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Early Photometry of Comet p/Halley: Development of the Coma[1]

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Broadband charge-coupled device photometry of Comet p/Halley at heliocentric distances R = 5.9 AU (1984 October) and R = 5.1 AU (1985 January) is presented. The mean brightness at R = 5.1 AU is greater than expected from an asteroidal brightness model fitted to earlier photometry. It is likely that this brightness increase is due to the release of dust grains from the nucleus beginning at about R = 5.9 AU. Simple thermal equilibrium sublimation models of a water-ice nucleus are shown to be consistent with weak activity even at R = 5.9 AU, provided the nucleus is dark (Bond albedo $A < 0.15$) and slowly rotating. The brightness of the comet varies on time scales from hours to days, with a range of nearly 1.0 mag at R = 5.9 AU, reduced to about 0.3 mag at R= 5.1 AU. The decrease in the range of the short-term variations is explained by the increased contribution from the coma to the total brightness of the comet. We find no convincing evidence for a dominant period in the short-term variations.

I can hardly doubt that the comet was fairly evaporated . . .
by the heat, and resolved into transparent vapour . . .

John Herschel (1847) of comet Halley
on January 28, 1836

1. INTRODUCTION

There is much to be learned from observations of comets over a large range of heliocentric distances. Such observations might reveal, for instance, the heliocentric distance at which true cometary characteristics first appear and so might provide a critical test of water ice sublimation models. It is generally believed that the sublimation of water ice does not contribute significantly to coma production at distances much beyond 2–3 AU. A few comets have been discovered at large heliocentric distances with very extended comae (e.g., Kohoutek at R = 4.6 AU and Bowell (1980b) at R = 7.3 AU); however, processes other than H_2O sublimation are thought to control the coma formation in these cases. Comet p/Halley is especially interesting in this regard since it was recovered at an unusually large heliocentric distance, more than 3 years before perihelion. In this paper we present photometric evidence of coma formation at $R \approx 5.9$ AU which can be attributed to water-ice sublimation.

The first observations at R = 11.04 AU (Jewitt *et al.*, 1982) marked the beginning of a concerted effort to monitor the brightness as a function of heliocentric distance: we briefly review the main results of this effort. The earliest postrecovery observations

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

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(Belton and Butcher, 1982, 1983; Baudrand *et al.*, 1982; Belton *et al.*, 1983; Sicardy *et al.*, 1983) showed the comet to be stellar, without a hint of coma or tail. Fluctuations in the brightness on time scales of hours and days were reported by several observers while the comet was between $R = 8$ and 11 AU. For example, West and Pedersen (1983) observed a brightness increase of 1.0 ± 0.4 mag at $R \approx 10.6$ AU (between 1982 December 10 and 1983 January 14). They found the image of p/Halley in 1983 January to be somewhat larger than the measured seeing but they could not uniquely attribute the larger profile to coma as opposed to guiding errors. Photometry at $R = 8.2$ AU (1984 January) by Jewitt and Danielson (1984) (hereafter referred to as Paper I) showed a stellar comet image but again with brightness variations of about 1 mag. The variations occurred on time scales less than the diaphragm-crossing time, suggesting that they could not be due to a freely expanding coma of refractory grains. A limit to the surface brightness of any coma was placed at $V_s > 28.0$ mag (arcsec)$^{-2}$ at 4 arcsec from the nucleus. A comparable limit was obtained from observations later in the month by West and Pedersen (1984). Le Fevre *et al.* (1984) reported recurrent brightness increases of about 2 mag when the comet was at $R = 8$ AU (1984 February). They suggested that the variations were caused by rotation of the nucleus, although they did not completely rule-out periodic bursts of dust from the nucleus as being responsible. They were unable to specify the rotation period.

The first clear evidence of coma was announced by Spinrad *et al.* (1984). Their observation of a faint extension 6 arcsec to the north of the nucleus was taken when p/Halley was at $R = 6.1$ AU (1984 September 25–27). Belton *et al.* (1985) obtained long slit spectra of p/Halley at $R = 5.8$ AU (1984 October 30) which showed coma extending approximately 16 arcsec in the sunward direction.

In the following sections we present new photometry of p/Halley obtained when the comet was at $R = 5.9$ and 5.1 AU, during 1984 October and 1985 January, respectively. We compare and contrast our new observations with data obtained at larger heliocentric distances. We argue that sustained mass loss from the nucleus began at about $R = 5.9$ AU, at a rate which is consistent with production by sublimation from a predominantly water-ice nucleus. Observations at larger R are used to characterize the size and overall shape of the nucleus.

2. OBSERVATIONS

The present observations were obtained using the MASCOT charge-coupled device (CCD) camera (Ricker *et al.*, 1981). This two-channel instrument was used in its direct imaging mode with a Johnson filter, R_J (central wavelength 0.7 and 0.2 μm FWHM). The MASCOT was placed at the f/13.5 Cassegrainian focus of the 1.3-m telescope of the McGraw–Hill Observatory on Kitt Peak. The image scale on the 490 × 328 pixel Texas Instruments chip was 1.6 arcsec per 25-μm pixel. Useful images were obtained on the nights of UT 1984 October 22, 24, and 27 and UT 1985 January 18, 19, 20, and 21. Bias level and dawn sky flat-field calibration exposures were taken each night. Intrinsic pixel to pixel sensitivity differences were removed, after bias subtraction, by dividing each image by the nightly mean flat field.

For instrumental reasons, the telescope was tracked at sidereal rate during all observations. In 1984 October the motion of the comet with respect to the stars was canceled by moving the software autoguider by 1 pixel in RA at time intervals corresponding to the expected motion divided by the pixel size. Exposures ranged from 600 to 1200 sec. The maximum trailing of the comet image was of order 1 pixel (1.6 arcsec), which was smaller than the atmospheric seeing (≈2 arcsec FWHM). In October, Comet p/Halley appeared projected so close to the galactic plane that as many as 60% of the observations were affected by glare from bright field stars. The affected observations have not been used in the present work. The October data were obtained during nonphotometric conditions; relative but uncalibrated photometry among frames on each night was established by measuring several bright-field stars on each frame. Absolute calibration was achieved when the nightly October fields were reexposed in photometric conditions in January. A representative image from 1984 October is shown in Fig. 1.

In 1985 January the comet was coincidentally projected against a dark interstellar cloud, thus reducing the problems caused by adjacent bright stars. However, the resulting lack of suitable guide stars forced us to keep exposures short in order to minimize trailing due to the motion of the comet with respect to the sidereal rate. The January seeing was in the range 2–3 arcsec FWHM. Photometric calibration of the data was obtained from observations of the standard stars Feige 34, BD+25°1981, BD+21°607, BD+54°1216, and HD 19445. These observations showed that each of the nights 1985 January 18, 19, 20, and 21 was photometric to better than 3%.

In October, photometry of Comet p/Halley was obtained within square diaphragms of 10–15 arcsec width centered on the apparent nucleus of the comet. The diaphragms were large compared with the atmospheric seeing and with any trailing of the image. Because of the diffuse appearance of the comet in January, the diaphragms were increased to 15–20 arcsec in width. Measurements showed that the brightness of the comet remained essentially constant in all larger diaphragms, implying that there was negligible contribution to the total brightness from any extended coma beyond the diaphragm. The largest source of error in the photometry was the uncertainty in the determination of the sky background. This uncertainty was found to be smaller when using square instead of circular diaphragms, probably because of re-

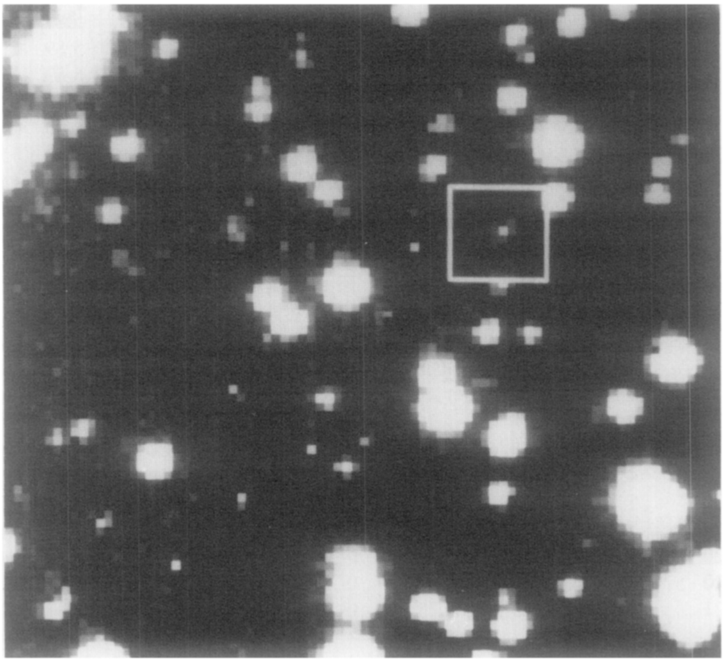

FIG. 1. MASCOT CCD image of Comet p/Halley taken UT 1984 October 24 at 8:41 (observation No. 6 in Table I). North is to the top, east is to the right in the figure. The box around the image of p/Halley is 16 arcsec on a side.

sidual column to column sensitivity differences left after flattening. When faint objects were too close to p/Halley to be excluded from the diaphragm, both the objects and the comet were measured together. Subsequent measurements of the faint objects in all frames where the comet–object separation was large compared to the diaphragm size enabled the comet brightness to be recovered.

A journal of observations is presented in Table I. The first five columns list the observation number, the date, the UT midtime of the observation, the exposure duration in seconds, and the airmass, respectively. The R_J magnitudes of the comet appearing in column 6 of Table I were obtained using extinction coefficients determined nightly from field stars. The uncertainties on the tabulated R_J magnitudes reflect the uncertainties of the sky brightness near the comet in each image (0.1–0.3 mag), extinction correction uncertainty (0.03 mag) and absolute photometric calibration uncertainty (<0.1 mag).

To be consistent with the majority of observations published by other observers, we elect to work in V magnitudes. The con-

TABLE I

p/HALLEY PHOTOMETRY

No.	1984/1985 Date	UT	Exp[a]	Airmass	R_J	$V(1,1,\alpha)$	R[b]	Δ[c]	α[d]
1	Oct 22	9:48	900	1.26	20.49 ± 0.30	13.44	5.90	5.52	9.23
2	Oct 22	10:58	1200	1.11	20.84 ± 0.15	13.79	5.90	5.52	9.23
3	Oct 22	11:29	1200	1.07	20.80 ± 0.30	13.75	5.90	5.52	9.23
4	Oct 22	12:29	1100	1.07	21.08 ± 0.30	14.03	5.90	5.52	9.23
5	Oct 24	8:19	900	1.70	20.62 ± 0.50	13.60	5.89	5.48	9.14
6	Oct 24	8:41	900	1.53	20.58 ± 0.20	13.56	5.89	5.48	9.14
7	Oct 24	9:01	600	1.42	20.46 ± 0.20	13.44	5.89	5.48	9.14
8	Oct 24	9:17	600	1.34	20.49 ± 0.15	13.47	5.89	5.48	9.14
9	Oct 24	9:33	600	1.28	20.77 ± 0.20	13.75	5.89	5.48	9.14
10	Oct 24	10:01	600	1.20	20.31 ± 0.15	13.29	5.89	5.48	9.14
11	Oct 24	12:15	600	1.06	20.49 ± 0.20	13.47	5.89	5.48	9.14
12	Oct 27	9:13	600	1.31	21.27 ± 0.20	14.28	5.87	5.42	9.02
13	Oct 27	9:29	661	1.25	21.16 ± 0.20	14.17	5.87	5.42	9.02
14	Jan 18	3:14	600	1.19	19.38 ± 0.10	13.19	5.12	4.30	6.59
15	Jan 19	2:56	600	1.22	19.14 ± 0.10	12.95	5.11	4.30	6.73
16	Jan 19	3:29	600	1.14	19.11 ± 0.30	12.92	5.11	4.30	6.73
17	Jan 19	4:39	600	1.07	19.22 ± 0.15	13.03	5.11	4.30	6.74
18	Jan 19	5:12	600	1.06	19.44 ± 0.10	13.25	5.11	4.30	6.74
19	Jan 19	7:23	600	1.28	19.51 ± 0.10	13.32	5.11	4.30	6.76
20	Jan 19	7:58	600	1.43	19.40 ± 0.20	13.21	5.11	4.30	6.76
21	Jan 20	2:35	600	1.26	19.32 ± 0.10	13.14	5.10	4.30	6.92
22	Jan 20	3:39	600	1.06	19.31 ± 0.25	13.13	5.10	4.30	6.93
23	Jan 20	4:11	600	1.06	19.00 ± 0.10	12.82	5.10	4.30	6.93
24	Jan 20	5:17	600	1.07	19.04 ± 0.15	12.86	5.10	4.30	6.94
25	Jan 20	5:53	600	1.09	19.15 ± 0.10	12.97	5.10	4.30	6.95
26	Jan 20	6:23	600	1.13	19.19 ± 0.25	13.01	5.10	4.30	6.95
27	Jan 20	6:57	600	1.21	19.28 ± 0.10	13.10	5.10	4.30	6.96
28	Jan 21	2:42	600	1.23	19.01 ± 0.15	12.83	5.09	4.30	7.12

[a] Exposure duration in seconds.

[b] Heliocentric distance in AU.

[c] Geocentric distance in AU.

[d] Phase angle in degrees.

version from the R_J magnitudes presented in Table I has been made assuming solar color $V - R_J = 0.52$ (Allen, 1976). The V magnitudes are plotted as a function of the Julian Date in Fig. 2. We also show photometry from Paper I, using the relations given there for converting between the Thuan and Gunn (1976) g and r filters and the Johnson filters. A heliocentric distance scale is shown at the top of the figure.

The brightness of Comet Halley is seen (Fig. 2) to increase by almost 5 mag between $R = 11$ AU and $R = 5.1$ AU but also to fluctuate on short time scales, with a range of about 1 mag prior to 1984 October. The general brightness increase is largely due to the changing position of the comet relative to the Sun and Earth. The solid line in the figure represents an inert "asteroidal" nucleus model in which the magnitude is taken to vary as

$$V = V(1,1,\alpha) + 5.0 * \log(R * \Delta) \quad (1)$$

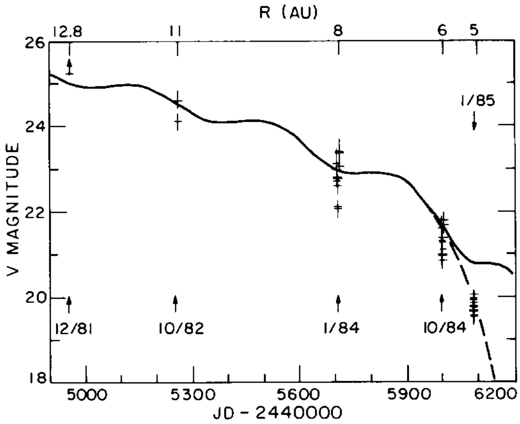

FIG. 2. The Johnson V magnitudes of Comet p/Halley (from Paper I and the present work) are plotted versus Julian Day (JD 2444900 = 1981 October 22.5 UT). The measurement from 12/81 represents a prerecovery magnitude limit. The solid line represents an inert nucleus model with zero phase coefficient (Eq. (1)). The normalization has been determined from observations prior to 1984 October. Note the enhanced brightness of the comet with respect to the inert nucleus on 1/85. The dashed line represents the total V magnitude (contributions from the nucleus and the coma) for a sublimating H_2O nucleus model as described in the text. The heliocentric distance in AU is indicated at the top of the figure.

TABLE II

OTHER SOURCES OF p/HALLEY MAGNITUDES

Date	Heliocentric distance	Reference
12/81	12.80	Felenbok *et al.* (1982)
10/82	11.03	Belton and Butcher (1982)
10/82, 11/82	11.04, 10.86	Sicardy *et al.* (1983); Baudrand *et al.* (1982)
12/82, 1/83	10.72, 10.51	West and Pedersen (1983)
12/82	10.70	Belton and Butcher (1983)
02/83	10.33	Belton *et al.* (1983)
12/83, 1/84	8.21 8.01	Racine (1984); Pedersen and West (1984)
01/84	8.01	West and Pedersen (1984)
02/84	7.96	Belton *et al.* (1985)
02/84	7.96	Le Fevre *et al.* (1984)
03/84	7.75	Belton *et al.* (1984)
09/84	6.13	Spinrad *et al.* (1984)
10/84, 11/84	5.84, 5.60	Belton *et al.* (1985)
11/84	5.60	Wyckoff *et al.* (1985b)
02/85	4.84	Wehinger *et al.* (1985)

where the constant $V(1,1,\alpha)$ is the V magnitude at unit heliocentric distance, $R = 1$, and geocentric distance, $\Delta = 1$, and at phase angle α. (Throughout most of the observing period the phase angle remained small, therefore we have neglected the phase function term in Eq. (1).) Figure 2 shows that the general increase in the brightness of the comet by a factor of 15 from $R = 11$ AU to $R = 5.9$ AU is consistent with the inverse square law (Eq. (1)). By implication, the mean cross section of the comet remained constant over the stated heliocentric distance range, leading us to believe that the nucleus was directly visible prior to $R = 5.9$ AU. Using all available p/Halley observations at $R > 5.9$ AU (i.e., prior to 1984 October; see Tables I and II, and Paper I), the weighted mean value of the constant in Eq. (1) is found to equal

$$V(1,1,\alpha) = 14.17 \pm 0.03 \text{ mag.} \quad (2)$$

The quoted formal uncertainty is the standard error on the mean of 64 observations. Our neglect of the (uncertain) nucleus phase function in Eq. 1 may cause $V(1,1,\alpha)$ to differ from the value given in Eq. (2) by at most a few times 0.1 mag. By 1985 January the comet was consistently brighter than expected from the "asteroidal" model (Eq. (1)), suggesting the presence of a coma about Comet Halley at $R = 5.1$ AU. Specifically, about two-thirds of the light from the comet at this R was due to coma.

3. DISCUSSION

i. Sublimating Nucleus Model

We now use the new photometry, in combination with the photometry of other observers, to constrain the possible mechanisms which might produce the brightness increase observed in p/Halley at $R = 5.1$ AU. In particular, we ask whether the brightness increase seen in 1985 January might be due to mass loss from the nucleus caused by the sublimation of H_2O ice. We stress that the following simple model for the sublimation of a water-ice nucleus contains many free parameters for which only estimates can be made: the model is certainly nonunique. Our intent is simply to show that a sublimating water-ice nucleus model can reasonably account for the presence of coma at $R = 5.1$ AU.

In the absence of gaseous emission features (suggested, for example, by the spectrum of Wehinger *et al.*, 1985), the optical brightness of the comet is due to scattering both from the nucleus and from solid grains in the coma. The brightness of the nucleus is described by Eq. (1), in which $V(1,1,\alpha)$ provides a measure of the product of the optical geometric albedo with the square of the radius of the nucleus.

The amount of scattered light received from the coma is proportional to the total dust grain cross section, $\pi\beta^2$ (m^2), where

$$(p_v\beta^2)_{\text{coma}} = 2.24 \times 10^{22} R^2\Delta^2 10^{0.4(V_0 - V_{\text{coma}})}. \quad (3)$$

Here R and Δ are in AU, $V_0 = -26.74$ is the V magnitude of the Sun (Allen, 1976), p_v is the geometric albedo of the grains in the V filter passband, and $\beta(m)$ is the radius of a sphere of cross section equal to the total grain cross section. The mass of grains within the projected photometry diaphragm is equal to the product of the total mass loss rate from the nucleus, dM/dt (kg $\sec^{-1}$), with the time, t (s), spent in the diaphragm (this relation is valid provided the diaphragm crossing time is short compared with the time for R, hence dM/dt, to change appreciably). The total mass of grains may also be expressed in terms of the grain cross section

$$(p_v\beta^2)_{\text{coma}} = \left(\frac{3p_v}{4\pi\rho a}\frac{dM}{dt}\right) t \quad (4)$$

where $\rho = 1000$ kg m^{-3} is the assumed grain density, and the representative grain size is taken to be $a = 1$ μm. (The absence of a blue continuum in p/Halley (Brooke and Knacke, 1985; Wehinger *et al.*, 1985) suggests that the mean grain size is larger than a wavelength.) The diaphragm crossing time in Eq. (4) may be approximated by $t = x/v$, where x (m) is the projected diaphragm radius at the comet and v (m $\sec^{-1}$) is the average speed of the grains relative to the nucleus. The empirical relation of Bobrovnikoff (1954), as modified by Delsemme (1982), $v \approx 600R^{-1/2}$ m $\sec^{-1}$ (R in AU), provides a useful approximation to the grain velocity. The total brightness of the grain coma, in magnitudes, is found by combining Eqs. (3) and (4):

$$V_{\text{coma}} = 30.7 - 2.5 \log\left(\frac{p_v(dM/dt)t}{\rho a R^2\Delta^2}\right). \quad (5)$$

The total mass loss rate in Eq. (5) may be obtained from the energy balance equation for a sublimating nucleus in thermal equilibrium, neglecting conduction:

$$F_0(1 - A)/R^2 = \chi[\varepsilon\sigma T^4 + L(T)(dm_s/dt)] \quad (6)$$

where F_0 is the solar constant, χ is a "rotation parameter" (equal to 2 for a slowly rotating nucleus and equal to 4 for an isothermal nucleus or one in rapid rotation), ε is the infrared emissivity, and σ is the Stephan–Boltzman constant. We define a rapidly (slowly) rotating nucleus to be one which has a rotation period which is short (long) compared to the time required for the nucleus to attain thermal equilibrium. For the purpose of these computations we set the Bond albedo $A = p_V$. The latent heat as a function of temperature, $L(T)$ (J kg^{-1}), is determined from a fit to data from Delsemme and Miller (1971) made by Cowan and A'Hearn (1982) (see Appendix). The mass loss rate per unit area, $dm_s/dt = (dM/dt)/(\chi\pi\beta^2)$, is related to the sublimation vapor pressure, $P(T)$, via

$$\frac{dm_s}{dt} = P(T)[\mu m_h/2\pi kT]^{1/2} \qquad (7)$$

where $[2kT/\mu m_h]^{1/2}$ is the thermal gas velocity. The sublimation vapor pressure is obtained from an empirical fit to data by Washburn (1928) (see Appendix).

Equations (6) and (7) were solved iteratively for dm_s/dt and combined with Eq. (5) and the nuclear magnitude (Eq. (1)) to produce the model plotted in Fig. 2 as a dashed line. The parameters and assumptions used in all the model computations are summarized in Table III. Models including both rapid and slow nucleus rotation have been computed, although only a slowly rotating ($\chi = 2$) nucleus model has been plotted. Note from the figure that this model fits the observations rather well. The rapid nucleus rotation models, however, do not fit the data. They more closely resemble the asteroidal nucleus model because rapid rotation lowers the mean surface temperature of the nucleus, thereby reducing sublimation. For the same reason, only low albedo nuclei ($A < 0.15$) gave significant sublimation near $R = 6$ AU.

The constant $V(1,1,\alpha) = 14.17$ (Eq. (2)), when substituted into Eq. (3), gives a nucleus cross section

$$p_V\beta_n^2 = (0.97 \pm 0.03) \times 10^6 \text{ m}^2. \qquad (8)$$

The cross section given in Eq. (8) may be taken to refer to the bare nucleus of p/Halley, since no coma was apparent at $R \geq 8$ AU. An effective nucleus radius, β_n, in the range

$$2.5 \leq \beta_n \text{ (km)} \leq 7.0 \qquad (9)$$

is computed from Eq. (8) using albedos suggested by the model ($0.02 < p_V < 0.15$). Formally, sublimation models which fit the photometry can be constructed with $p_V = 0$. However, $p_V = 0.02$ is the practical lower limit on the albedo, here set equal to the albedo of the darkest known Solar System

TABLE III

H_2O Model Parameters

Model parameter	Symbol	Value[a]	Units	Notes
Nucleus cross section	$p_v\beta^2$	0.97×10^6	m^2	Eq. (8)
Geometric albedo	p_v	0.02–0.15		Typical for dark bodies
Bond albedo	A	0.02–0.15		Set equal to p_v
Infrared emissivity	ε	0.85–0.90		
Phase function	$\varphi(\alpha)$	0		Assumed
Density	ρ, ρ_n	$0.7\text{–}1.3 \times 10^3$	kg m^{-3}	For water ice
Grain size	a	$1\text{–}1.5 \times 10^{-6}$	m	See text
Atomic mass	μ	18		H_2O
Dust/gas ratio		1		
Spin parameter	χ	2, 4		Slow, fast

[a] Ranges of parameters which produce sublimating water nucleus models consistent with the data.

objects. The upper limit on the albedo, hence the lower limit on the radius of the nucleus, is well constrained, since water-ice sublimation models using $p_V > 0.15$ cannot be made to fit the photometry. The low nucleus albedo suggests that the surface ice is dirty.

ii. Comparison with Other Observations

The agreement between the model of a dark, slowly rotating nucleus and the observations persists when the observations of other investigators are included. Figure 3 presents the absolute $V(1,1,\alpha)$ magnitudes of p/Halley calculated using data from this paper, from Paper I, and from the many sources listed in Table II. The horizontal line in the figure represents the "asteroidal" nucleus model (Eq. (1)). Solid lines show two slow-rotation nucleus models with input parameters as listed in Table III. The smaller values quoted in the table (i.e., slow rotation, low albedo) produce the model which has the highest mean surface temperature and so shows the earliest onset of coma production. It is apparent from Fig. 3 that measurable coma production may have begun on the nucleus of p/Halley as far out as $R \approx 5.9$ AU (1984 October). The water model can readily account for the coma observed at $R = 5.9$ AU, provided the nucleus is both dark and slowly rotating. The model successfully reproduces the observed rapid brightness increase at smaller heliocentric distances.

The October images of the comet discussed in this work showed no evidence of an extended coma down to a limit of ≈26.8 mag arcsec^{-2}. A low surface brightness coma ($V_s > 27$ mag arcsec^{-2}) could therefore have gone unnoticed in October. In contrast, the images of p/Halley in 1985 January were somewhat extended and diffuse. Figure 4 presents a surface brightness profile of the comet on UT January 20.25

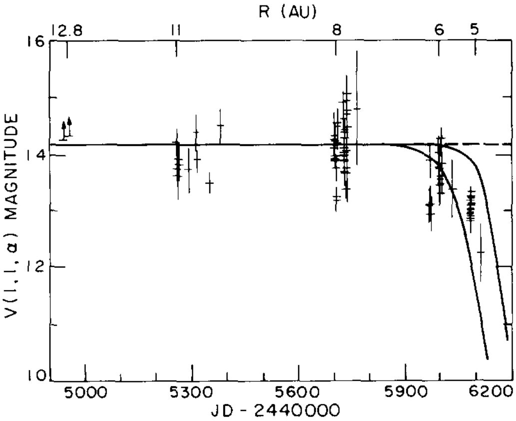

FIG. 3. The total $V(1,1,\alpha)$ magnitude of p/Halley (magnitude reduced to unit R and Δ) is plotted versus Julian Day. Data are from the present work, from Paper I, and from sources listed in Table III. The absolute visual magnitude of the nucleus, $V(1,1,\alpha) = 14.17$, is shown as a horizontal line. The solid lines represent two sublimation models of a low albedo, slowly rotating nucleus with a plausible range of input parameters as described in the text.

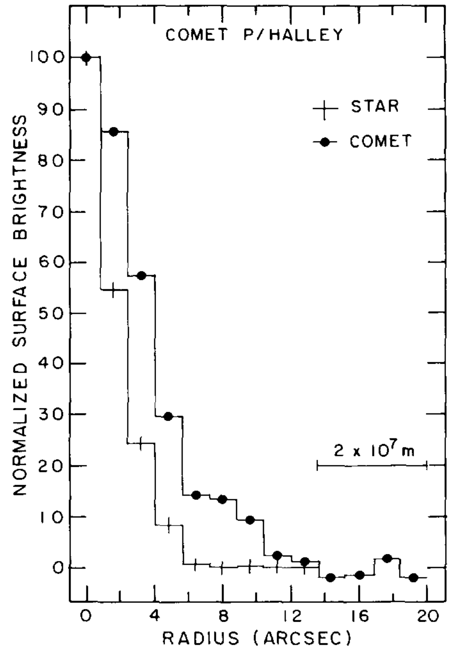

FIG. 4. Azimuthally averaged surface brightness distribution of Comet p/Halley in 1985 January (observation No. 25 in Table I). The surface brightness distribution from a field star on the same image is shown for comparison. The curves have been normalized to 100 surface brightness units at the peak. For Comet Halley this corresponds to $V_s = 23.7$ mag arcsec^{-2}. The average sky brightness near the comet is ≈21.8 mag arcsec^{-2} in the V filter.

computed by azimuthal averaging of pixels in concentric annuli centered on the nucleus. A star profile from the same CCD image is shown for comparison. The star and comet profiles are normalized to the same peak surface brightness. For Comet Halley, 100 surface brightness units corresponds to $V_s = 23.7$ mag arcsec^{-2}. Figure 4 clearly shows coma extending several times 10^7 m from the nucleus of p/Halley in 1985 January. The fact that photometry from 1984 October to 1985 February and beyond shows a growing separation from the inert nucleus model (see Fig. 3), suggests strongly that *sustained* coma production began near 1984 October at $R \approx 5.9$ AU.

Recently, Cruikshank *et al.* (1985) have claimed to measure the color and size of the *nucleus* of Comet p/Halley using observations taken at $R = 4.8$ AU (1985 February). However, when compared with Fig. 3, their photometry is similar to other photometry reported near this time and the comet is brighter than expected from the asteroidal nucleus model (Eq. (1)) by about 1.2 mag. Hence we believe that their observations refer as much to the coma as they do to the nucleus, and are consistent with our finding sustained coma production in February.

Another recent paper, by Wyckoff *et al.* (1985a), presents photometry derived from continuum spectra of Comet p/Halley. They use their four data points, in addition to a small subset of the p/Halley data published prior to 1985 February, to suggest that the onset of sublimation began near 6 AU. The spectra taken in February, March, and April of 1985 were obtained several months after the brightening of the comet seen in 1984 September and October. Assuming a $1/r$ coma profile, and using the estimate that $\approx$60% of the total light was contributed by the coma in January, the correction for their diaphragm size (2.5 arcsec radius) is estimated to be at least 1 mag. Even without correcting for their use of a small diaphragm, the photometry from the spectra is more than 1 mag brighter than the asteroidal model. The present work strengthens the conclusion that the coma formation began around 6 AU and further shows that it is consistent with sublimation from a predominantly water-ice nucleus of low albedo.

The optical cross section of the nucleus derived by Wyckoff *et al.* (1985a) appears to be in error by a factor of π, but otherwise agrees with the value in our Eq. (8), within the uncertainties of measurement.

iii. Other Coma Producing Mechanisms

We briefly consider mechanisms, other than water-ice sublimation, which might produce a grain coma. Other comets which appear active at large R, such as Kohoutek, have comae which may be controlled by the sublimation of substances more volatile than water, such as CO_2 (Delsemme, 1975). The model in Section 3i was used to compute a lightcurve for a coma produced by pure CO_2-ice sublimation, using the latent heat measured by Smith (1929) and the vapor pressure as fit to data by Eggerton and Edmondson (1928) (see Appendix). When restricting the albedo of the nucleus to fall within the range of known Solar System albedos, the resulting CO_2 nucleus sublimation model does not fit the p/Halley photometry in the sense that the CO_2 model yields a curve which is too shallow to follow the rapid brightening of p/Halley seen after 1984 October. However, if albedos of $p_v > 0.9$ are allowed, the resulting CO_2 sublimation model does follow the rapid brightening of the comet seen around 5.9 AU. Nevertheless, the fit to the data is not as good as the fit obtained from H_2O ice. For this reason, and because such high albedos are not typical, we find no evidence that CO_2 *controlled* the onset of sublimation of p/Halley seen at $R = 5.9$ AU. However, we cannot exclude the possibility that small amounts of volatiles other than H_2O are present.

It has been suggested by Lanzerotti *et al.* (1978) that the dominant process for the erosion of water ice from the surfaces of interplanetary grains at large heliocentric distances is sputtering by energetic solar wind protons. From Fig. 1 of their paper, the water-ice erosion rate at $R = 5.9$ AU corresponds to $dM/dt \approx (1\text{–}10) \times 10^{-7}$ kg sec^{-1} when integrated over the surface of a nucleus of radius 3–7 km. The mass loss rate computed using the present model at the same heliocentric distance is $dM/dt \approx (4\text{–}40) \times 10^{-3}$ kg sec^{-1}. Hence, sputtering by solar wind protons gives a mass loss rate many orders of magnitude too small to be considered a plausible coma producing mechanism, even in 1984 October.

The amorphous-to-crystalline phase transition in water ice may provide an internal energy source in comets (Klinger, 1980). The transition occurs at temperature similar to the probable nucleus temperature of p/Halley at the time of its first activity ($T \approx 135$ K). However, the transition does not represent a likely energy source for Comet p/Halley since the outer layers of its nucleus have almost certainly been heated above this temperature during previous orbits (for instance, on the outbound leg of the previous orbit).

iv. Nucleus Rotation

We concluded, from the photometry in Section 2, that the bare nucleus was visible at $R > 5.9$ AU, raising the question of the origin of the brightness fluctuations seen at large distances. Possible explanations include rotation of the irregular nucleus and the transient ejection of matter from the nucleus. The observed decrease in the range of the brightness fluctuations, from 1.0 mag at $R \geq 8$ AU, to 0.8 mag at $R = 5.9$ AU, to 0.3 mag at $R = 5.1$ AU, strongly suggests that the mechanism producing the fluctuations *is* nucleus rotation but diluted by increasingly large amounts of coma. The invariance of the reduced magnitude $V(1,1,\alpha)$ at $R > 5.9$ AU also suggests that the nucleus is directly observed.

The observations listed in Table I were used to attempt to find the rotation period of the nucleus of Comet p/Halley. For this purpose, the data from 1984 October and from 1985 January were reduced separately. A minimum χ^2 fit of a sinusoid to the 1984 October observations found χ^2 minima at several periods including relatively deep ones at

$$T_1 = 8.3 \pm 0.1 \text{ hr}$$
$$T_2 = 12.7 \pm 0.2 \text{ hr}. \qquad (10)$$

These periods are aliassed by the 24-hr sampling interval used in the observations. The fit for T_1 with a range of 0.8 mag is shown in the upper panel of Fig. 5. For January, the fit revealed relatively deep χ^2 minima at several periods including

$$T_3 = 6.6 \pm 0.1 \text{ hr}$$
$$T_4 = 9.3 \pm 0.2 \text{ hr}, \qquad (11)$$

each with a range of about 0.3 mag. These periods are also aliassed by the sampling

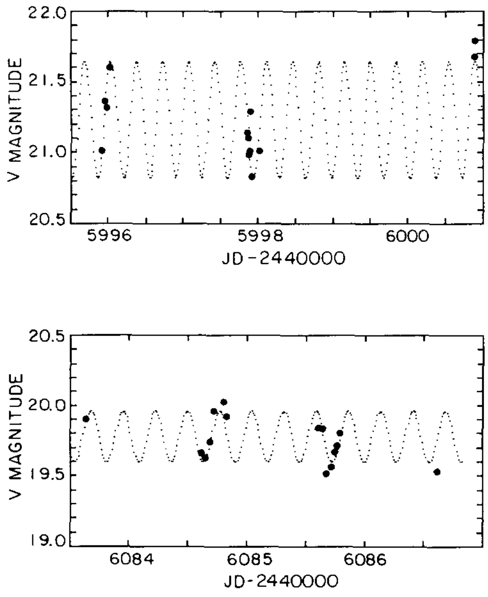

FIG. 5. The results of separate least-squares fits to the photometry of 1984 October and 1985 January are plotted. Photometry in the upper panel is from 1984 October: the best fit sinusoid has range 0.8 mag and period $T_1 = 8.3$ hr. Photometry in the lower panel is from 1985 January: the best fit sinusoid has range 0.3 mag and period $T_3 = 6.6$ hr. No common period has been found which fits both the 1984 October and the 1985 January data. The error bars on the photometry have been omitted for clarity (see Table I for errors).

interval. The fit for T_3 is shown in the lower panel of Fig. 5. Unfortunately, no single period was found which provided good agreement with the data from both 1984 October and 1985 January. It is possible that fluctuations in the relatively strong coma in 1985 January modify the apparent period. If so, we must attach greater significance to the periods found in the 1984 October data. Even so, it is difficult to pinpoint the nucleus rotation period from the available photometry. The 8.3-hr period sinusoid fits the photometry and would imply a nucleus rotation period near 16.7 hr, if rotational symmetry of the lightcurve is assumed. However, the 12.7-hr alias of the 8.3-hr sinusoid also fits the photometry, within the uncertainties of measurement, and suggests a nucleus period near 25.4 hr. In the absence of additional photometry, we cannot unambiguously specify the rotation period of the nucleus of p/Halley, although we are confident that the rotation period is at least a large fraction of a day.

In principle, independent evidence for periodicity in the data might be obtained from examination of a histogram of the $V(1,1,\alpha)$ magnitude distribution. A bimodal distribution is expected from any periodic lightcurve, since there is a higher probability of finding the nucleus near the extremities of its photometric range than near the mean. For a sinusoidal variation, $x = x_0 \sin \omega t$, we find

$$dP = \frac{1}{x_0 \pi} \frac{dx}{[1 - (x/x_0)^2]^{1/2}} \qquad (12)$$

where dP is the probability of finding x in the range x to $x + dx$. This distribution is illustrated in the upper panel of Fig. 6. The plotted histogram was constructed from 500 data points sampled continuously along one period of a sine curve.

The observations from 1984 October are plotted in the histogram in the lower panel of Fig. 6. Numerical models, which were constructed by simulating the same sampling method as used to obtain the data, produce histograms which are similar to that in the lower panel. The models suggest that the clear bimodal distribution of Eq. (12) may be hidden in the real data by the effects of irregular and infrequent sampling. In addition, errors in the data equal to a significant fraction of the range of the variation would also cause the bimodal distribution to be smoothed out. The difference between the observed magnitude distribution and the model is therefore not constraining. (In the limit of errors large compared to the range we expect the distribution to approach the Gaussian error distribution. In fact, a histogram constructed from all available observations through 1984 October is closer to a Gaussian than to a bimodal distribution, probably due to relative uncertainties present among disparate data sets.) We reluctantly conclude that the distribu-

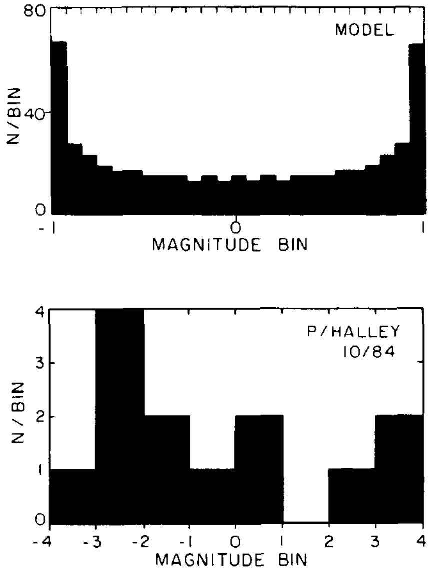

FIG. 6. Upper panel: The histogram formed from a continuous sample of 500 data points from one period of a model sinusoid (see section iv for description). Magnitude bins are plotted along the horizontal axis. Bin zero corresponds to the mean magnitude of the sine curve. Note the bimodal shape of the distribution (see also Eq. (12)). Lower panel: The histogram formed from the 13 observations of p/Halley obtained in 1984 October. The mean magnitude of the observations of 1984 October is $V = 21.24 \pm 0.30$ mag ($V(1,1,\alpha) = 13.70 \pm 0.30$). Each bin is 0.12 mag wide. The magnitude distribution is not obviously bimodal.

tion of cometary magnitudes does not provide any conclusive evidence concerning the existence of periodicities in the photometry.

Many investigators besides ourselves have tried and failed to determine the rotation period of the nucleus p/Halley from observations taken since its recovery (e.g., Paper I; Le Fevre *et al.*, 1984; West and Pedersen, 1984; Sekanina, 1985; Morbey, 1985). If the short-term brightness fluctuations are due to nucleus rotation, why have investigators been unable to find the rotation period? We believe that photometric errors and incomplete sampling are the two main reasons for our failure to find the nucleus rotation period. On the one hand, aggregates of observations by different observing groups are susceptible to relative systematic errors of measurement and are therefore very difficult to compare. For example, Le Fevre *et al.* (1984) report brightness variations consistently about a factor of 2 greater than those reported by either West and Pedersen (1984) or Jewitt and Danielson (1984). On the other hand, subsets of observations taken using a single detector and telescope are free of systematic errors but are too small to firmly establish the period. Although the systematic decrease in the amplitude of variation strongly suggests that the brightness fluctuations are caused by rotation of the nucleus, it is also possible that the data are affected by transient nucleus activity (such as outgassing from volatiles other than H_2O) even prior to the onset of sustained water sublimation at $R \approx 5.9$ AU. This, in addition to the factors described above, probably contributes to the difficulty in obtaining a period for p/Halley which is consistent with all of the data.

4. CONCLUSIONS

1. The observed increase in the mean brightness of Comet p/Halley, from $R = 11$ AU to $R = 5.9$ AU, is consistent with the increase expected of an "asteroidal" nucleus devoid of a coma. Most of the light from the comet at $R > 5.9$ AU was scattered from the bare nucleus.

2. A coma was present at $R = 5.1$ AU (1985 January). About 60% of the light from the comet at $R = 5.1$ AU was due to scattering from this coma. The photometry suggests that sustained coma production began near $R = 5.9$ AU (1984 October).

3. The formation of the dust grain coma beginning at $R \leq 5.9$ AU may be due to the equilibrium sublimation of water ice on the nucleus of the comet, provided the nucleus is both dark (Bond albedo $A < 0.15$) and slowly rotating. It is not necessary to invoke any more exotic processes to account for the activity observed at large R. Sputtering by solar wind protons is unable to account for the brightness increase seen at $R = 5.1$ AU.

4. The rotationally averaged value of the product of the optical geometric albedo of the nucleus with the square of the radius is 0.97 ± 0.03 km^2 (standard error on the mean of 64 observations). The product varies with rotation in the range 0.5–1.5 km^2. The implied mean nucleus radius is in the range 2.5–7.0 km for geometric albedos from 0.02 to 0.15.

5. Brightness variations on time scales from hours to days were seen at all heliocentric distances in the range 11.0 to 5.1 AU. The range of these short-term variations decreased from about 1.0 mag at $R > 8$ AU to 0.8 mag at $R = 5.9$ AU and 0.3 mag at $R = 5.1$ AU. This decrease is probably due to the increased contribution from the coma to the total light from the comet. If attributed to geometric effects alone, the magnitude range of the nucleus suggests an axis ratio of order 3 : 1.

6. No period of rotation has been found which is consistent with both the 1984 October and 1985 January photometry. We suspect that photometric errors, inadequate sampling, and possible fluctuations due to irregular outgassing of volatiles other than H_2O conspire to hide the rotation period from us.

APPENDIX

The formulae for the latent heats and vapor pressures used in this paper are as follows. All latent heats, $L(T)$, are in J kg^{-1} and pressures in N m^{-2}.

$$L_{H_2O}(T) = 2.863 \times 10^6 - 1.106 \times 10^3 * T \qquad \text{(after Cowan and A'Hearn, 1982)}$$

$$\log(P_{H_2O}/760) = -2445.5646/T + 8.2312 * \log(T) - 0.0167706 * T + 1.20514 \times 10^{-5} * T^2 - 1.757169 \qquad \text{(Washburn, 1928)}$$

$$L_{CO_2}(T) = 5.724 \times 10^5$$

$$\log(P_{CO_2}/760) = -1367.3/T + 14.9082 \qquad T > 138 \text{ K}$$

$$\log(P_{CO_2}/760) = -1275.6/T + 0.00683 * T + 13.307 \qquad T < 138 \text{ K}$$

(Eggerton and Edmondson, 1928)

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Additional note (January 13, 1986). Preliminary analysis of near-IR and thermal IR data taken UT 1985 November 12 at the NASA IRTF indicates that the albedo of the grains in the coma of p/Halley is $p_v \approx 0.07$. If the albedo of the nucleus is the same as the albedo of the grains, then the mean equivalent spherical radius of the nucleus is $\beta_n = 3.7 \pm 0.1$ km (standard error on the mean of 64 observations).

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