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Letter to the Editor

Short-term variability in comet C/1995 O1 Hale-Bopp

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Abstract. Simultaneous *uvby* Strömgren photometric observations of the comet Hale-Bopp have been collected during nearly three weeks. The Fourier transform method has been used to analyse the periodicities in luminosity present in this comet. Two different periodicities have been found: a long period of 7.19 days and a shorter one of 5.5 hours. The 5.5-hour periodicity may correspond to a full rotation of 11 hours whereas the 7.19-day periodicity could be related with the precession period. Other possibilities are discussed.

Key words: comets: individual: Hale-Bopp – techniques: photometric

1. Introduction

The rotational period of a comet is a key parameter to understand its coma morphology as well as its energy balance, activity and other characteristics. Photometry of the inner part of the coma of comet Halley has proven extremely valuable to analyse its rotational status (e.g. Millis & Schleicher 1986; Festou et al. 1987; Neckel & Münch 1987) although different interpretations of the periodicities found in Halley's light curves have been made by different authors, resulting in several proposed rotational periods.

Based on Halley's case, we expected the occurrence of luminosity fluctuations in the inner part of the coma of Hale-Bopp related to its rotation and therefore we performed a careful photometric study to derive a possible rotational period of its nucleus. Here we report on high quality *uvby* observations of the inner coma of comet Hale-Bopp and the search for periodicities in the reduced light curves.

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2. Observations

The observations were carried out on sixteen nights during March, 1997 using the 90 cm telescope at Sierra Nevada Observatory, Spain. This telescope is equipped with a six-channel $uvby\beta$ spectrograph photometer for simultaneous measurements in *uvby* or in the narrow and wide H_β channels, respectively (Nielsen, 1983), but only *uvby* measurements were collected during this observing run.

In order to make differential photometry and due to the fast movement of the comet, two sets of comparison stars were used. These comparison stars were chosen taking into account similar brightness (around V=4^m), spectral type (around G) and in the neighbouring of the comet for a better reduction of the data avoiding extinction problems. Each set of comparison stars contains one main comparison and two check stars. In order to make compatible both sets of differential magnitudes the two main comparison stars were simultaneously observed almost all the nights in the campaign. During the first part of the campaign, C1=HR 8130 (V=3.^{m}72, F2, Bright Star Catalogue, 1982) was used as main comparison star and HR 8079 (V=3.^{m}72, K4) and HR 8028 (V=3.^{m}94, A1) as check stars. During the second part of the campaign, C1=HR 8498 (V=4.^{m}13, K3) was used as main comparison star and HR 8475 (V=5.^{m}33, K2) and HR 8454 (V=4.^{m}29, F5) as check stars. However, due to the brightness of the comet ($<$3.^{m}0) a calibrated neutral filter was used for all these objects. One diaphragm of 45 arcsec was used throughout the campaign. Each observation consisted of 20 s for each object. During this short time, the comet drift within the diaphragm was negligible. Hence, differential tracking was not used. Each comet observation was performed with the aperture centered on the brightest part of the coma, which was easily recognizable from night to night. Due to the position of the comet in the sky, it could only be photometrically observed for about one hour before sunrise each night. The airmass ranged commonly from 3.2 to 2.2 during every session. In Table 1, we summarize the relevant data of the comet for every day at O^{h}UT.

Table 1. Comet parameters relevant to the observations

Date 1997	R.A.(2000) (h,m,s)	Dec.(2000) (°,',")	r (AU)	Δ (AU)	Phase (deg)
Mar 4	21 39 27.2	35 33 50	1.042	1.447	43.3
Mar 5	21 45 43.4	36 19 00	1.033	1.434	43.8
Mar 6	21 52 13.5	37 03 46	1.025	1.421	44.3
Mar 7	21 58 58.2	37 47 56	1.018	1.409	44.7
Mar 8	22 05 57.7	38 31 23	1.010	1.398	45.2
Mar 9	22 13 12.3	39 13 55	1.003	1.387	45.7
Mar 10	22 20 42.3	39 55 21	0.996	1.378	46.1
Mar 11	22 28 27.8	40 35 29	0.989	1.368	46.5
Mar 12	22 36 28.8	41 14 07	0.982	1.360	46.9
Mar 13	22 44 45.2	41 51 03	0.976	1.352	47.2
Mar 14	22 53 16.6	42 26 03	0.970	1.344	47.6
Mar 16	23 11 02.8	43 29 27	0.959	1.332	48.1
Mar 17	23 20 16.1	43 57 25	0.953	1.328	48.4
Mar 18	23 29 41.5	44 22 39	0.949	1.323	48.6
Mar 19	23 39 17.9	44 44 58	0.944	1.320	48.8
Mar 20	23 49 03.8	45 04 13	0.940	1.318	48.9

To transform our data into the standard system we have used the same procedure described in Rodríguez et al. (1997). During the observations reported here, neither of the comparison stars showed any sign of variability within $0.^{m}005$. The data obtained, as magnitude differences comet minus C1=HR 8130 in the standard system versus Universal Time, are available upon request to the authors.

3. Results

After differential magnitudes in the standard system were obtained with respect the main comparison star, we fitted an empirical law of the form $m_{obs} = m(1,1) + 5\log(\Delta) + 2.5n\log(r)$ to account for the increase in brightness and activity as the comet approached the Sun and the Earth, where Δ is the Earth-comet distance in AU, r the Sun-comet distance in AU, m_{obs} the observed magnitude, n is a fitted activity parameter, and $m(1,1)$ is the fitted magnitude at $\Delta = 1$, $r = 1$.

The residuals of the fit are plotted in Fig. 1 in the *b* filter, as an example. Similar results are obtained in the other three *uvy* filters.

Then, analysis of frequencies of the residuals was carried out using the Discrete Fourier Transform method, as described in López de Coca et al. (1984), on our data in the *b* filter. After several swepts in frequency, the periodograms showed a main peak at frequency ν_1=0.139 (c/d), that is a period of P_1=7.19 days, with a full amplitude, from peak to peak, of $0.^{m}0420$ ($\pm$0.0036). The corresponding synthetic light curve is plotted in Fig. 1 together with the data. After prewhitening for this frequency, the resulting periodograms show another peak at ν_2=4.376 (c/d), corresponding to a period P_2=5.5 hours, with a full amplitude from peak to peak of $0.^{m}0208$ ($\pm$0.0036). When these two frequencies are extracted from the spectra, it seems that there are no remaining periodicities in the light curves.

Fig. 2 shows the data phased with the period P_1 after prewhitening the frequency ν_2. In addition, Fig. 3 shows the data phased with P_2 after prewhitening ν_1. From these figures we can see that both periodicities in the luminosity of the comet are clearly present.

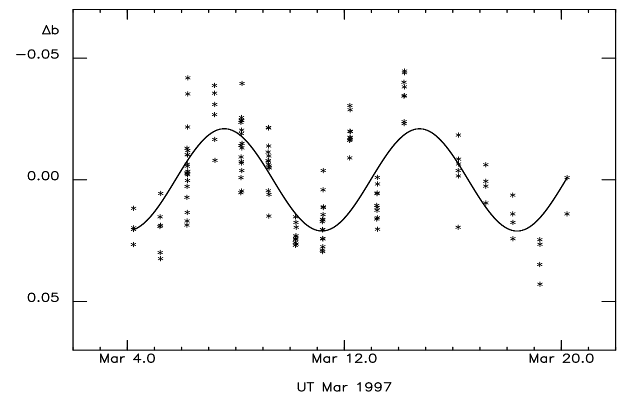

Fig. 1. Observed light curve of the comet Hale-Bopp in the *b* filter, after distance corrections, together with the Fourier fitting corresponding to the period of 7.19 days versus Universal Time

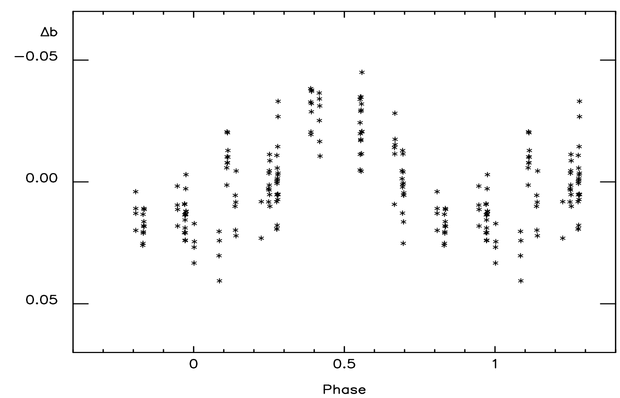

Fig. 2. Phased light curve respect to the period of 7.19 days,in the *b* filter, after the frequency ν_2 is subtracted

4. Discussion

Since the observations were made when the comet had a large and bright coma, the comet nucleus was completely hidden by the coma. Therefore, the short-term variability in the coma brightness must be connected to the activity and not to the light reflected by the nucleus. The most straightforward interpretation of our data could be that there is an area that becomes active when sunlight reaches it once every 5.5 hours, implying that the spin period could be 5.5 hours. However, one cannot say whether the variability is due to on and off switching of active areas on the nucleus surface or whether the entire surface of the nucleus is active and the changes in coma brightness are due to an elongated shape of the nucleus and the changes in cross section, due to the rotation. The maxima in cross section facing the sun would occur twice per rotational period, thus arguing for an 11-h rotational period, which is close to the results from other investigations, as discussed below. Another possibility could be

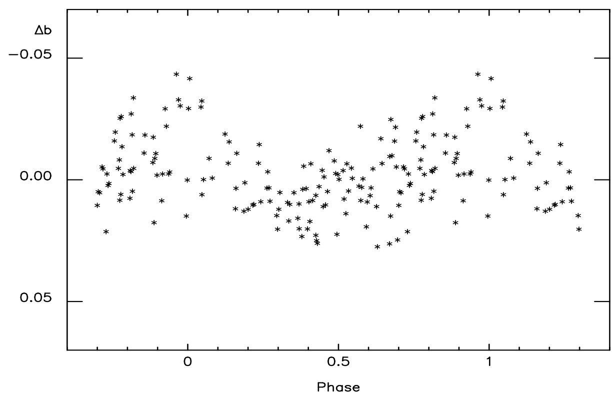

Fig. 3. Phased light curve respect to the period of 5.5 hours,in the *b* filter, after the frequency ν_1 is subtracted

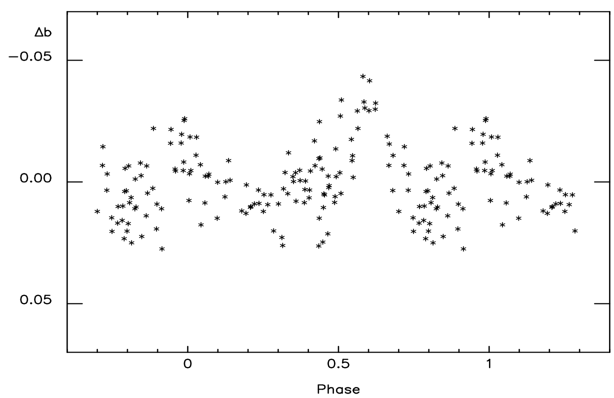

Fig. 4. Phased light curve respect to the period of 11.0 hours, in the *b* filter, after the frequency ν_1 is subtracted

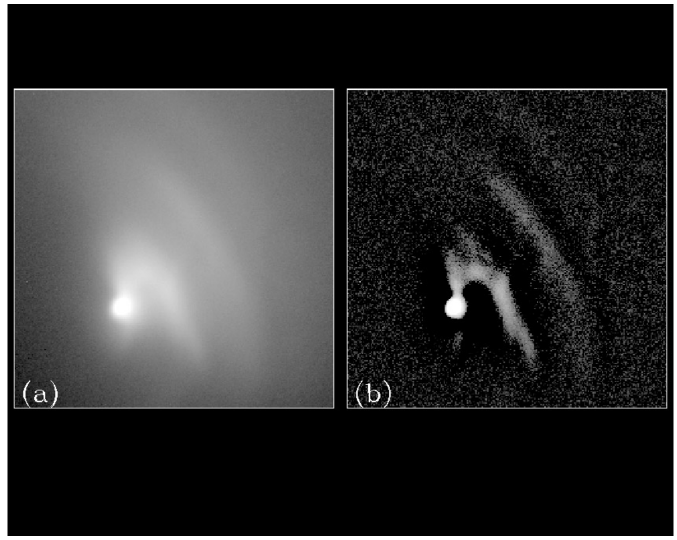

Fig. 5. a) CCD image of the inner coma of comet C/1995 O1 obtained using the 1.5m telescope of the Sierra Nevada Observatory on March 10th, through an interference filter at 5157 Å. The total field of this image is 84 x 84 arcsec^2. North is to the left and West is up. b) Same as a) with low spatial frequencies substracted

Table 2. Characteristics of the filters used for our CCD observations

λ (Å)	FWHM (Å)
4866	50
5157	50
7500	50
8920	50

that the entire nucleus is not active, but a big comet nucleus could have a large number of active areas, which could be randomly distributed on the surface. For such scenario, the total activity would be proportional to the cross section facing the sun, in the same fashion as for an entirely active surface and therefore we would expect two photometric maxima per rotational period.

We favour the third option since the detection of jets revealed anisotropic emission of localized areas rather than emission from the entire surface and because several investigations (Weaver et al. 1997; Schleicher et al. 1997) have addressed the issue of nucleus size, presenting results that are consistent with a nucleus diameter larger than at least 17 km. Such a big comet nucleus may have many active areas and the total activity could be linked to the total cross section facing the sun. For this physical scheme to take place, one might expect different amplitudes of the maxima corresponding to the two opposite sides that have the largest cross sections. Our data do not show that phenomenon unambiguously, but there is a slight indication that this could be the case as can be seen in Fig. 4, where the data are phased with twice P_2, that is 11.0 hours, after prewhitening ν_1.

Another possibility could be that there are two important spots, one in each hemisphere (one in the sunlit hemisphere and the other in the dark hemisphere). Both of them would never be exposed to sunlight simultaneously. This would cause a periodicity in the light curve of half the rotation period.

We also observed the comet's inner coma using a 1024 by 1024 CCD attached to the 1.5-m telescope at Sierra Nevada Observatory on several dates (March 9th, 10th, 28th, 29th). In Fig. 5 we show the arc structure we observed through a filter centered at 5157 Å. This structure was also observed in the rest of the filters we used (Table 2). The arc structure resembled some of the results by Sekanina (1987) (see his Fig. 3e) on coma morphology based on anisotropic emission models of a fast rotating nucleus (spin period of 9.6h) with a high-latitude active area, which is illuminated by the Sun continuously or quasicontinuously. Therefore, our CCD images suggest a rotational period of the order 10 h.

A persisting jet associated to an active area matching the characteristics described above has been observed and a possible rotational period of 11.47(±0.05) hours has been derived by analysing its movement (Jorda et al. 1997), with the period oscillating between 11.65(±0.10) and 11.20(±0.10), which is close to our determination.

The rotational status of the nucleus must be complex in view of the two photometric periods we have detected. Our long period could be related to precession of the nucleus. The precession period could be twice the 7.19-day period, or maybe

7.19 days if the changes in brightness are due to a single active area rather than the changes in the total cross section.

The complex rotational state could also explain the fact that the spin period inferred from the observations of the position angle of the jet by Jorda et al. (1997) is slightly different than our suggested spin period, because the jet might return to a reference position angle in a slightly different period than the true spin period. The nature of the 22($\pm$2)-day modulation of the period reported by Jorda et al. (1997) is somehow difficult to interpret, since this modulation time is higher than our low period of 7.19 days. However, with the quoted uncertainty, 22 days could be three times 7.19 days, which might suggest that the true precession period would have three photometric periods. Nevertheless, the 22($\pm$2)-day modulation may not be a precession period because, as reported by Jorda et al. (1997), no periodic tilt of the spin axis seems to have been detected in their jet measurements.

An alternative explanation of the observations could be that the 11-h period is the precession period whereas the long period is connected to the rotation. This might be favoured by the fact that our measured magnitude oscillations are higher for the long period than for the short period. A similar model of a fast precession and slow rotation has been proposed for Halley's nucleus by Festou et al. (1987).

We conclude that a complex rotation of the nucleus seems to be the most likely scenario for the rotational state of comet Hale-Bopp, as is also believed to be the case for Halley's nucleus, although more data are still needed to build an undoubtful picture of the true situation.

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