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Rotation of the Nucleus of Comet p/Arend–Rigaux[1]

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Time-resolved charge-coupled device photometry of Comet p/Arend–Rigaux shows a cyclic variation in cometary brightness consistent with the periods T_1 = 574 ± 5 min (9.58 ± 0.08 hr) and T_2 = 407 ± 5 min (6.78 ± 0.08 hr). The variation has a 30% range and is confined to the inner coma. The relative photometric stability of the outer coma indicates that the variations in the inner coma are associated with the nucleus and probably result from its rotation at, or at a multiple of, one of the above periods.

1. INTRODUCTION

Knowledge of the rotation periods of cometary nuclei is important for an understanding of the physics of comets. For instance, the temperature distribution and rate of mass loss from the nucleus are both affected by the rotation rate. The magnitude and direction of the nongravitational acceleration also depend on the rotation. Finally, interpretations of the radar reflection from nuclei can be made only when the rotation is independently determined. Unfortunately, the measurement of nucleus rotation is complicated by the relative brightness of the cometary coma near the nucleus and by the intrinsic coma variability.

The most direct method for the determination of rotation involves the photometric detection of periodic brightness changes (the same method used to determine the rotations of asteroids). The only published photoelectric photometry having the necessary time resolution and accuracy is by Fay and Wisniewski (1978) concerning the relatively inactive Comet p/d'Arrest. They found a nucleus period 5.17 ± 0.01 hr and brightness range 0.15 mag from observations over 3 nights. However, their photoelectric measurements could not distinguish variations in cometary brightness due to nucleus rotation from similar variations due to a change in the amount of dust in the observing diaphragm. Indeed, their result is in disagreement with the 6.7- and 7.9-hr periods determined from Whipple's (1982) halo method, and no photometric confirmation of their result appears to have been attempted. The halo method itself suffers from uncertainties concerning the nature and dynamics of the halos (bright sunward arcs seen in some comae), and its validity is largely untested.

Comet p/Arend–Rigaux (orbital period P = 6.84 years, eccentricity e = 0.599, inclination $i = 17^\circ\!.8$) is one of the least active of the known periodic comets. Its low-integrated magnitude and coma surface brightness make it a leading candidate for membership in the class of "evolved comets"—comets in which the supply of volatiles may have been depleted by prolonged solar heating. The absence of a measurable nongravitational parameter provides independent evidence of the low rate of mass loss from the comet nucleus (Marsden, 1968). The low activity makes p/Arend–Rigaux an attractive comet in

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[1] Observations were taken at the McGraw–Hill Observatory, which is operated jointly by Dartmouth College, University of Michigan, and MIT.

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which to seek photometric evidence of nucleus rotation.

In this paper we describe time-resolved charge-coupled device (CCD) photometry of Comet p/Arend–Rigaux at optical wavelengths. A novel feature of the present work is the simultaneous monitoring of the central region of the comet, including the nucleus, and an outer region of pure coma. Simultaneous photometry of the two regions allows us to discriminate photometric variations due to the nucleus from variations due to the coma.

2. OBSERVATIONS

The present observations were taken using the "MASCOT" CCD camera (Meyer and Ricker, 1980). The MASCOT ("MIT Astronomical Spectrometer Camera for Optical Telescopes") was placed at the *f*/13.5 Cassegrainian focus of the 1.3-m telescope at McGraw–Hill Observatory and was used in its direct imaging mode. The image scale on the 490 × 328 pixel Texas Instruments chip was 1.6 arcsec/25 μm pixel.

Images were obtained on the nights of UT 1985 January 18, 19, 20, and 21. The Johnson *R* filter (centered at 0.70 μm and of about 0.2 μm FWHM) was used. Photometry of Comet p/Arend–Rigaux was calibrated by observing the standard stars Feige 34, BD+25°1981, BD+21°607, BD+54°1216, and HD 19445. From these observations, each night was found to be photometric to better than 3%. The seeing was in the range 1.5 to 2.0 arcsec FWHM. Flat-field calibration frames were taken by exposing on the morning twilight sky. The bias level of the CCD was measured after every recorded image. Intrinsic pixel to pixel sensitivity differences in the CCD chip were removed, following bias subtraction, by dividing each image by the mean flat field.

A total of 61 images, each of 70-sec duration, was obtained through the *R* filter. The images show a bright, condensed nucleus region plus a curved, low surface brightness tail. Photometric measurements of each image were taken in a circular spot of projected radius 8.0 arcsec, centered on the apparent nucleus, and also in a concentric annulus having inner and outer projected radii 8.0 and 12.8 arcsec, respectively. In the subsequent discussion, these are referred to simply as the inner diaphragm and the outer diaphragm. The radius of the inner diaphragm was selected to be large in comparison with the atmospheric seeing, while the dimensions of the outer diaphragm were chosen so as to provide a significant signal from the relatively low surface brightness coma in p/Arend–Rigaux. (The mean surface brightness within the outer diaphragm was only 21.4 *R* mag/(arcsec)^2.) At the time of the observations, the radius of the inner diaphragm corresponded to 3.3×10^6 m at the comet, while the outer diaphragm extended from 3.3×10^6 to 5.3×10^6 m. The brightness of the sky in each image was measured in a circle of 8.0 arcsec radius centered 50 arcsec to the south of the nucleus. Photometric measurements of several field stars were taken in each frame to determine the atmospheric extinction. All of the photometric measurements were checked for contamination by field stars.

The statistical uncertainty in the inner diaphragm photometry is about 4% (0.04 mag). This results from a combination of sky subtraction uncertainty ($\simeq$1%), extinction correction uncertainty ($\simeq$3%), photometric uncertainty associated with the centering of the apparent nucleus within the inner diaphragm (1 to 2%), and slight 60-Hz interference. In addition, there may be a systematic magnitude zero point uncertainty amounting to about 10% (0.1 mag).

A short list of the parameters of the comet appropriate to our observations of 1985 January is given in Table I. The results of the p/Arend–Rigaux photometry, corrected for atmospheric extinction using empirical extinction coefficients, are given in Table II and are plotted as a function of time in Fig. 1. Measurements from both the

TABLE I

OBSERVATIONAL PARAMETERS OF P/AREND–RIGAUX

UT date 1985 JANUARY	JD[a]	R[b]	Δ[c]	α[d]
18.0	2446083.5	1.538	0.567	10.053
19.0	2446084.5	1.541	0.569	9.337
20.0	2446085.5	1.545	0.571	8.637
21.0	2446086.5	1.549	0.574	7.958

[a] Julian Day number.
[b] Heliocentric distance (AU).
[c] Geocentric distance (AU).
[d] Phase angle (deg).

inner and outer diaphragms have been plotted. It is evident from Fig. 1 and Table II that the brightness of the central 8 arcsec of Comet p/Arend–Rigaux changed significantly on each of the nights of 1985 January 19, 20, and 21, while the brightness of the coma in the outer diaphragm varied only slightly.

Although there is no a priori reason to expect that the data may be fit by a simple closed curve, we have chosen a sinusoid as a reasonable approximation to the observed brightness variation. In Fig. 2 we have plotted the results of a minimum χ^2 search for the angular frequency ($\omega = 2\pi/T$) of the best fit sinusoid in the range $0.31 \leq \omega$ (rad/hr) ≤ 1.25. We attach no significance to the magnitude of χ^2 except that smaller values are taken to represent better fits. The search reveals likely solutions at $\omega_1 = 0.656$ and $\omega_2 = 0.927$ rad/hr, corresponding to periods near $T_1 = 9.58$ and $T_2 = 6.78$ hr, respectively. (Local χ^2 minima near angular frequencies 0.38 and 1.22 rad/hr (Fig. 2) do not represent plausible fits to the photometry.) The spacing between successive minima in Fig. 2 is about $2\pi/24$ rad/hr, and results from the daily sampling in our photometry. A period search using the string-length method described by Dworetsky (1983) also revealed ω_1 and ω_2. Formal nonlinear least-squares fits to the photometry from Table II, using ω_1 and ω_2 as initial parameters, show that the measurements are consistent with the common periods

$$T_1 = 574 \pm 5 \text{ min } (9.58 \pm 0.08 \text{ hr})$$

and

$$T_2 = 407 \pm 5 \text{ min } (6.78 \pm 0.08 \text{ hr}) \quad (1)$$

and a peak to trough range about 0.3 mag.

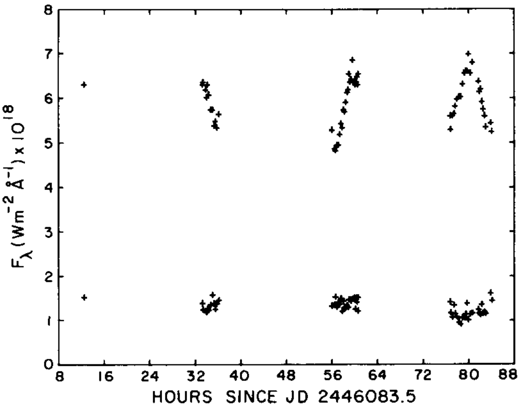

FIG. 1. The flux density at $\lambda = 0.7$ μm through the inner and outer diaphragms (upper and lower points, respectively) is plotted as a function of the time of observations (uncorrected for light travel time). The flux density scale is obtained from the measured R magnitudes (Table II) by assuming that 1.0×10^{-18} W m^{-2} Å^{-1} corresponds to $R = 15.6$ (Johnson, 1966). The error bars are suppressed for clarity. Compare the relatively constant brightness from the outer diaphragm (pure coma) with the highly variable signal from the inner diaphragm (nucleus plus coma).

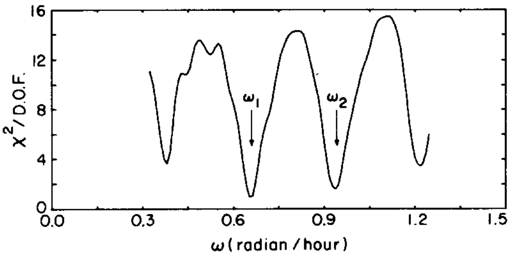

FIG. 2. Plot of χ^2 per degree of freedom (χ^2/DOF) versus angular frequency ($\omega = 2\pi$/period) for a sinusoid ($f(t) = a + b \sin(\omega t + \phi)$) fit to the inner diaphragm photometry from Table II. The minima at frequencies ω_1 and ω_2 provide roughly equally plausible estimates of the frequency of the photometric variations (corresponding to periods $T_1 = 9.58$ and $T_2 = 6.78$ hr, respectively). The remaining local minima are formally less significant and suggest periods which are inconsistent with the photometry.

TABLE II

PHOTOMETRY OF P/AREND–RIGAUX

Image	UT	Time[a]	R[inner][b]	R[outer][b]
UT 1985 JANUARY 18				
1	12:29	12.4847	13.61	15.15
UT 1985 JANUARY 19				
2	9:15	33.2486	13.61	15.25
3	9:22	33.3600	13.60	15.37
4	9:49	33.8203	13.63	15.41
5	10:00	34.0061	13.66	15.42
6	10:10	34.1606	13.61	15.35
7	10:23	34.3817	13.65	15.38
8	10:42	34.7033	13.71	15.28
9	11:01	35.0236	13.71	15.11
10	11:17	35.2792	13.78	15.26
11	11:31	35.5139	13.76	15.36
12	11:47	35.7847	13.79	15.26
13	12:08	36.1361	13.73	15.20
UT 1985 JANUARY 20				
14	7:59	55.9758	13.80	15.30
15	8:03	56.0481	13.80	15.30
16	8:28	56.4681	13.89	15.28
17	8:36	56.6019	13.90	15.14
18	8:52	56.8628	13.87	15.32
19	9:07	57.1208	13.87	15.24
20	9:22	57.3589	13.82	15.27
21	9:35	57.5792	13.77	15.17
22	9:48	57.8069	13.79	15.41
23	10:03	58.0453	13.71	15.21
24	10:12	58.1969	13.72	15.33
25	10:27	58.4492	13.68	15.34
26	10:38	58.6406	13.64	15.30
27	10:50	58:8378	13.63	15.33
28	10:59	58.9847	13.57	15.19
29	11:10	59.1722	13.60	15.19
30	11:23	59.3767	13.59	15.21
31	11:36	59.6078	13.52	15.18
32	11:56	59.9314	13.60	15.16
33	12:06	60.0953	13.62	15.36
34	12:15	60.2547	13.60	15.16
35	12:25	60.4081	13.58	15.23
36	12:31	60.5228	13.61	15.16
37	12:35	60.5911	13.57	15.40
UT 1985 JANUARY 21				
38	4:44	76.7342	13.74	15.23
39	4:49	76.8247	13.80	15.44
40	5:05	77.0747	13.74	15.55
41	5:23	77.3856	13.73	15.29
42	5:37	77.6225	13.70	15.46
43	5:56	77.9261	13.67	15.53
44	6:16	78.2675	13.66	15.67
45	6:36	78.6006	13.66	15.71
46	6:54	78.8961	13.61	15.55
47	7:16	79.2664	13.57	15.55
48	7:28	79.4689	13.56	15.47
49	7:42	79.7067	13.56	15.26
50	7:58	79.9675	13.50	15.60
51	8:16	80.2744	13.57	15.47
52	8:40	80.6606	13.53	15.45
53	9:43	81.7228	13.60	15.37
54	9:53	81.8883	13.64	15.45
55	10:04	82.0739	13.63	15.49
56	10:19	82.3186	13.68	15.28
57	10:32	82.5269	13.71	15.46
58	10:47	82.7822	13.74	15.43
59	10:59	82.9900	13.79	15.46
60	11:52	83.8656	13.77	15.09
61	12:04	84.0664	13.81	15.22

[a] Time in hours since UT 1985 January 18.0000 (JD 2446083.5).

[b] R magnitude in the inner and outer diaphragms, respectively.

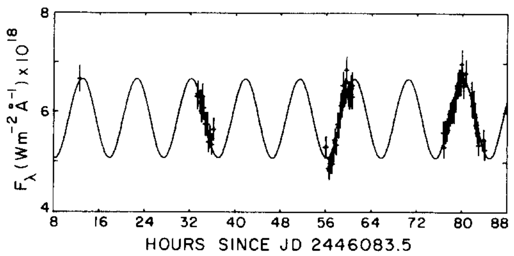

FIG. 3. The flux density measurements within the inner diaphragm are compared with a least-squares fit sinusoid of period T_1 = 9.58 hr. The 4% measurement uncertainties are indicated. The fit is shown for comparison purposes only and is not intended to model the detailed shape of the brightness variations (see text). Small differences in shape between successive observed maxima are probably the result of variable amounts of coma in the inner diaphragm.

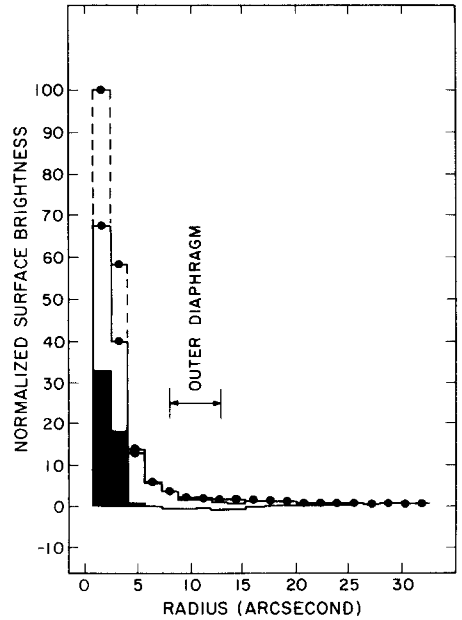

FIG. 4. Surface brightness (in linear, arbitrary units) of Comet p/Arend–Rigaux versus projected distance from the nucleus (in arcsec). The surface brightness (indicated by dots) is the average within concentric annuli about the nucleus. One hundred units of surface brightness correspond to 17.37 R mag/arcsec^2. The uppermost profile corresponds to UT 1985 January 21, 07^h58^m (maximum brightness), the middle profile to UT 1985 January 21, 11^h52^m (minimum brightness), and the lower profile (shaded) is the difference between the first two curves. Error bars are mostly too small to be plotted on the scale of this graph. The figure shows that photometric variations in Comet p/Arend–Rigaux are confined to the innermost region of the coma.

The best-fit sinusoid of period T_1 is shown for purposes of illustration in Fig. 3. Note that the plotted curve is not intended to model the detailed shape of the brightness variations, but only to demonstrate their periodicity. Close examination of Fig. 3 shows that the lightcurve peaks change shape with time, probably as a result of small variations in the amount of coma within the inner diaphragm.

The periods given in Eq. (1) are formally only the shortest of several possible periods of magnitude nT ($n = 1, 2, \ldots$) corresponding to more complicated (n-peaked) lightcurves. We find no reason to assume a lightcurve any more complicated than the one shown in Fig. 3, particularly in view of the known presence of coma in the inner diaphragm and of its variable effects on the shapes of the individual lightcurve peaks.

3. DISCUSSION

Several plausible intepretations may be placed on the brightness variations observed in the inner diaphragm. In this section we discuss interpretations in terms of variable coma production and in terms of a rotating nucleus. Although we cannot prove that the observed brightness variations are due to nucleus rotation we argue that this is by far the most plausible explanation. The simultaneous photometry through two diaphragms strongly constrains mundane explanations involving only variable coma production from the nucleus.

A gaseous origin for the brightness variations may be ruled out, since spectrophotometric observations during UT 1985 February (Jewitt and Meech, in preparation) show no gas emission bands. Sporadic outbursts of refractory grain production are observed to occur in the comae of many comets and might be responsible for the observed brightness variations in p/Arend–Rigaux. Objections to this hypothesis include the low activity of this comet and the periodic nature of the observed variations, both in time and in amplitude (the mean magnitude of the comet is remarkably constant from night to night). However, the strongest constraint on the ejection of coma grains is provided by the photometry of the outer diaphragm. A burst of grains ejected from the nucleus at speed v would cross the inner diaphragm in time $t_1 \approx r/v$, where $r = 3.3 \times 10^6$ m is the linear radius of the inner diaphragm. The time t_1 may be identified with the observed time of decline of the brightness of the inner diaphragm, namely $t_1 \approx 10^4$ sec (see Fig. 1). Grains leaving the inner diaphragm must subsequently cross the outer diaphragm. Hence, a brightness surge due to the injection of grains into the inner diaphragm should be followed by a surge of equal amplitude in the outer diaphragm, but delayed by the time t_1. Photometry of the outer diaphragm supplies no evidence for such delayed brightness surges: it may be concluded that the variations in the inner diaphragm are not caused by bursts of refractory grains from the nucleus.

It could be postulated that bursts of *volatile* grains may cause the brightness variations in the inner diaphragm. Volatile grains might sublimate on a time scale $t_s < t_1$, such that they never reach the outer diaphragm. An approximate lower limit to the sublimation lifetime of a volatile grain may be obtained by assuming that the grain is perfectly absorbing and that the incident solar energy is partitioned exclusively into sublimation. These assumptions lead to the minimum sublimation lifetime

$$t_s = 4\rho a R^2 L / 3F_\odot \qquad (2)$$

where ρ is the grain density, a is the grain radius, L is the latent heat of sublimation, $F_\odot$ is the solar constant, and R is the heliocentric distance (in AU). We take, for water ice, $\rho = 10^3$ kg m^{-3}, $L = 2.6 \times 10^6$ J kg^{-1}, and $R = 1.5$ AU, to find

$$t_s = 6 \times 10^6 a \text{ (sec).} \qquad (3)$$

The condition $t_s < t_1$ is satisfied by water-ice grains of radius $a \leq 10^{-3}$ m (1 mm). Accordingly, the volatile grain hypothesis *may* be consistent with the relatively constant brightness within the outer diaphragm. However, the hypothesis must also be reconciled with the apparently repetitive nature of the variations in the inner diaphragm. If volatile grains exist in Comet p/Arend–Rigaux, then their release from the nucleus would seem to be modulated in a periodic fashion. The most likely source of modulation is, of course, the rotation of the nucleus. We conclude that the brightness variations in the inner diaphragm are most likely caused by nucleus rotation, either directly as a result of the asymmetry of the nucleus, or indirectly by the rotation modulated periodic ejection of volatile grains. In the former case, the nucleus rotation period would be twice the lightcurve period, since by symmetry, rotation is expected to give a two-peaked ($n = 2$) lightcurve. In the latter case, the noontime ejection of volatile grains would give a single-peaked ($n = 1$) lightcurve. In the absence of further evidence, we are unable to choose between these two interpretations of the photometry.

The apparent magnitude within the inner diaphragm may be used to compute an upper limit to the product of the geometric albedo of the nucleus, g_r, with the square of its spherical-equivalent radius, β. From the relation given by Spinrad *et al.* (1979), we calculate

$$\begin{aligned} g_r\beta^2 &= (10.0 \pm 0.4) \times 10^5 \text{ m}^2 \\ &\qquad \text{(at maximum brightness)} \\ g_r\beta^2 &= (7.3 \pm 0.3) \times 10^5 \text{ m}^2 \\ &\qquad \text{(at minimum brightness)} \end{aligned} \tag{4}$$

using the photometry in Table II. The phase coefficient of the nucleus is assumed to equal 0.03 mag/deg.

More stringent limits may be placed on the nucleus by using the outer diaphragm photometry to estimate the amount of coma present in the inner diaphragm. The surface brightness of the comae of many comets is proportional to the reciprocal of the projected distance from the nucleus. With this assumption, the ratio of the brightness of the coma in the inner diaphragm to the brightness in the outer diaphragm is $8/(12.8 - 8) = 5/3$, corresponding to a magnitude difference between the diaphragms $\Delta R = 0.55$. From ΔR, and from the photometry of the outer diaphragm (Table II), we estimate that about 30% of the light in the inner diaphragm at maximum brightness, and 50% at minimum brightness, could be due to coma. This estimate is supported by Fig. 4, which shows the surface brightness profiles of the comet at maximum and at minimum light. The profiles were computed from azimuthal averages within concentric annuli centered on the nucleus. The pixel by pixel difference between the two profiles is plotted at the bottom of the figure. It may be seen that the surface brightness of the nuclear region of the comet changed appreciably (by about 30%) between the two images, whereas the surface brightness of the coma remained almost constant. The coma-corrected estimates of the nucleus are

$$\begin{aligned} g_r\beta^2 &= (7.1 \pm 0.3) \times 10^5 \text{ m}^2 \\ &\qquad \text{(at maximum brightness)} \\ g_r\beta^2 &= (3.7 \pm 0.1) \times 10^5 \text{ m}^2 \\ &\qquad \text{(at minimum brightness).} \end{aligned} \tag{5}$$

Assumed geometric albedos in the range $0.1 \le g_r \le 0.5$ imply nucleus radii in the range $8.6 \times 10^2 \text{ m} \le \beta \le 3.2 \times 10^3 \text{ m}$ (i.e., 1 to 3 km). The coma-corrected magnitude range of the nucleus is 0.7 mag. This large range, together with the likelihood that the nucleus is rotating in the minimum energy configuration, leads us to believe that the rotation axis lies close to the plane of the sky. Future observations of the type described here may allow us to quantitatively determine the orientation of the rotation axis.

A detailed comparison between the nucleus of p/Arend–Rigaux and the smaller asteroids is premature. However, we note that the small optical cross section ($g_r\beta^2 \le 0.7 \text{ km}^2$), the large rotational lightcurve range ($\approx$0.7 mag), and the short rotation period ($T = 9.57$ or 6.78 hr, or a small multiple of these) of this comet are well within the range of the corresponding properties of the smallest asteroids (Binzel, 1984). The only physical property which distinguishes Comet p/Arend–Rigaux from a small asteroid is its faint coma.

Finally, while writing this paper we learned that Wisniewski and Fay (1985) have reported a $T = 27.2$ hr rotation period and 0.6-mag range for p/Arend–Rigaux based on photoelectric measurements. While we do not understand the reason for the discrepancy, we observe that their period is almost precisely four times our period T_2 and that their 27.2-hr period is not consistent with our observations (Fig. 3), unless a complicated (multipeaked) lightcurve is assumed. Other observations by A'Hearn and co-workers (M. A'Hearn, May 1985, private communication) agree well with the ones presented here. However, A'Hearn favors a two-peaked lightcurve with a period near $2T_2$.

4. CONCLUSIONS

(1) Optical observations of the central region of Comet p/Arend–Rigaux reveal periodic brightness variations of range $\Delta R = 0.3$ mag ($\simeq 30\%$) and a period of either 574 ± 5 min (9.58 ± 0.08 hr) or 407 ± 5 min (6.78 ± 0.08 hr). The variations are confined to the region within 3.3×10^6 m of the nucleus. Photometry of nearby coma shows only slight, apparently irregular variations unrelated to the periodic changes observed in the central region.

(2) The variations in the central region are most plausibly attributed to rotation of the cometary nucleus. The variations may result from nucleus irregularity or from the rotation-modulated periodic ejection of *sublimating* grains. Ejection of *refractory* grains is ruled out as the cause of the variations by the absence of correlated but time-lagged variations in the coma. The rotation period may be a multiple of either of the two lightcurve periods.

(3) The product of the 0.7-μm geometric albedo of the nucleus with the square of its equivalent-sphere radius (corrected for the presence of coma) varies in the range 0.71 ± 0.03 to 0.37 ± 0.01 km^2. The implied nucleus radius is a few kilometers.

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