THE ROTATION OF COMET C/1995 O1 HALE–BOPP FROM INNER COMA PHOTOMETRY

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Abstract. We present a further investigation of the periodogram resulting from the photometric data by Rodríguez et al. (1997) for comet C/1995 O1 Hale–Bopp and interpret that the main period in the data is 11.23 ± 0.01 h, but not 7.19 days. The latter is now attributed to an alias of the 11.23-h period. Assuming that the periodicity observed in the photometry is the solar day, the 11.23-h period is consistent with estimates of the sidereal rotation period by Farnham et al. (1998), and Jorda et al. (1997–1999) provided that the obliquity of the comet's equatorial plane to its orbital plane is larger than 75° and 80°, respectively. This result is in agreement with estimates of the obliquity by Sekanina (1998) and Jorda et al. (1997–1999). A weaker periodic signal in the light curve could be 5.48 ± 0.01 h, but we suggest that this is an alias of a 3.25 ± 0.01 h period of unknown origin.

Keywords: Comets, Hale–Bopp, photometry, rotation period

1. Introduction

In a recent paper, Rodríguez et al. (1997) presented results on inner coma photometry of comet Hale–Bopp, focussing on the analysis of the short term variability to search for periodicities related to the rotation of the nucleus. Their conclusion was that there were two main frequencies, one at 0.139 c/d (cycles per day) and another one at 4.376 c/d, equivalent to periods of 7.19 days and 5.5 h respectively. They suggested that the short period could be half the rotation period, and the longer period could be related to a possible precession of the nucleus.

However, several lines of evidence have encouraged us to reanalyse the light curve presented in Rodríguez et al. (1997), in order to find possible errors or misinterpretations in assigning periodicities. In particular, the nondetection of a complex rotation of the nucleus as pointed out by most investigators (e.g., Farnham et al., 1998; Jorda et al., 1997–1999) strongly supports that there cannot be a 7.19-day period, or it would have been observed in other data. The 20-day to 24-day periodicity claimed by some other investigators (Kidger et al., 1998; Licandro et al., 1998), which they attribute to a precession, cannot be related to the 7.19-d period proposed by Rodríguez et al.

Therefore, we have carried out a reanalysis of the Rodríguez et al. light curve in the frequency domain and we have found that the 7.19-day period (a frequency of 0.139 c/d) is an alias of the true period of 11.23 h (2.138 c/d). There is also a secondary weaker periodic signal 3.25 h (a frequency of 7.383 c/d), although its exact value is more uncertain as we will point out. In the following, we describe the observations, show the spectral power density as a function of frequency and explain the nature of the peaks in the periodogram.

2. Observations and Data Reduction

We will briefly describe the observations and reductions, since they were already given in Rodríguez et al. (1997). The data were taken from UT dates March 4th, 1997 to March 20th, 1997, using a 6 channel *uvby* Strömgren photometer attached to the 0.9-m telescope at Sierra Nevada Observatory, Granada, Spain (see Rodriguez et al., 1997, for a log of the observations). A neutral density filter was used in order not to saturate the detector. The data were taken through a 45 arcsec diaphragm with integrations of 20 sec. No differential tracking was used since the drift of the comet within the aperture was negligible for that integration time. Two comparison stars and a check star were observed before and after each comet integration in order to accurately correct for extinction. The uncertainty of the measurements was typically 0.01 magnitudes.

After the reduction process was completed, absolute magnitude was determined as a function of time for all the 4 bands. Since the data with the highest signal/noise ratio corresponded to the *b*-channel, the analysis was restricted to this band. The overall shape of the curve was fitted by using a power law in r (the sun-comet distance) and the residuals were subsequently used to search for periodicities. The fit and the residuals are shown in Figure 1.

The spectrum of the residuals was computed in the range of frequencies from 0 to 10 c/d, using the method described in Rodríguez et al. (1998) where single-frequency and multiple-frequency techniques are employed. These techniques make use of both Fourier and multiple least squares algorithms. Figure 2 shows the spectrum of the residuals in units of millimagnitude squared (mmag^2).

Figure 2a illustrates the difficulty in choosing one main frequency among all the peaks. Each peak at a given frequency ν_0 has aliases at approximately $\nu_0 + i$, with i being an integer. Also, the peaks at approximately $i - \nu_0$ are artifacts. These aliases arise as a result of the periodicity of 1 day in the observations. The aliases have a high power because the data were collected during a very short time (only about an hour) in each night, and from only one observatory. Since the peaks at $\sim$0.138 c/d, $\sim$1.138 c/d, $\sim$2.138 c/d and $\sim$3.138 c/d have almost the same spectral power, it is difficult to decide which one corresponds to the main frequency and which ones are aliases.

Rodríguez et al. (1997) assumed that the main frequency was 0.139 c/d and $\sim$1.138 c/d, $\sim$2.138 c/d and $\sim$3.138 c/d were all aliases. However, the frequency ν_1 = 2.138 c/d has a slightly higher spectral power and gives a result closer to the sidereal period reported by several investigators. According to this, the main

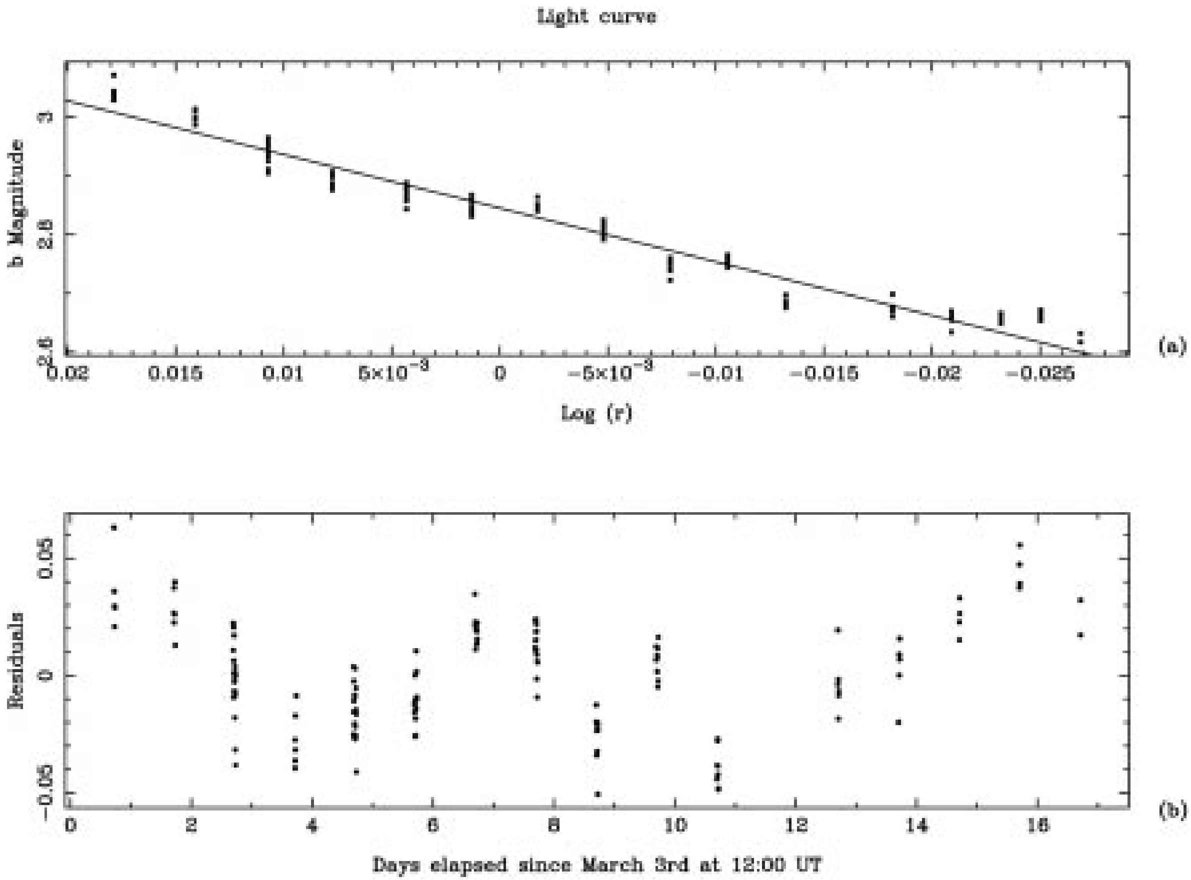

Figure 1. (a) Light curve based on the data presented by Rodríguez et al. (1997). Absolute magnitude in filter *b* is plotted versus the logarithm of the comet's distance to the sun (r). The straight line is an empirical fit to the data. (b) Residuals of the fit as a function of time.

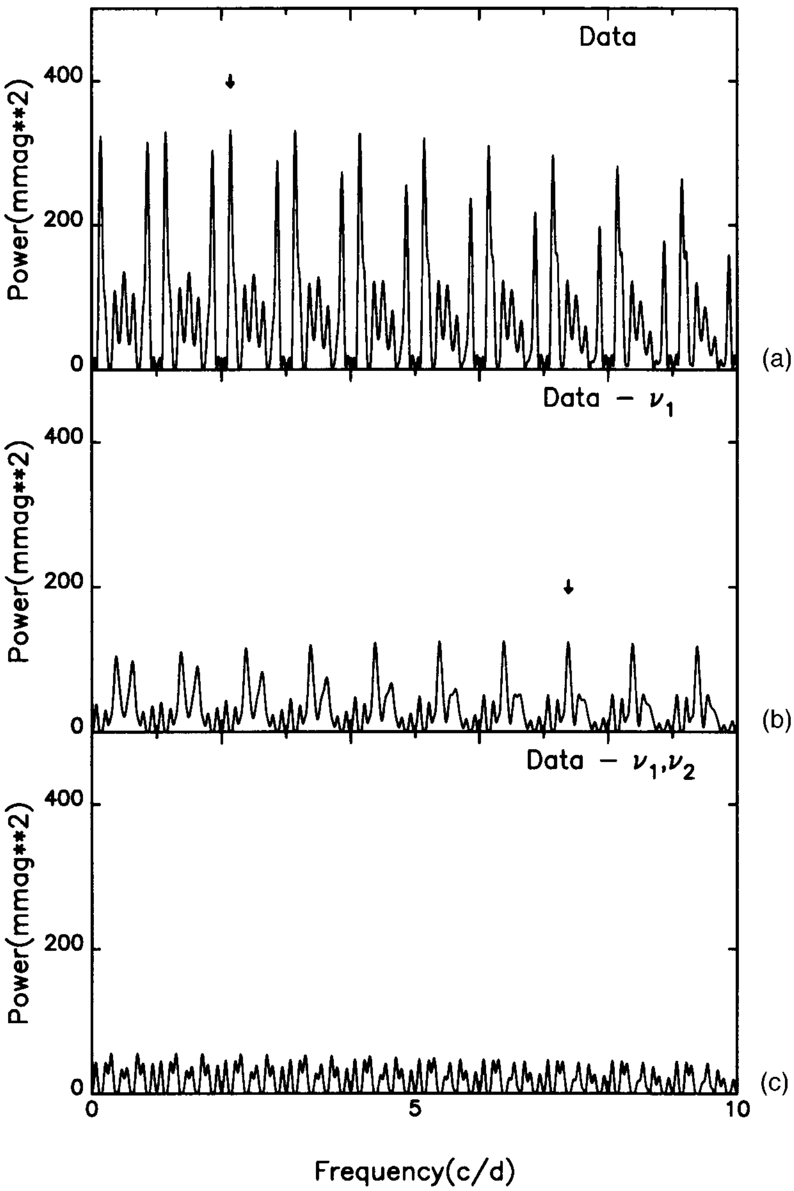

Figure 2. (a) Periodogram of the residuals shown in Figure 1b. The power is expressed in units of millimagnitudes squared. The arrow indicates the main peak. (b) The same as (a) after the main frequency (ν_1 = 2.138 c/d) has been subtracted to the data. (c) The same as (b) after subtraction of the secondary frequency (ν_2 = 7.383 c/d).

frequency is at ν_1 = 2.138 cycles per day (a period of 11.23 h), and the peaks at approximately 2.138 + k, with $k = -2, -1, 1, 2, 3 \ldots$, are aliases due to the typical frequency of one day in the observational window. The peaks at $j - 2.138$ with j = 3, 4, 5, 6 . . . are also artifacts. We thus conclude that the 7.19-day period proposed by Rodríguez et al. (1997) is very likely an alias of the main frequency.

In order to unambiguously determine the presence of a periodic signal in the residuals, we tested our results using a different method. We computed the Lomb periodogram (Lomb, 1976), which is aimed at the spectral analysis of unevenly sampled data, using the fast implementation of this technique described in Press and Rybicki (1986). This method allows us to determine the confidence level as a function of the normalized spectral power density. The periodogram resulting from this method shows the same maxima as in Figure 2a, with the absolute maximum (and thus the most statistically significant peak) at about 2.14 c/d with a normalized spectral power density of 26.5. This value represents a confidence level of 99.99999992% in the detection of the periodicity. The confidence levels were obtained following a similar procedure to that described in Press et al. (1992) for the case in which the data are clumped.

After subtraction of the main frequency, the periodogram (Figure 2b) shows a set of peaks with very similar spectral power. For ν = 7.383 c/d (a period of 3.25 h) the spectral power is maximum, so we tend to favor this peak instead of 4.376 c/d (a 5.5-h period), although the difference is so small that we cannot confidently attribute it to 7.383 c/d.

After subtracting the secondary frequency, no other frequencies have amplitudes higher than 0.01 magnitude (Figure 2c). There is a peak at 0.28 c/d (85.7 h), but as the amplitude is smaller than our suspected accuracy in the determination of the absolute magnitude level from night to night, we believe this is likely an artifact.

3. Discussion

One can wonder why there is a difference of a few minutes between the main period reported here and the period of 11.30 $\pm$ 0.05 h or 11.35 $\pm$ 0.03 found by other investigators (e.g., Farnham et al., 1998; Jorda et al., 1997–1999; Licandro et al. 1998). We believe this difference stems from the fact that the activity is controlled by the solar day, not the sidereal day whereas the above studies are sensitive to the sidereal period. The activity of a large area of sublimating ices should reach a maximum every time the sun is on its local meridian. Since photometric studies monitor the activity, we think that the period we report is the solar (or synodic) day, not the sidereal one. If we take 11.30 h as the sidereal day, the solar day we derive here is shorter than the sidereal period by at least 0.07 h. This has an immediate consequence: the comet must be rotating in the reverse sense to its revolution around the sun. This conclusion is in agreement with the estimates of the position of the rotation axis by Sekanina (1998); Jorda et al. (1997–1999) and Serra-Ricart et al. (1998).

If a comet with prograde orbital motion rotates clockwise, the sun reaches the local meridian of a given active area some time ($t_{\rm sun}$) before the sideral rotation is completed:

$$t_{\rm sun} = \frac{\beta}{\Omega_{\rm sid}} = \frac{\beta}{360}\tau_{\rm sid}, \tag{1}$$

where β is the change in the right ascension of the sun (as seen from the comet) in one rotation, $\Omega_{\rm sid}$ is the angular speed and $\tau_{\rm sid}$ is the sidereal period. We can relate the change in right ascension of the sun ($d\alpha_{\rm sun}$) to a change in orbital longitude ($d\lambda_{\rm sun}$) by:

$$\mathrm{d}\alpha_{\rm sun} = \frac{\cos\epsilon}{\cos^2\delta_{\rm sun}}\,\mathrm{d}\lambda_{\rm sun}, \tag{2}$$

where ϵ is the obliquity. Therefore,

$$\beta = \frac{\mathrm{d}\alpha_{\rm sun}}{\mathrm{d}t}\tau_{\rm sol} = \frac{\cos\epsilon}{\cos^2\delta_{\rm sun}}\frac{\mathrm{d}\lambda_{\rm sun}}{\mathrm{d}t}\tau_{\rm sol}. \tag{3}$$

If we define $\phi = (\mathrm{d}\lambda_{\rm sun}/\mathrm{d}t)\tau_{\rm sol}$, with τ_{sol} being the solar period, and using Equations (1) and (3), the solar and sidereal periods are related by:

$$\tau_{\rm sol} = \tau_{\rm sid} - t_{\rm sun} = \tau_{\rm sid} - \frac{\cos\epsilon}{\cos^2\delta_{\rm sun}}\frac{\phi}{360}\tau_{\rm sid}, \tag{4}$$

or

$$\tau_{\rm sid} = \frac{\tau_{\rm sol}}{\left(1 - \frac{\cos\epsilon}{\cos^2\delta_{\rm sun}}\frac{\phi}{360}\right)}. \tag{5}$$

Considering that the mean value of ϕ is about 0.61 degrees during the observations (this value was computed from the orbital ephemeris by Yeomans (JPL Ref. Solution: 55. Planetary Ephemeris: DE403)) and for a hypothetical obliquity of 0 degrees, this would yield a sidereal period of 11.23/(1 − (0.61/360)) = 11.25 h. In order to match the (11.30 ± 0.05)-h sidereal period, β needs to be $2.40^{+1.40}_{-1.79}$ degrees. Hence, the required obliquity is at least 75^{+5}_{-75} degrees, which is the value reported by Sekanina (1998). If we use Jorda et al.'s (1997–1999) 11.35 ± 0.03 h rotation period, the minimum obliquity needed is 80^{+10}_{-3} degrees, in agreement with their estimate of the obliquity.

Figure 3 shows the value of $\tau_{\rm sid}$ for a number of possible obliquities and for all their possible solar declinations, using Equation (5). The acceptable values of the obliquity are those corresponding to the curves that intercept the y = 11.30 straight

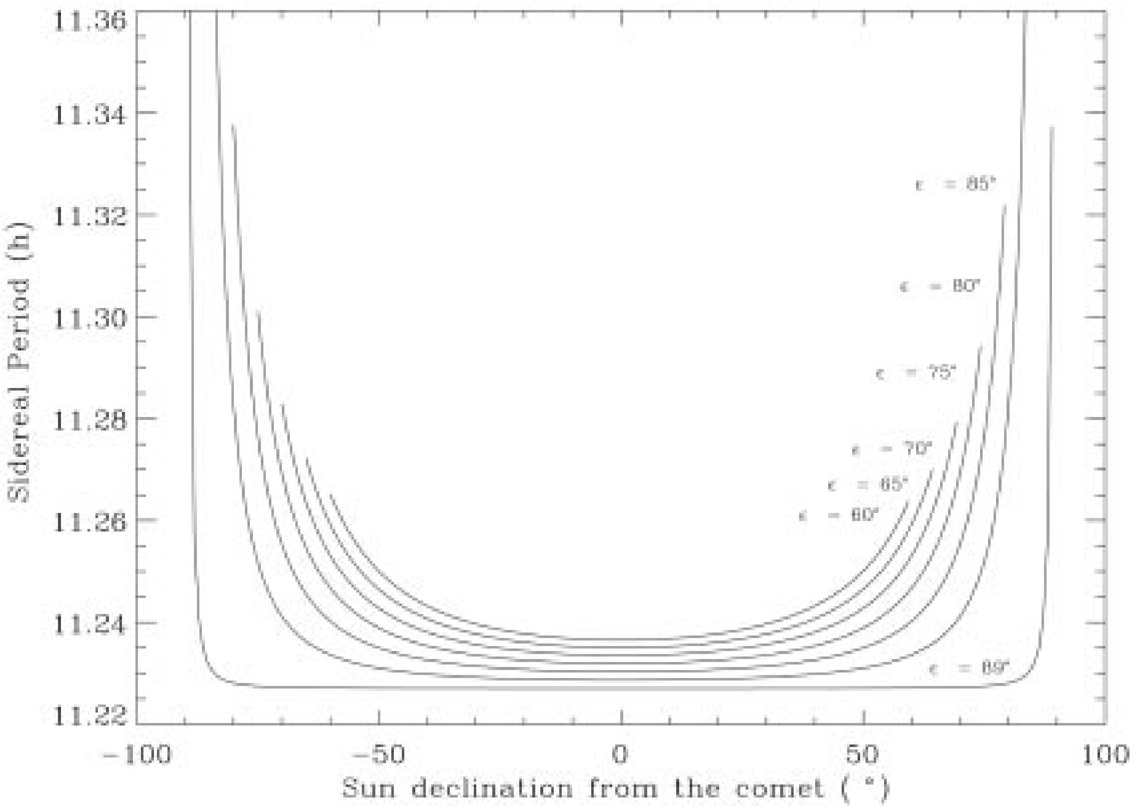

Figure 3. Plots of Equation (5) for the obliquities (ϵ) shown next to each curve and for a solar period of 11.23 h. Acceptable obliquities and declinations are obtained by the intercept of the line $y = 11.30$ or $y = 11.35$.

line or the $y = 11.35$ straight line. A large obliquity is also consistent with the low amplitude of the oscillations seen in the light curve because the zenith angle of the sun as seen from the main active area experiences only minor amplitude changes in the case of large obliquity.

Concerning the physical interpretation of the secondary frequency at 7.383 c/d (3.25-h period) or at approximately 7.383 c/d $\pm k$ (with $jk = 1, 2, 3, \ldots$) we do not find any convincing explanation of it. One possibility is free precession of the nucleus, for which the peak at ~0.38 c/d (63 h) looks especially attractive although its spectral power is significantly less than the peak at 7.383 c/d (3.25 h). Based on Euler's equations, the axial ratio required for an oblate ellipsoid to precess 0.38 times per day would be 0.92. There is also the possibility that 3.25-h is a precession period; this would require a prolate ellipsoid and the axial ratio would be 2.09. In any case, the amplitude of the precession would necessarily have to be small or this would have been evident in other observational data. Another possibility, although highly speculative, is that the secondary frequency in our data might be related to the rotation period of a hypothesized satellite orbiting the main nucleus. Such a system has been proposed by Sekanina (1997–1999) from the analysis of Hubble Space Telescope images, but our preferred period seems too fast for a kilometer-sized comet nucleus to retain its integrity as the centrifugal force would not be balanced by the gravitational force.

4. Conclusions

In the present analysis we showed that the 7.19-day period proposed by Rodríguez et al. (1997) is an alias of the true period of 11.23 h and suggested that this main periodicity is related to the solar period. This, together with the sidereal rotation period estimated by Farnham et al. (1998) and Jorda et al. (1997–1999), places a lower limit of 75 and 80 degrees for the obliquity of the spin axis of the comet's equator to its orbital plane. Photometric results in conjunction with imaging techniques are therefore useful to constrain the rotational parameters of cometary nuclei. In addition to these results, we found another significant photometric period of 3.25 h whose nature is not clear to us.

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