COMET HALE–BOPP SHELLS EXPANSION: A CCD STUDY

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Abstract. Using a CCD camera attached to the 0.335 m and 0.20 m reflectors of S.A.S. Observatory (Novara, Italy), we followed the linear jets and shells of comet Hale–Bopp between May 1996 and May 1997. In addition to confirming the model of Sekanina and Bohenhardt (1997), the study of the linear jets provided indications concerning the orientation of the comet's axis of rotation over time. The study of the shells revealed that the speed at which they move away from the nucleus was not constant. A periodic variation of the shell expansion velocity may not be excluded : if so, a possible precessional effect on the axis of rotation of the comet's nucleus could explain this behavior.

Keywords: Comet Hale–Bopp, jets, precession, rotation axis, shells

1. Introduction

The discovery of comet Hale–Bopp a long time before its passage at perihelion, the extremely favorable observing conditions and the remarkable size of the nucleus made it possible to perform a detailed study of several phenomena that have rarely been observed on other great comets in the past.

We extended our observations for more than one year. So, the availability of a large number and continuous series of observations allowed us to analyze the coma phenomena neighbourhood of the nucleus. It was thus possible to make some important observations concerning the nature and evolution of the two most evident morphological features of the comet: the porcupine jet pattern and dust shells in the coma.

2. Methods

We observed the inner coma of comet Hale–Bopp for a total of 35 nights between May 1996 and May 1997 using CCD cameras (equipped with Kodak KAF-0400 and Thomson TH-6853 CCD chips) attached to the 0.335 m (f/4.8) and 0.20 m (f/10) reflectors of the Stazione Astronomica di Sozzago (S.A.S. Observatory, near Novara, Italy).

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All of the images except those on 9 September 1996 (which were taken through a IR filter open from 0.85 to 1.5μ) were obtained without filter. Images taken through various Schott filters (BG12 centered at 0.405μ, BG18 centered at 0.54μ, KG3 centered at 0.5μ) during some of the nights of observation did not show differences in the comet's structures in comparison with those taken without filters. Since we only analyzed the separation between the shells and the shape of the jets, the white-light images resulted adequate for our purposes.

Until January 1997, we studied the jets originating from the nucleus with exposures of 30 seconds; ten images (twenty on 9 September) were taken during each night of observation and then co-added after suitable normalization (that's each picture being before darkened and flattened). In order to increase the contrast between the jets and the coma, the co-added images were processed by means of the radial and rotational shift algorithm of Larson and Sekanina (1984).

From 8 February to 13 April 1997, we monitored, by our CCD images, also the coma shells around the nucleus. Our images taken during March 1997 were also investigated by radial masking techniques (Schwarz, 1997)

During each of 10 nights in this period, with very favorable weather conditions, we took about 50 CCD images over continuous periods lasting some hours: the time interval between the first and the last image of each series progressively increased from about one to almost three hours.

Each image (4-second exposure) was then processed using either the Larson–Sekanina (Larson and Sekanina, 1984) or an ellipsoid modelling algorithm (Buil, 1995).

A comparison was made of the position of the brightest area of the innermost shell at the beginning and end of each daily observing session with the aim of calculating their linear separation and REAL speed of radial expansion. The brightest point of the innermost shell, easily determined from a photometrical light-curve created by the computer, was normally confined into a single pixel (computer may be asked for a table of brightness of each pixel along the line of the photometrical measurement). So the accuracy of the measurements was in the order of a fraction of a pixel, with a maximum error of ±0.5 pixels.

To obtain the REAL speed of radial expansion, the measurement was normally made along the major axis of the shell system

3. Observational Data: Porcupine Jets

Between 21 May and 26 June 1996, three jets were observed; between 25 July and 16 August, this number increased to six and, from the middle of November, it stabilized at eight jets, whose surface brightness was comparable with that of the anti-solar tail. Sekanina and Boehnhardt (1997) have hypothesized an axis of symmetry that may be explained by the presence of active zones located at different latitudes on the nucleus: the material emitted into space forms cones as a result of nuclear rotation. When seen projected on the plane of the sky, the cones appear to be denser at their edges because of the bi-dimensional perspective. The term “porcupine jets” for these most easily observed peripheral areas, first introduced by us (Manzini et al., 1996), was then accepted by all people.

The possible link between jets and active zones of the nucleus is demonstrated by the explosive phenomena that were observed at their bases. We followed the evolution of one of the most important bursts of this type. On 9 September 1996, we observed a marked increase in the brightness and size of the false nucleus of the comet, making it appear about three times larger than on the previous days; on 11 September, there was a luminous spot at the base of the jet in position angle 310° that progressively moved away from the nuclear region and, over the following days, gave the impression that the jet itself was becoming detached.

Ten images taken under identical instrumental conditions on each of the nights of 9, 11, 13 and 14 September 1996 were co-added, leading to four final images. Two images representing the change in the coma structure in between the observing dates, were then produced by dividing the image of 9 September by that of 11 September, and the image of 11 September by those of 13 September, after they had been corrected. for the differences in the distance of the comet and phase angle variations. These showed that, in the immediate vicinity of the nuclear region, the burst had led to the ample expulsion of a bow-like shaped material that moved across the coma and was subsequently dispersed (Figure 1). A similar result was obtained on images taken at ESO between 10 and 16 September 1996 (Schulz, 1997).

The helical emission stopped before at least one complete spiral had been produced. However, from the same images, we were able to establish that the real speed of radial expansion of the emitted material (measured along the major axis of the shell) was about 0.35 km/s and that the probable source was located near to the equatorial region of the nucleus.

The speed of expansion remained quite constant during the days of our observation: it can be hypothesized that the burst detached a fragment of the surface crust (in our images the possible detachment of the linear jet located at P.A. = 310° is visible!) and that this led to the leakage of the fresh material underlying it. With the comet at 3.15 A.U. from the Sun, and given its very low nuclear temperature (about 160° K in the presence of an albedo of 0.04) (Klinger, 1981; Wipple, 1987) the emission could not have been very abundant, which may explain the fact that it was exhausted before a complete spiral structure was produced.

4. Observational Data: Orientation of the Comet’s Axis of Rotation

A significant image for our purposes was acquired on 17 January 1997, with the comet at $r = 1.56$ A.U. and $\Delta = 2.30$ A.U., because both the position and intensity of the jets were favorable for calculating the direction of the axis of rotation (Fig-

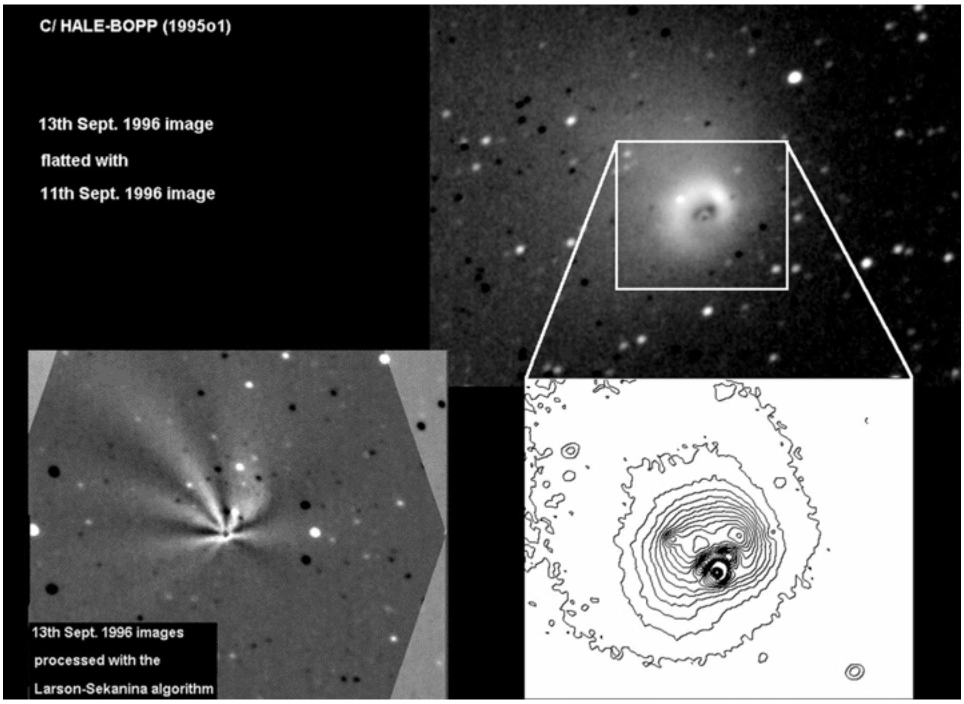

Figure 1. CCD images taken from 11 to 14 September 1996 show the possible detachment of the linear jet located at P.A. 310° when elaborated with a Larson–Sekanina algorithm (left), and the presence of a helical-shaped structure when "flattened" to obtain an auto-differential image.

ure 2). On January 15 and 18 other our images showed a similar aspect of the inner coma but the images acquired on January 17 are preferred because of excellent seeing conditions (typical of the Po plain in the Northern Italy near Novara, during the winter). In particular, the most luminous jet showed a symmetrical counterpart of a similar length and intensity, positioned exactly on its extension through the false nucleus. This morphology was suggestive of an emission perpendicular to the equatorial region of the comet's nucleus, whose axis of rotation could be seen almost exactly projected on the plane of the sky.

Pictures taken during the following weeks showed that the axis of rotation, which was located on the plane of the sky on 17 January 1997, gradually inclined towards the Earth until, by the end of March 1997, it was in an almost radial position. From then on, it started to become inclined in the opposite direction until it was once again projected on the plane of the sky by about the middle of May 1997.

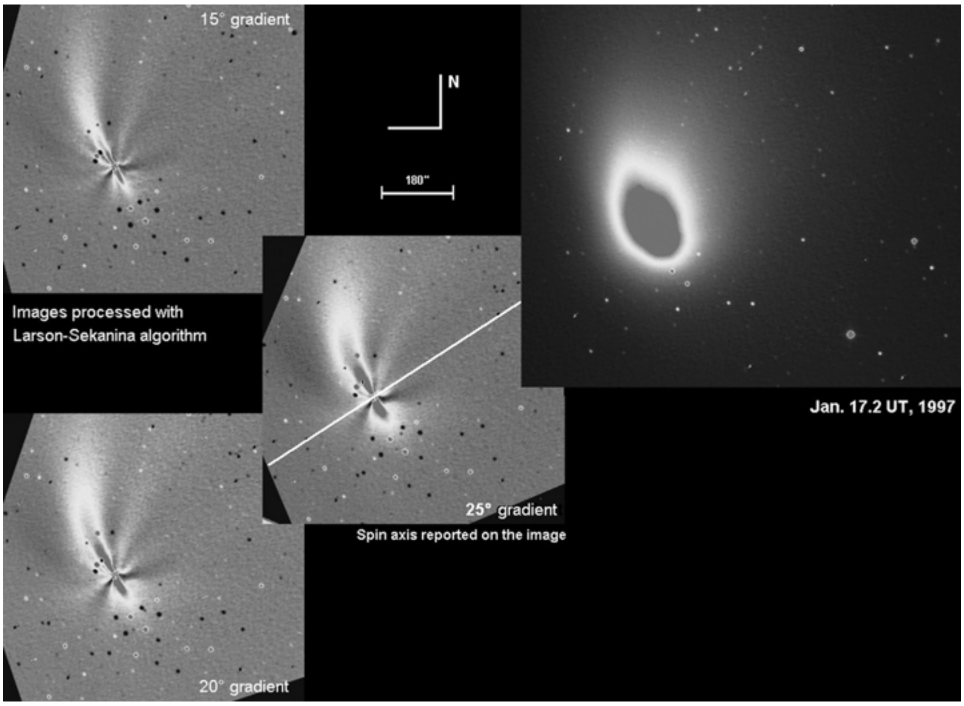

Figure 2. 17 January 1997: the most luminous jet had a symmetrical counterpart of similar length and brightness; the comet's axis of rotation was probably perpendicular to this jet at that time.

5. Observational Data: Shells

The images between 8 and 22 February 1997 confirmed the existence of a shell system around the nucleus of comet Hale–Bopp that had been vaguely visible in our images since the beginning of the month (Figure 3). In our opinion, the visibility of the shell system was due to the progressive shifting of the direction of the comet rotation axis toward the Earth.

The images taken on these days gave the impression of shell systems with separated geometrical centers, whereas the study of the geometric conditions of the observation performed with a simulation program made it clear that the shells originated from a single nucleus at different latitudes.

The shells visible in our CCD images of March 1997, when the observation conditions were very good, can be interpreted as the result of an apparently continuous spiral-shaped structure (Figure 4a) produced by a jet visible in our images of 17 January 1997: The same jet observed at Haute Provence Observatory proved to be located at equatorial latitude. This shell system appeared to predominate over all of the other emissions.

The rotation of the nucleus led to the formation of a continuous multiple-loop spiral-shaped structure that we were able to observe easily in March and the first

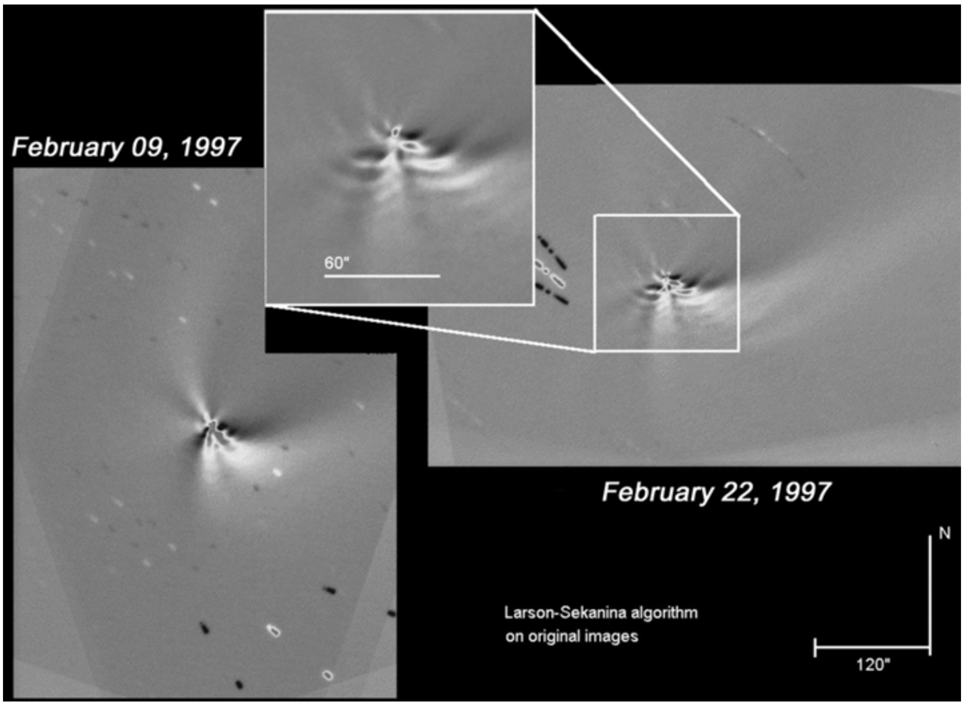

Figure 3. February 1997: Many shell systems with apparently different geometrical centers were visible.

weeks of April thanks to the favorable geometry of the position of the comet, whose axis was turned towards the Earth.

The higher number of shells was visible on 31 March, even if asymmetries in the south-west quadrant suggested the presence of at least two separate sources of material (Figure 4b).

On ten different dates between February 9th and April 13th, we measured (along the major axis) the speed of dilatation of the individual shells on our images, and found that it did not seem to be constant: the values ranged from 0.4 km/s to 1.4 km/s (see Table I). All of the measurements were based on observation periods ranging from 75 to 160 minutes. We also investigate the possibility that the shell expansion velocity may have a periodic nature. We have summarized all details of all our observations in Table II.

On 22 February 1997, we could take images for only 14 minutes because of a sudden occurrence of fog over the observatory but despite this, we were able to deduce a low speed of expansion by comparing our images with those obtained 60 minutes later with the 0.50 m telescope at Cavezzo Observatory (Facchini and Nicolini, 1997). After calibrating (to take in account the different focal length of the Cavezzo reflector) all of the available images, we could deduce (along the major axis of the principal shell system) a real shell expansion velocity of less than

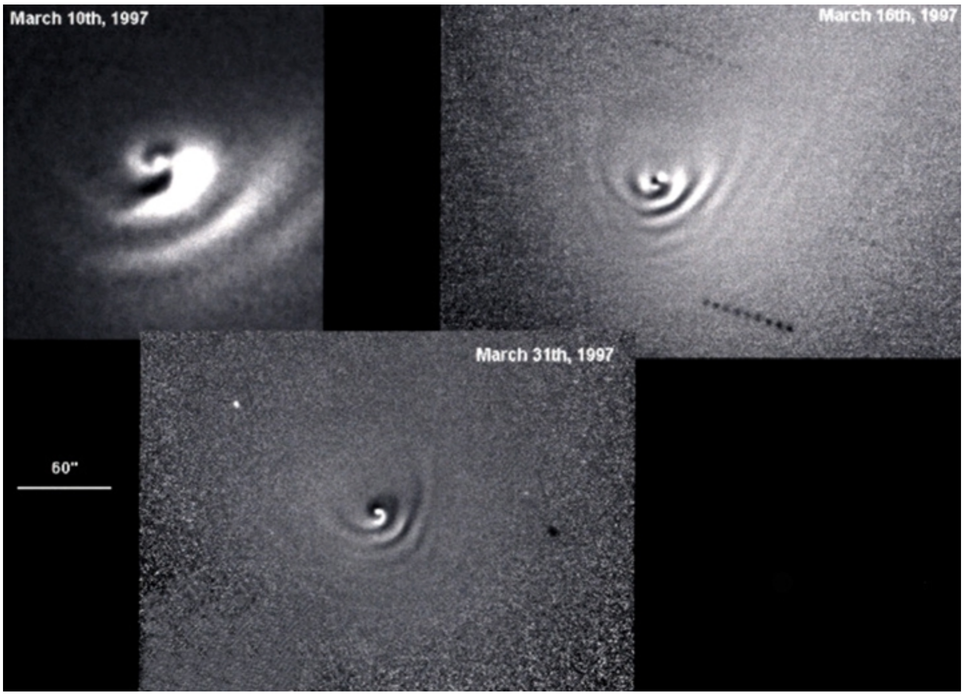

Figure 4a. CCD images clearly show the helical shape of the shell system during March 1997.

TABLE I

Hale–Bopp shell expansion

Date (1997)	Time interval (U.T.)	CCD frames (number)	Resolution (km/pixel)	Expansion speed (m/s)
9 February	4:12– 5:27	39	1260	1200
22 February	4:40– 5:54	20	1060	400
1 March	4:00– 5:15	36	1015	1100
3 March	2:59– 4:21	26	990	1050
8 March	3:40– 5:05	30	950	1405
10 March	2:53– 5:05	54	940	905
16 March	2:09– 4:50	62	905	620
27 March	19:08–20:54	28	900	900
31 March	19:40–21:20	40	910	1200
13 April	20:02–21:47	44	2735	1165

March/April maximum error = 10%.
February maximum error = 15%.

TABLE II
Hale–Bopp observations from S.A.S. Observatory

Date	Medium U.T. time	*R* (A.U.)	Delta (A.U.)	Instrument diameter (mm)	Resolution	
					Arcsec/pix	Km/pixel
21/05/96	01	4.35	3.67	335	2.25	6150
28/05/96	02	4.28	3.51	335	2.28	5880
07/06/96	23	4.18	3.30	335	2.41	5850
24/07/96	21	3.67	2.75	335	2.41	4870
30/07/96	22	3.61	2.74	335	2.41	4850
31/07/96	21	3.60	2.73	335	2.41	4840
04/08/96	21	3.55	2.74	335	2.41	4850
09/08/96	20.5	3.50	2.74	335	2.41	4850
16/08/96	20.5	3.42	2.76	335	2.28	4625
30/08/96	20.5	3.26	2.81	335	2.28	4710
04/09/96	22	3.20	2.84	335	2.28	4760
09/09/96	21.5	3.15	2.87	335	2.28	4810
11/09/96	22	3.12	2.88	335	2.28	4830
13/09/96	21.5	3.10	2.89	335	2.28	4840
14/09/96	21	3.09	2.90	335	1.14	2430
15/09/96	22	3.08	2.90	180/1600	01.53	3260
23/11/96	18	2.25	2.98	335	1.14	2490
24/11/96	17.5	2.23	2.98	335	1.14	2490
17/01/97	05	1.56	2.30	335	01.53	2590
08/02/97	05	1.29	1.88	152	2.48	3426
09/02/97	05	1.28	1.86	203	0.92	1260
17/02/97	05	1.19	1.70	152	2.48	3098
22/02/97	05	1.14	1.61	203	0.92	1260
01/03/97	04	1.07	1.50	203	0.92	1015
03/03/97	03	1.05	1.47	203	0.92	990
08/03/97	04.5	1.01	1.41	203	0.92	950
10/03/97	03.5	1.00	1.39	203	0.92	940
16/03/97	04.5	0.96	1.34	203	0.92	905
27/03/97	19.5	0.92	1.33	203	0.92	900
30/03/97	20	0.92	1.34	152	4.96	4490
31/03/93	20	0.92	1.35	203	0.92	910
13/04/97	20	0.94	1.50	152	4.96	5030
14/03/97	20	0.94	1.50	152	4.96	5030
01/05/97	20	1.06	1.77	203	0.92	1195

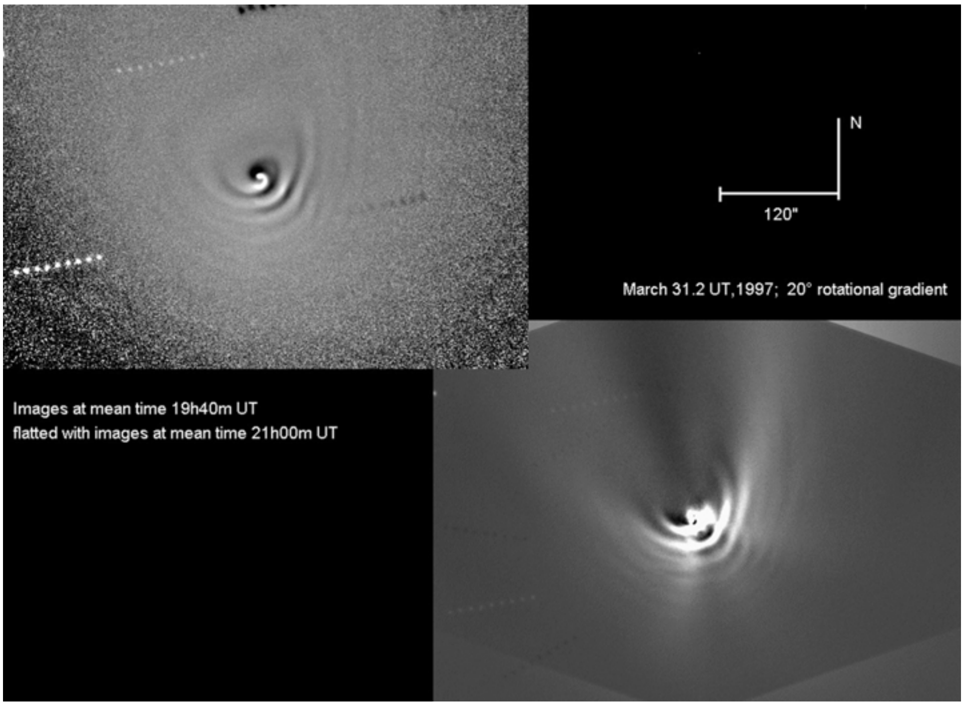

Figure 4b. 31 March 1997: At least 6 spiral shaped structures are visible in this image. The contribution of two separate sources is plausible.

0.5 km/s, in good agreement with a value of about 0.4 km/s obtained by Lecacheux et al. (1997) from images taken over a period of 157 minutes with the 1.05 m reflector at Pic du Midi.

A second lowest value of the shell expansion velocity was obtained on 16 March 1997: we could observe the comet for 163 minutes with very favorable weather conditions and were able to perform very accurate measurements of the speed of expansion, which proved to be as little as 0.6 km/s.

Given the fact that we had only 10 measurements separated by large time intervals, our search for a possible periodicity in shell emission speed involved the use of statistical techniques that is able to manage a small number of data: with the collaboration of Adriano Gaspani of the Brera-Merate Observatory, we applied artificial neuronal networks and even some techniques based on evolutionary calculus and genetic algorithms (Masters, 1994).

As Figure 5 shows, the application of a genetic algorithm reveals two possible periodicities: P1 = 19.2 ± 0.3 days and P2 = 21.9 ± 0.2 days. However, since the gaps separating our data give rise to a spurious period of 4.3956 days whose alias P × 5 equals precisely 21.978 days, the P2 value is the least acceptable. As the period of 19.2 days is not affected by this problem, the results of this analysis

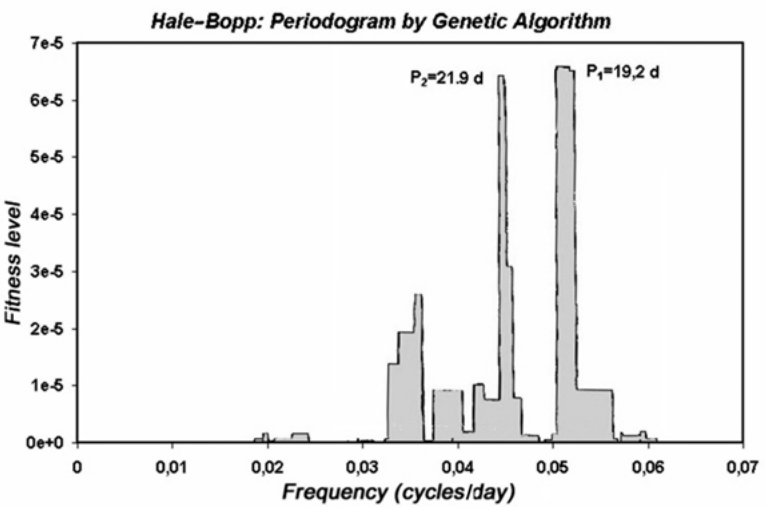

Figure 5. Expansion velocity reveals an alternative between two periodicities of 19.2 and 21.9 days.

suggest that a periodicity in shell expansion velocity of slightly less than 20 days is not an unreasonable estimate.

The significance of this kind of statistical approach is always over 99% (Maren, 1990) Based on the hypotesis that this periodicity is sinusoidal, we attempted to fit it to our available data. The results show that the data fit a sinusoid quite well: the speed of 0.4 km/s measured on 22 February and that of 0.600 km/s measured on 16 March correspond to the lowest points of the curve itself (Figure 6).

A neuronal network interpolation confirms that a periodicity exists, but that it is probably more complex than a pure sinusoid.

6. Discussion

Our observations clearly demonstrate that the comet's axis of rotation progressively moved, something that we initially thought was exclusively due to changes in the geometric conditions.

A variation of 60° in P.A. of the comet's axis of rotation had already been identified by Sekanina (1996) following the observations of some bursts in August and October 1996 that came from the same active region of the nucleus. The author claimed that this demonstrated the presence of an axis of rotation not fixed in the space.

The hypothesis of a gradual shift in the direction of the axis of rotation to a radial position in the months of March and April 1997 is supported by the measurements made by the group of Jorda at Pic du Midi (Jorda et al., 1997), who observed a

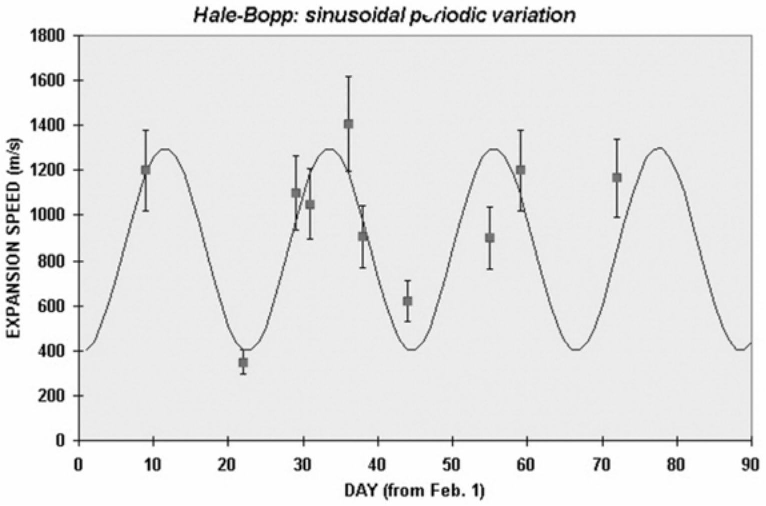

Figure 6. The variation of the shell expansion velocity measured between March and April 1997 fits quite well with a sinusoidal periodicity of slightly less than 20 days.

clockwise rotation of the nucleus until the end of February and an anti-clockwise rotation in March.

Mannucci and Tozzi came to the same conclusion using the Tirgo infra-red telescope between 3 and 10 February 1997 (Mannucci and Tozzi, 1997).

Our data concerning the speed of dilatation of the shells are also in agreement with those of other authors. Using the La Palma J.K.T. 1.0 m telescope in August 1996, Williams (Williams, 1997) observed clouds that moved away from the nucleus at a speed of 0.250 km/s; our measurements made a few weeks later, show that the speed of dilatation of the pseudo-shell produced by the burst of 9 September 1996 was about 0.350 km/s.

On 6 March 1997, using a CN filter applied to the same telescope, West and Kidger measured a shell expansion velocity of 1.3 km/s (West and Kidger, 1997) and Birkle and Boehnhardt obtained similar values on 7 February 1997 with the 1.2 m telescope at Calar Alto (Birkle and Boehnhardt, 1997); these values are in agreement with the maximum expansion velocities that we measured on our images taken on 8 March and 9 February 1997, 1.405 km/s and 1.200 km/s, respectively.

Our calculations of shell expansion velocity showed a periodicity similar to that observed by Jorda's group (Jorda, 1997) in relation to their measurements of the speed of nuclear rotation made using the 1.05 m telescope at Pic du Midi. They found that the mean speed of rotation was 11.47 hours, with a minimum of 11.2 hours and a maximum of 11.65 hours, values that give rise to a super-periodicity between 18 and 22 days.

Sekanina studied the time distribution of the bursts occurring during the second half of 1996 (Sekanina, 1996), and came to the conclusion that these did not occur randomly but had a periodicity from 18 to 20 days.

Furthermore from observations of the light curve of the inner coma of the Hale–Bopp taken at Teide Observatory, M. R. Kidger (Kidger, 1997) found an apparent periodicity of 19.5 d: a nuclear precession of similar period was clearly claimed as the most possible explanation by Kidger but also by other authors (Licandro et al., 1998).

It is difficult to hypothesize a common cause that could give rise to such similar periodicities (of about 20 days) in the case of such apparently different phenomena (the rotation of the comet's nucleus, bursts and shell expansion), but it is unlikely that it is just a coincidence.

The periodicity of shell expansion could be the result of a periodic variation in the expansion speed of the material ejected by the jet producing the shells themselves, and it is possible that it may have been caused by a long-term seasonal effect that was still present when the comet reached the perihelion.

If we assume the existence of an about 20-day precessional movement of the axis of rotation of the comet nucleus, it is possible that periodic increases/decreases in solar heating at the point of origin of the principal jets may have produced simultaneous increases/decreases in the speed of expulsion of gases and dusts.

Sekanina (1996) also suggested that oscillations in the axis of rotation may explain the apparent changes in the angular position of the bursts produced by the same active region between August and October 1996.

The data shown in Figure 1 indicate that the minimum speed of shell expansion was about 0.350 km/sec: on the basis of the hypothesis suggested above, this corresponds to a situation in which the axis of rotation of the comet is maximally inclined in relation to the sun, and solar heating is at its minimum – a sort of "precessional super-winter". On the contrary, when the rate of expansion reached its maximum speed of about 1.400 km/sec, the comet may have been in a sort of "precessional super-summer" – a situation in which the inclination of the solar irradiation on the source of the jet connected to the shells would be at its minimum, and so heating would be at its maximum.

It seems to be very difficult to calculate the true angle of the cone of precession of the comet's axis of rotation. Nevertheless, our previously mentioned observation of the burst that took place on 9 September 1996 provides information that may be useful for this purpose: for a few days, it was possible to observe a "pseudo-shell" whose slow expansion velocity of 0.350 km/sec we think may have been due to the fact that the comet nucleus was so far from the sun (3.15 A.U.) that it received little solar heating.

The fact that we observed a similar expansion velocity at the perihelion as a result of the probable precession of the nucleus, makes it plausible to suppose that the level of solar irradiation during the "precessional super-winter" at the perihelion was similar to that received by the comet when it was 3.15 A.U. away from the sun.

In relation to the hypothesis of a primary emission of CO, H_2O and dust, it is at least theoretically possible to calculate the extent to which the solar irradiation would have to rise, in order to justify the increase in shell expansion velocity to as much as 1.4 km/sec. A preliminary estimate of the difference necessary between the inclination of the sun rays at the two extremes of the cycle leads to a precessional cone angle up to 20°.

It is of course very difficult (and outside the purpose of this paper) to hypothesize what may have caused the precession of the comet's axis of rotation in the way and with the period described above: it is possible that an important role may have been played by an irregularly-shaped nucleus, or even a nucleus consisting of two or more components in close contact with each other (Sekanina, 1997–1999).

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