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The nucleus of comet P/Levy 1991XI

A. Fitzsimmons[1] **and I.P. Williams**[2]

[1] APS Division, Department of Pure and Applied Physics, Queen's University, Belfast BT7 1NN, Northern Ireland
[2] Astronomy Unit, School of Mathematical Sciences, Queen Mary and Westfield College, Mile End Road, London E1 4NS, England

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Abstract. We have obtained post-perihelion CCD images of Comet P/Levy 1991XI when it was 2.2 AU from Earth and 3.1 AU from the sun. Inspection of the comet images shows seeing profiles very similar to those of field stars, with a contribution to the measured flux from associated coma of only 4%, implying that the bare nucleus was observed. The same images show a faint anti-tail whose morphology implies that we observed the nucleus shortly after it had ceased outgassing. Differential photometry with field stars has allowed us to detect a periodic modulation in the light curve attributed to the the rotation of the nucleus, implying a spin period of 8.34 hours. From the amplitude of the lightcurve and the absolute magnitude we deduce that the nucleus is elongated with dimensions in the ratio 1:1.3 or larger, and possesses a mean effective radius of $\leq$ 8.2 km if an albedo $p_R \geq 2\%$ is assumed. The mean density of the nucleus is $\geq$ 200 kg m^{-3}. This comet has extremely similar physical dimensions and orbital parameters to comet P/Halley, but has a spin period more typical of main-belt asteroids.

Key words: comets: photometry

1. Introduction

By their very nature, cometary nuclei are extremely difficult to observe. When near the sun, sublimation of surface volatiles creates a transient atmosphere or coma that effectively shields them from observation at visible wavelengths. This continuous outgassing generally does not cease until the comet reaches a heliocentric distance R_h of greater than about 3 AU, but the point at which sublimation stops varies greatly from comet to comet (Jewitt 1991). Thus in most cases bare cometary nuclei can only be observed at large heliocentric distances. Their small size ($\sim 1 - 10$km) combined with evidence that the majority have very low surface albedos of $p_V \simeq 0.04$ (Spinrad 1987, and references therein), has made investigations of their nuclei extremely difficult.

Several investigators have attempted to use observations of the morphology of the inner coma to deduce rotation periods (e.g. Whipple 1982; Sekanina & Larson 1986). Yet in a comprehensive review of the problems associated with deriving nuclear rotation rates, Belton (1991) noted that out of over 60 such determinations, only four comets (P/Neujmin 1, P/Encke, P/Arend-Rigaux and P/Tempel 2) had reliable spin periods to the date of writing. This lack of data is unfortunate, for investigations of the lightcurves of cometary nuclei may hold vital clues as to their formation and evolution. For example, from the lightcurve amplitudes of 5 cometary nuclei, Jewitt & Meech (1988) suggested that comets may be more elongated than asteroids of similar size, possibly due to anisotropic mass loss from their surfaces. Another particularly intriguing possibility is that their rotation periods may be significantly different from that of asteroids. Main-belt asteroids of diameters $\leq$ 50km have a mean rotation period of 8.8 hours (Binzel et al. 1989). This contrasts with comets such as P/Halley, whose lightcurve shows periodicities with of 2.2 days and 7.4 days (Williams et al. 1987).

With an orbital period of 51.3 years, an eccentricity of 0.929 and a perihelion distance of 0.983 AU, comet P/Levy 1991XI currently has an orbit similar to the best studied comet of all, P/Halley. During its most recent perihelion passage it reached a maximum apparent visual magnitude of 8.1 as viewed from Earth in September 1991, but by late November 1991 its brightness had fallen to below magnitude 14.5 (Green 1992). We have an on-going program to investigate comets beyond 2 AU from the sun, where outgassing begins to diminish to the point where it may be possible to detect modulation of the lightcurve due to either light reflected by the rotating nucleus itself or by outgassing from localized areas moving into and out of sunlight. Comet P/Levy was observed by us in February 1992 as part of this programme. Initial inspection of the first images showed no sign of a coma, indicating the possibility that most of the light was reflected sunlight from the nucleus itself. The subsequent analysis and interpretation of these observations are reported here.

Send offprint requests to: A. Fitzsimmons

Table 1. Position of P/Levy during observation. Δ and R_h are the geocentric and heliocentric distances in AU, α is the phase angle

Date (1992)	Δ (AU)	R_h	α
February 7.0	2.153	3.102	6.0°
February 8.0	2.168	3.113	6.2°
February 9.0	2.182	3.123	6.5°
February 10.0	2.197	3.134	6.8°
February 11.0	2.213	3.144	7.1°

2. Observations and reduction

Images of Comet P/Levy were obtained using the 1-m Jacobus Kapteyn Telescope on the island of La Palma on 1992 February 6th-10th. Table 1 lists the positions of the comet relative to the Sun and Earth on the dates of observation. A GEC 400 × 590 pixel CCD combined with a KPNO R filter (effective central wavelength 6000Å, FWHM = 1200Å) was used at the f/15 focus, giving an image scale of 0.30 arcsec per pixel. All exposures were of 300 seconds duration, during which the telescope was tracked at the sidereal rate. Therefore while the stellar images were circular the image of the comet was noticeably elongated due to the relative motion of the comet and the Earth, the image being 3 arcsec long in position angle 261°. Each night bias frames were measured and flat fields were obtained on the dusk or dawn sky. Bias subtraction and flat fielding of the CCD frames were carried out using the image processing package KAPPA (Currie 1992) on Sun workstations of the Northern Ireland STARLINK node.

Unfortunately only the night of 7th February and the first part of the following night was clearly photometric, with all other observations obtained in skies containing some cirrus. On these photometric nights the cometary images were interspersed with observations at a range of airmasses of the standard field in M67 (Joner & Taylor 1990) to enable absolute flux calibration. Stellar magnitudes were measured using the PHOTOM two-dimensional aperture photometry package (Eaton 1989) with a software aperture radius of 4.5 arcseconds ($\equiv$ 15 pixels) matching the cometary measurements below. Extinction coefficients and zero-point constants were calculated in the standard manner. The resulting R-band extinction of 0.35 ± 0.01 magnitudes per airmass was much greater than the value of 0.09 expected from theoretical calculations (King 1985), and was probably due to the presence of dust in the atmosphere from the eruption of Mount Pinatubo the previous year (Morrison & Buontempo 1993).

Due to the non-photometric weather we were prevented from obtaining absolute calibrations for the majority of our data. Thus we performed differential photometry on the comet with the field stars simultaneously imaged in each individual observation. This was done in several stages. First the relative magnitudes of the stars in a given frame were measured using the point-spread function calculation and fitting routines included in the DAOPHOT II photometry software package (Stetson 1992). In 54 images of the comet, 37 exhibited a seeing profile of FWHM < 5 pixels (1.5 arcsec). It was found that 5 frames were not suitable for analysis due to either tracking errors or the sky conditions being so poor that the image of the comet was extremely faint, and these were excluded from the subsequent analysis. As consecutive frames always overlapped to some extent, it was possible to derive relative magnitudes for all stars observed on a given night. Variable stars were identified and not used in the subsequent analysis.

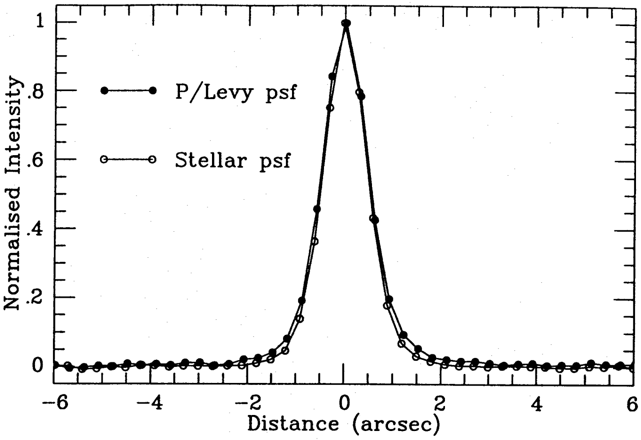

Fig. 1. Comparison of image profiles of P/Levy and a nearby field star on February 7th 1992. The cometary profile is perpendicular to the apparent motion vector

Point-spread fitting could not be used to obtain differential magnitudes between the field stars and the comet due to the trailing of the image. Instead the PHOTOM two-dimensional aperture photometry package was again used to interactively place software apertures over the comet and field stars, the automatic centering being checked by eye. Instrumental magnitudes were measured in a circular aperture of radius 15 pixels, with the sky measured in a concentric annulus of inner and outer radii of 15 pixels and 20 pixels. While this aperture size never contained 100% of the light from the seeing disc, as the same aperture was used for both comet and stars the fraction of light not measured from each object should be almost equal. Also, although the comet aperture would lose fractionally more flux due to the elongation of the image, this extra fraction should remain constant throughout the night and therefore not affect the relative magnitudes. Therefore differential magnitudes of frames obtained on a single night should be directly comparable.

The resulting differential magnitudes were scaled to nightly local standards using the relative magnitudes from the point-spread function fits above. The night-to-night results were then put on a common magnitude scale simply by adding a constant so that the mean magnitude of the comet on any one night was zero. These data are listed in Table 2. For each frame the seeing is also given, as measured from the FWHM of the point spread function of field stars perpendicular to the direction of tracking (*i.e.* North-South).

Table 2. Nightly differential magnitudes for Comet P/Levy

Date	UT (start of exposure)	Δm_R	Seeing (arcsec)	Date	UT (start of exposure)	Δm_R	Seeing (arcsec)
6-7/2/92	21.575	0.099 ± 0.037	1.2	8-9/2/92	01.073	-0.107 ± 0.028	2.4
	21.692	0.009 ± 0.039	1.3	(cont.)	02.075	0.125 ± 0.027	2.3
	21.892	0.217 ± 0.041	1.3		03.400	0.100 ± 0.042	2.1
	23.358	-0.171 ± 0.032	1.1		04.083	0.025 ± 0.042	2.0
	23.975	-0.153 ± 0.027	1.3		04.650	-0.070 ± 0.041	2.1
7-8/2/92	20.083	-0.021 ± 0.106	1.7	9-10/2/92	20.383	0.125 ± 0.091	1.1
	20.450	-0.137 ± 0.092	1.3		20.400	-0.055 ± 0.112	0.9
	21.400	0.031 ± 0.072	1.2		21.133	-0.138 ± 0.078	1.4
	21.917	0.115 ± 0.033	1.2		21.733	0.046 ± 0.073	1.3
	22.567	0.131 ± 0.033	1.3		22.417	-0.198 ± 0.078	1.2
	23.417	0.041 ± 0.024	1.1		23.083	-0.048 ± 0.074	1.6
	00.567	-0.110 ± 0.021	1.4		23.867	0.140 ± 0.069	1.6
	01.750	-0.058 ± 0.027	1.0		00.633	0.112 ± 0.038	2.3
	02.467	0.097 ± 0.033	0.9		01.400	0.034 ± 0.043	2.8
	03.583	0.085 ± 0.033	1.1		02.350	-0.081 ± 0.042	2.6
	04.217	-0.075 ± 0.032	1.1		04.117	0.068 ± 0.058	2.5
	04.733	-0.097 ± 0.033	1.1				
8-9/2/92	20.800	-0.093 ± 0.026	1.2	10-11/2/92	20.250	0.043 ± 0.042	1.4
	21.217	-0.126 ± 0.023	1.1		21.033	0.084 ± 0.042	1.5
	21.633	-0.083 ± 0.023	1.0		21.567	0.064 ± 0.040	1.3
	22.333	0.035 ± 0.033	1.0		22.550	-0.003 ± 0.147	1.2
	23.067	0.133 ± 0.033	1.1		23.350	-0.199 ± 0.044	1.3
	23.783	0.083 ± 0.031	1.2		01.117	0.007 ± 0.030	1.4
	00.367	0.084 ± 0.023	1.5		04.367	-0.037 ± 0.047	1.6
	01.033	-0.096 ± 0.023	2.4		04.900	0.038 ± 0.066	1.7

3. Results and discussion

3.1. Search for coma

At this point it should be asked whether or not the bare nucleus was observed, or whether there is some contamination from any existing coma. To answer this we closely inspected each image obtained in photometric conditions on the 7th and 8th February. The ten images with seeing measured as 1.1 arcsec or less were first co-added by shifting each frame so that the images of the comet were superimposed. This subset of the data was chosen as co-adding profiles with widths similar to 20% should avoid any major artificial broadening of the cometary image, while the good seeing should maximise the resolution of any coma near the comet.

The resulting frame was rotated so that the trailing of the cometary image was aligned with the pixel rows. The central eight pixel columns were then extracted to produce a mean profile perpendicular to the apparent motion of the comet, and the normalised profile is shown in Fig. 1. Figure 1 also shows the mean normalised point-spread function of two nearby field stars on the co-added and rotated image, so that any any change of the profile due to resampling of the image during rotation should not affect the comparison.

The cometary profile appears to be very similar to that of the stellar psf. The extremely small widening of the profile ($<$ 0.1 arcsec FWHM) may easily be caused by small unavoidable errors in the centering of the images before co-addition, and cannot be taken as evidence of a resolved coma. Extractions of the cometary profile from single images, although noisy, showed similar widths to the corresponding stellar profiles, supporting this hypothesis. Clearly the wings of the cometary profile are larger than for the stars, implying the presence of a low-surface brightness coma. To the South of the comet (negative x values) it extends no more than 2.5 arcsec from the nucleus, equivalent to 3900 km at a distance of 2.168 AU. To the North it appears to extend to $\simeq$ 5 arcsec (7800 km). This larger extension is on the same side of the comet as the anti-tail discussed below.

The mean R magnitude of the comet as obtained from the absolute photometry on this night within a 4.5 arcsec radius was 17.65 ± 0.02. Using this as the R magnitude of the comet in the co-added image, the sky brightness is 20.6 mag/arcsec^2, in excellent agreement with that expected at La Palma (Wall et al. 1989) By averaging the observed North and South profiles shown in Fig. 1 the mean surface brightness of the coma at a distance of 4.5 arcsec from the comet is $\Sigma(r) = 0.5\%$ of sky brightness, or an R magnitude of 26.4 mag/arcsec^2. The contamination of the nuclear magnitude from coma $m_{\rm coma}$ within

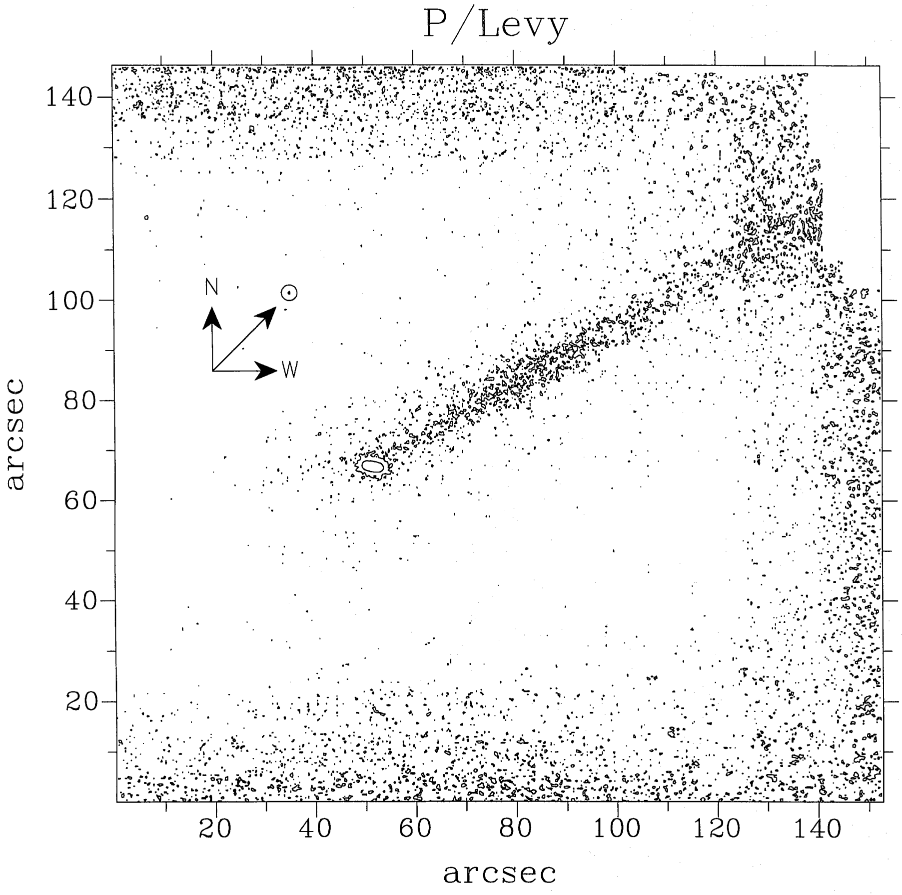

Fig. 2. Contour representation of nine co-added images of comet P/Levy on February 7th 1992. Contour levels are at 1.1 and 1.5 times sky background. Orientation of the image and the direction of the sun are shown

the 4.5 arcsec aperture can then be calculated via the expression of Jewitt (1991)

$$m_{\text{coma}} = \Sigma(r) - 2.5 \log(2\pi r^2). \qquad (1)$$

This gives $m_{\text{coma}} = 21.1$, or just 4% of the total brightness measured within a radius of 4.5 arcsec. We can therefore state that our measurements were dominated by light reflected from the nucleus.

3.2. Anti-tail

Every image of the comet obtained in good seeing displayed a linear feature of extremely low-surface brightness just above the surrounding sky, lying at position angle 300 degrees and extending from the comet to the edge of the field. As the position of the cometary image in the field varied considerably, this feature could not be a fault with either the detector or the flatfielding (it was visible on the un-processed frames) but rather must be associated with the comet itself. A contour representation of the summed image created above is shown in Fig. 2, created using the KAPPA routine CONTOUR, with the sky count well away from the comet set to unity. The feature, which we identify as a dust tail, can clearly be seen. However, it has a very low maximum surface brightness of only $\simeq$ 10% of the surrounding sky, corresponding to 23.1 mag/arcsec^2. The tail in fact shows an apparent spatial width equivalent to that of the trailed image of the comet, implying that the true width was less than or equal to the seeing prevalent during the observations and that the untrailed magnitude was $R \geq 21.9$ mag/arcsec^2.

As the antisolar vector on this date was at position angle 135°, a surprise is that the tail is pointing towards the sun as seen from the Earth. Such anti-tails are generally well understood in terms of particle trajectory analysis, whereby the apparent positions of a given mass distribution of dust particles emitted from the nucleus are calculated taking into account the varying geometry of the Earth and comet. For example, Sekanina (1983) predicted the appearance of an antitail for comet P/Halley post-perihelion, which was duly observed (Birkett 1988). However, later during its apparition, P/Halley also displayed a sunward spike which could not be explained by geometry alone. Sekanina et al. (1987) found that it was caused by dust grains of diameter $<< 0.1\mu$m that were only visible when the Earth was near the plane in which they lie.

At the time of observation, the Earth was only 11° away in heliocentric longitude from the descending node of the comet, and therefore almost in the comets orbital plane. Given the relative positions of the Earth and P/Levy during our observations, either of the two possibilities above may be possible (although we suspect that the geometrical explanation is the correct one), and a detailed analysis is outside the scope of the present paper. More importantly, although the anti-tail is clearly associated with the comet, there is no enlargement of the feature around

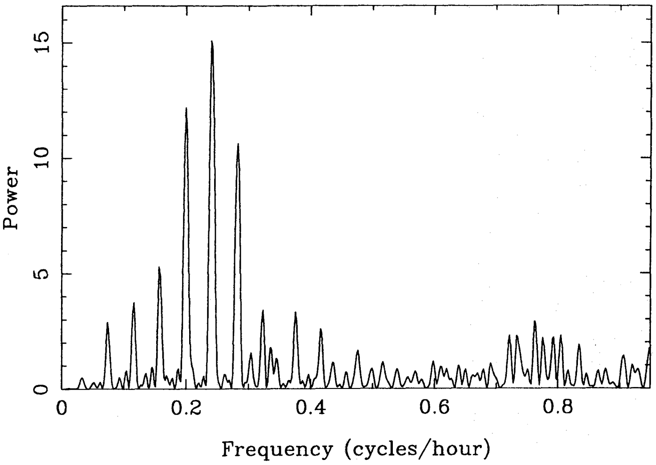

Fig. 3. Lomb periodigram of the differential magnitudes given in Table 2. The highest peak lies at a frequency of 0.2399 hour^{-1}, corresponding to a period of 4.17 hours

the comet as would be expected from an outflowing coma. Indeed, there is some indication that it may be detached from the comet itself. Therefore we hypothesize that our observations took place at a time soon after the comet had ceased outgassing.

3.3. Spin period

Inspection of the data in Table 2 (especially from the 7th-9th February 1992) show a clear modulation implying a rotation period of just over 8 hours. To measure this period more precisely we have analyzed the entire data set using the method of Lomb (1976) as implemented by Press et al. (1992). The times of observation were first corrected for light-travel time, and the resulting periodigram is shown in Fig. 3. The frequency of the largest peak is 4.17 hours, and the entire lightcurve folded to this period is shown in Fig. 4a. The significance level (the false alarm probability) of this peak is 2.7×10^{-5}.

This periodicity could be due to either the rotation of an elongated nucleus, the presence of a region of higher albedo in one area, or regular outgassing from an active region. The lack of any easily detectable coma as discussed above effectively rules out the latter possibility. An albedo spot is unlikely on such a comet, as any bright area would presumably be due to exposed surface ices, in which case outgassing should occur and again a coma should be evident. With these reasons, and given that other cometary nuclei have been shown to be elongated in shape, we believe the modulation to be caused by the rotation of the nucleus varying the surface area as seen from the sun. Assuming that each rotation of the nucleus produces two maxima and minima, the true rotation period is then 8.34 hours. The entire dataset folded to this period is shown in Fig. 4b.

This rotation period appears to be somewhat shorter than those found previously for other comets. Table 3 lists cometary rotation periods that have been measured photometrically to date. The mean of these (calculated ignoring P/Halley due to the uncertain nature of its rotation) is 11 hours but with a large

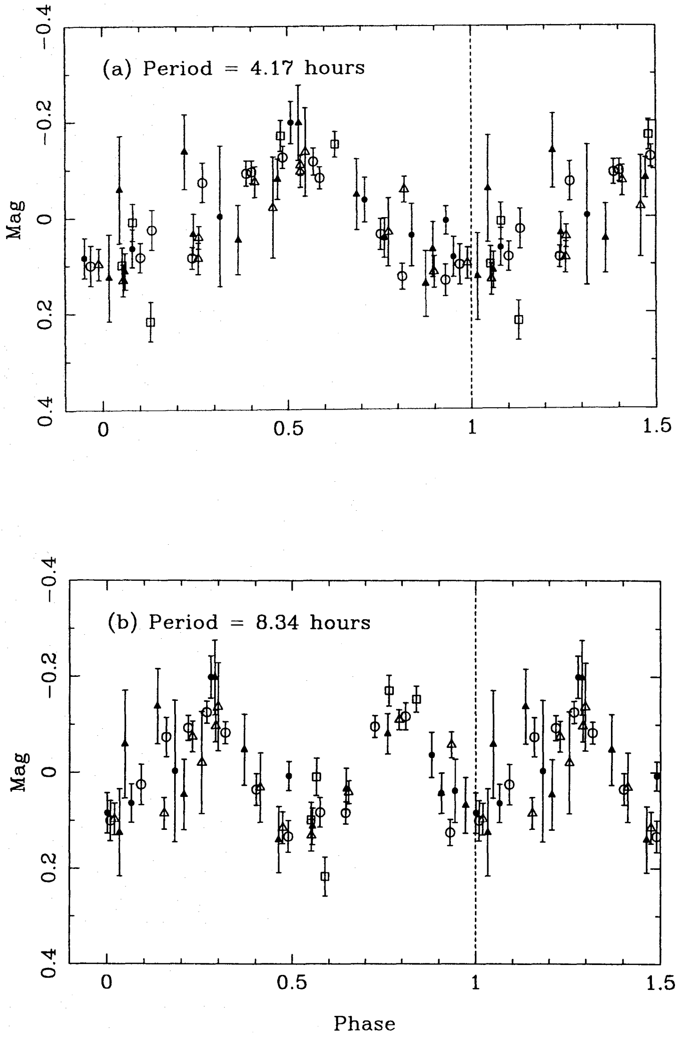

Fig. 4a and b. Differential magnitudes for comet P/Levy folded onto **a** the most probable period from Fig. 3 and **b** twice that period. Data after phase 1.0 (indicated by the dotted line) is repeated to improve the clarity of the lightcurves. Data from separate nights are indicated by different symbols

Table 3. Photometrically derived rotation periods for cometary nuclei, listed in order of decreasing spin rate

Comet	Period (hours)	Ref
P/Schwassmann -Wachmann 2	5.58	Luu & Jewitt (1992)
2060 Chiron	5.92	Bus et al. (1989)
P/Levy 1991XI	8.34	This paper.
P/Tempel 2	8.95	Jewitt & Luu (1989)
P/Arend-Rigaux	13.47	Millis et al. (1988)
P/Neujmin 1	12.68	Jewitt & Meech (1988)
P/Encke	15.08	Luu & Jewitt (1990)
Levy 1990XX	~ 18	Feldman et al. (1992)
P/Halley	53 or 178	Belton (1991)

spread. P/Levy falls comfortably within this range, even though its rotation period is similar to those possessed by main-belt asteroids (Binzel et al. 1989). Therefore although there is still some evidence that comets may indeed rotate slower than asteroids of a similar size, we conclude that this dataset needs to be considerably enlarged before firm conclusions may be drawn.

3.4. Nucleus size and shape

The peak to peak amplitude of the lightcurve is $\simeq 0.3$ magnitudes, corresponding to a projected axial ratios of $1:1.3$. This is a lower limit for the asymmetry of the nucleus, as we do not know the direction of the axis of rotation. In the manner of Luu & Jewitt (1992) we can use this measurement to obtain an lower limit to the density ρ of the nucleus, which is given by assuming a balance between the centripetal and gravitational accelerations at the extrema of an oblate rotating spheroid

$$\left[\frac{2f^2(1-f^2)^{1/2} + f^2\ln f^2 - f^2\ln(2-f^2+2\sqrt{1-f^2})}{(1-f^2)^{3/2}}\right] = -\frac{2\pi}{P^2 G\rho} \tag{2}$$

Here P is the rotation period and f is the ratio of the semiminor and semimajor axes (in this case 1:1.3). This results in a density of the nucleus of P/Levy of $\rho \geq 200$ kg m^{-3}. Although this is a lower limit, it agrees well with the measurements of other nuclei presented in the above work.

The intrinsic magnitude of the comet nucleus at 1 AU from the Earth and Sun and at zero phase angle is given by

$$m_{\rm R}(1,1,0) = m_{\rm R} - 5\log(R\Delta) - \beta\alpha \tag{3}$$

where β is a linear phase coefficient assumed to be 0.04 from previous studies (Luu & Jewitt 1992). As 96% of the observed flux originates from the nucleus, then the absolute (spin averaged) magnitude of P/Levy is $m_{\rm R}(1,1,0) = 13.39 \pm 0.05$. The magnitude of the comet nucleus is related to the geometrical cross-section by the relationship (Russell 1916)

$$\mathrm{p_R} C = \frac{2.25 \times 10^{22} R^2 \pi \Delta^2 10^{0.4(m_\odot - m_{\rm R})}}{10^{-0.4\alpha\beta}} \tag{4}$$

where the denominator expresses the phase angle dependence of the brightness, C is the geometric cross-section, $\mathrm{p_R}$ is the geometric albedo in the R filter, and $m_\odot$ and $m_{\rm R}$ are the R magnitudes of the sun and comet respectively as seen from Earth. From the mean magnitude of the comet on the night of 7th February ($R = 17.65 \pm 0.02$), the product of the cross-section and albedo is in the range $\mathrm{p_R} C = 4.2 \pm 0.2$ km^2 when the uncertainty of coma contamination is taken into account. The majority of cometary nuclei albedos suggest a value of 4% at visible wavelengths (see Fig. 6 in Fitzsimmons et al. 1994). Using this value results in $C = 106 \pm 5$ km^2, or an effective mean radius of $r_{\rm e} = 5.8 \pm 0.1$ km. The lowest albedo yet measured for a comet is 0.02% to 0.03% for P/Neujmin 1 (Campins et al. 1987), resulting in a maximum effective radius of P/Levy of 8.2 ± 0.1 km.

Thus in conclusion P/Levy shares not only a similar orbit to that of P/Halley, but in all probability is of a similar physical size. However, the rate of rotation of P/Levy is very much shorter (by at least a factor of 6.5). P/Levy is similar in rotation period to other known comets and underlines the fact that P/Halley may be highly abnormal in this respect. Whether or not the spin rate is due to the primordial rotation of these bodies, or may be in part due to the torques produced on the nucleus by directed outgassing, is unclear. Hence it is uncertain whether the calculation of an average spin period for known cometary nuclei is of any meaning for classification purposes.

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