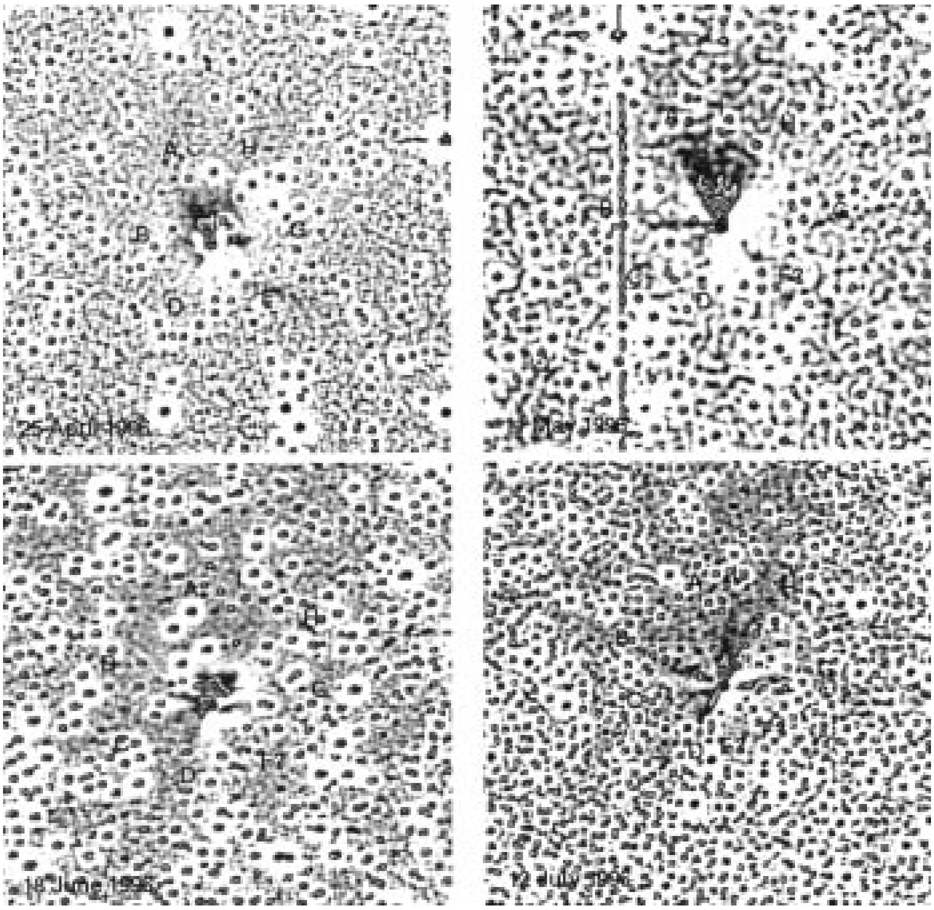

Figure 1. The development of the dust coma structures in comet Hale–Bopp: April to July 1996. North is up and East to the left. The field of view is 210 × 210 arcsec in April and June, 165 × 165 arcsec in May and July 1996. Vertical streaks in the images are due to bad CCD columns or charge overflow from bright stars in the field of view.

was found to be most appropriate for the enhancement of the detailed inner coma structure of comet Hale–Bopp (background stars remained unmasked). Figures 1 and 2 show Laplace filter enhanced images of the inner coma region.

3.1. The pre-perihelion coma structures in 1996

From late April to early July 1996 the coma was dominated by a bright and broad northward fan structure. Some fainter mostly narrow and straight jet features, partially overlapping with a diffuse fan-like background, are found in the South-East and South-West coma quadrants. During August to early November 1996 a very pronounced jet pattern developed in the coma of the comet while the northern fan resolved into a single jet around position angle (counted north over east) PA = 20–

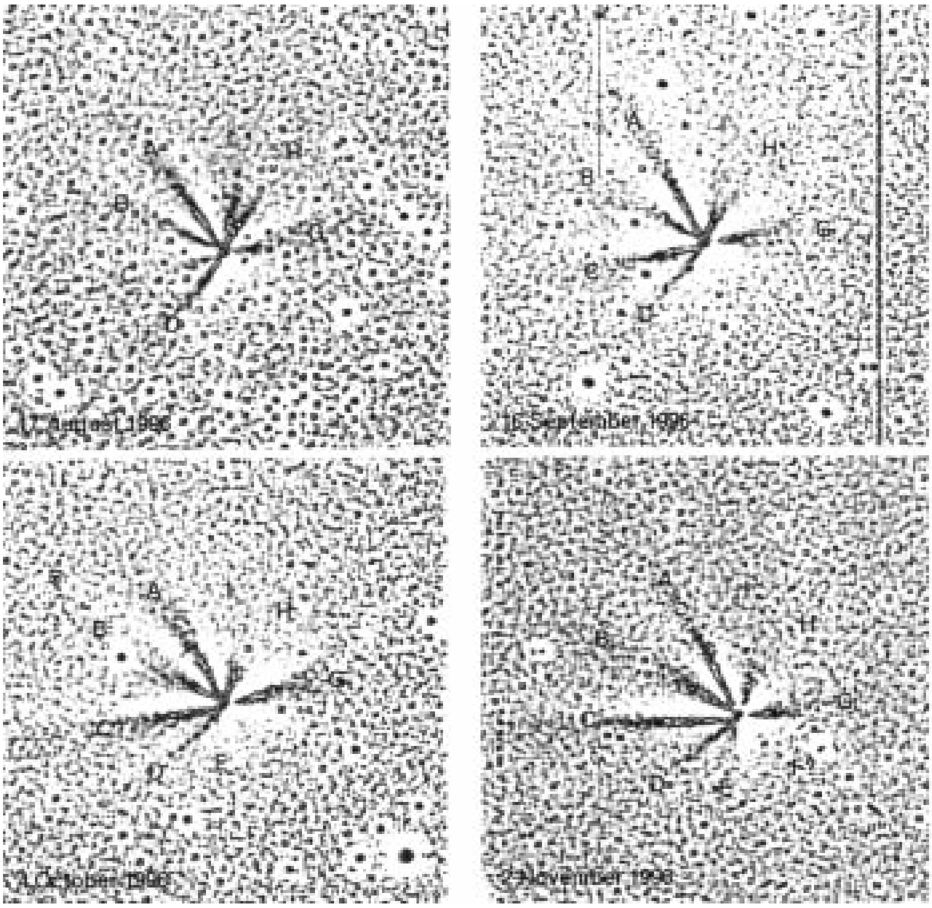

Figure 2. The development of the dust coma structures in comet Hale–Bopp: August to November 1996, North is up and East to the left. The field of view is 210 × 210 arcsec in August, October and November, 140 × 140 arcsec in September 1996. Vertical streaks in the images are due to bad CCD columns or charge overflow from bright stars in the field of view.

30 deg and a double jet around PA = 330–350 deg. The overall characteristics of the various coma patterns jets, and fans) are: the geometry and relative intensity were very similar in all three filters (BVR), the jet orientations were stable on a short time-scale (i.e., some days to one week), but varied slowly with time (i.e., within one month) in their intrinsic structure and relative brightness, in particular from August to November 1996. In total nine coma features (jets and fans) could be identified. They are numbered by capital letters (A-I) with increasing PA (examples are given in Figures 1 and 2). Table II lists the measured near-nucleus position angles of the fan and jet structures as identified in the images of the various observing runs.

From the similarity of the detected features in the BVR filter band-passes we conclude that dust reflected sunlight dominates the coma signal in our images

TABLE II

Near-nucleus position angles of coma structures in C/1995 O1 Hale–Bopp

Date	A	B	C	D	E	F	G	H	I
25/4/96	−31	84	??	−146	??	225	278	339	–
11/5/96	−30	86	107−	150	??	230?	275	337−	–
18/6/96	−19	75	106−	−153	??	215?	270	297−	−349−
9/7/96	−25	69	98−	−150	164?	224?	272	336−	−356−
19/8/96	35	68	110	147	??	??	274	328−	−355
16/9/96	28	59	103	145	??	??	274	326−	−345
4/10/96	26	59	100	135	164	??	283	333−	−350
2/11/96	26	58	95	135	165	225?	276	330−	−353

The jet/fan structures are indicated by letters A to I (see Figures 1 and 2). For the straight and narrow jets the PA of the jet axis is measured. Fans are indicated by the PAs of the sector boundaries (for instance, 98− for a fan with a boundary angle of 98 deg and extending towards increasing PA, −98 for one with the same boundary angle, but extending towards decreasing PA). A single question mark denotes a marginal detection of a coma structure, a double question mark indicates the non-detection of the respective coma feature. The measuring accuracy for narrow jets is ±2 deg, for fainter and broader fans it is ±5 deg.

and the contamination from gas molecule emission is rather low. Therefore, the identified jet and fan patterns indicate the dust distribution in the coma and, hence, trace the activity of individual active regions on the nucleus. With the exception of the E and F sources all other emission regions were active during our whole observing interval, although on a different level.

From the perihelion period it is known that the nucleus of comet Hale–Bopp rotates with a period of 11.3 hours (for instance Licandro et al., 1998; Jewitt, 1997, and references therein). In our data such a fast rotation is not reflected by rapidly varying coma structures as one could expect for an almost top-on view of the nucleus rotation axis from Earth. A more consistent interpretation of the observed coma pattern is possible following the conceptual approach of Sekanina and Boehnhardt (1997a), i.e., assuming a more side-on viewing geometry of the nucleus rotation. For the observer on Earth the three-dimensional emission cones from the active regions (at different latitudes) on the nucleus (Sekanina, 1987) appear – due to projection – as coma fans with – in some cases – sharp boundary lines which can resemble straight jet features. The interior of the fan sectors can be rather diffuse depending on the emission profile during the rotation and depending on the viewing geometry. Ideally, each fan is represented by one pair of boundary lines, i.e. two straight jets. For the nine jet and fan structures identified in the coma of comet Hale–Bopp during April to November 1996 five active regions can be assumed (based upon the simple embedded fan model). In many cases the fan axis – or in other words the PA of the bisector line between a corresponding pair of jets from the same emission cone – is close to the PA of the rotation axis of the nucleus projected onto the sky (Sekanina, 1987). Hence, the PAs of the axes from different coma fans produced by active regions at different latitudes on the nucleus should be very similar.

If this interpretation is correct, the jet pattern in the coma of comet Hale–Bopp should exhibit a (widely) symmetric appearance in the PAs of the structures as well as in the PA differences between jets seen in both coma hemispheres intersected by the projected rotation axis of the nucleus (however, diurnal effects in the dust production may cause "incomplete" emission cones and thus their fan projection may become asymmetric with reference to the projected rotation axis). Table III lists the differences in the PAs between corresponding, but opposite coma jets together with the calculated PA of the fan axis of the respective jet pair. On the background of the fan scenario outlined above it is evident that jet pairs A and B, C and I, D and H, and G and E could be the boundaries of 4 individual coma fans, i.e., each pair is produced by the same active region on the nucleus. The fifth active region is responsible for coma structure F which is only marginally seen during certain observing periods and which extends essentially along the south-west direction of the projected rotation axis of the nucleus, i.e. it could be near-polar. In summary: our 1996 observations of the dust coma structures in comet Hale–Bopp can – at least qualitatively – be understood by a fan-shaped coma model with five active regions at polar distance of 15–25 (A + B), 50–60 (C + I), 85–95 (D + H), 115–125 (G + E), and about 180 deg (F) on the nucleus (since from the images we cannot conclude on the rotation sense of the nucleus, the actual latitudes of the regions on the nucleus can either be those listed above or 180 deg minus the listed values). The position angle of the projected rotation axis varied with time between PA = 40–60 deg on the sky.

Although the PA measurements of the jets and fans are in general agreement with our model scenario of embedded fans, some peculiarities are to be notified. The non-detection of jet E during certain time intervals while its boundary counterpart (G) is easily seen in the images can at least qualitatively be understood by illumination effects of the underlying active region on the nucleus, i.e., the G side of the fan was in sunlight while the E side was not. A similar explanation may also apply to the marginally detected F structure. Furthermore, a slight asymmetry in the PAs of jets D and H with reference to the assumed projected rotation axis is occasionally observed. This could also be due to illumination effects. A very special case is the northward coma fan observed between April and July 1996 (PA = 330 − 30 deg). While this fan is widely unresolved between the sector boundaries A to H during the two earlier observing periods, a weak jet-like substructure is found around PA = 350 deg in June and July 1996. This particular feature falls very close to the direction of the isolated jet I seen in this PA range from August to November 1996. Hence, the embedded fan model for comet Hale–Bopp would allow the interpretation of the northward coma fan as actually being due to three overlapping emission cone boundaries each of which caused by a separate active

TABLE III

PA differences of correlated jet pairs and the PA of the projected rotation axis

Date	A-I (deg)	B-C (deg)	A-H (deg)	B-D (deg)	A-G (deg)	B-E (deg)
25/4/96	–	–	52	62	113	–
11/5/96	–	22	57	64	115	–
18/6/96	30	31	82	78	109	–
9/7/96	29	29	49	81	113	95
19/8/96	40	42	67	79	121	–
16/9/96	43	44	62	86	114	–
4/10/96	36	41	63	76	103	105
2/11/96	33	37	56	77	110	107

Date	(A + B)/2 (deg)	(C + I)/2 (deg)	(D + H)/2 (deg)	(G + E)/2 (deg)
25/4/96	58	–	63	–
11/5/96	58	–	64	–
18/6/96	47	48	45	–
9/7/96	47	47	63	38
19/8/96	52	53	58	–
16/9/96	44	44	55	–
4/10/96	43	45	54	44
2/11/96	42	44	53	41

Each columns A-I to B-E list the PA differences between the indicated jets/fans (see Figures 1 and 2). The PA differences for two active regions represented by their corresponding jet pairs are very similar (for instance A-I and B-C). Columns (A + B)/2 to (G + E)/2 show the calculated PA of the fan axis of a pair of jets from a single active region on the nucleus. Each column A-I to B-E lists the PA differences between the indicated jets. The PA differences for two active regions represented by their corresponding jet pairs are very similar (for instance A-I and B-C).

region (i.e., those at polar distances of 15–25, 50–60 and 85–95 deg). At the same time, a very diffuse and weakly enhanced brightness sector is present in the PA range between C and D, i.e., in the opposite direction to the northward coma fan.

4. Concluding Remarks

Our results on the 1996 jet and fan structures in comet Hale–Bopp are in qualitative good agreement with the hypothesis of several embedded coma fans as proposed and described by Sekanina and Boehnhardt (1997a, b). A North-West to South-

East orientation of the projected rotation axis would match the observed jet/fan pattern assuming active regions on the nucleus at polar distances around 20, 55, 90, 120 and 180 deg ($\pm$5 deg). This scenario also allows a new interpretation for the prominent northward coma fan observed in the comet during the second quarter of 1996 (boundaries from 3 overlapping emission cones). On the background of this interpretation one could also speculate on a similar nature of the northward coma fan seen in the second half of 1995 (Kidger et al., 1996). Alternatively, a precession motion of the rotation axis between 1995 and 1996 may be required to explain the similarity of the northern coma fans in both periods.

Our observations demonstrate that the fan/jet pattern in the dust coma of comet Hale–Bopp did not change much in its geometry during 1996. However, the relative strength of the coma structures varied considerably from April to November 1996 (although no short-term – of the order of hours to a few days – variability is found). The weak jet/fan structures in the first half of our observing period were followed by a very pronounced jet pattern starting in August 1996. The turnover period between both situations lasted most likely from mid June to the end of July 1996.

Based upon similar image material for the 1996 coma jets, different conclusions on the projected rotation axis and the location of active regions on the nucleus are published (Licandro et al., 1997–1999; Samarasinha et al., 1997–1999; Vasundhara et al., 1997). The underlying scenario of these interpretations of the porcupine jet pattern in Hale–Bopp is the (embedded) fan model (Sekanina, 1986; Sekanina and Boehnhardt, 1997a, b). However, the above mentioned authors concentrate on the analysis of selected isolated coma structures without giving a full explanation of the complete jet pattern observed. At present, convergence of the numerical results of the various analysis is not yet achieved.

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