COMETARY BRIGHTNESS VARIATION AND NUCLEUS STRUCTURE*

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Abstract. The Bobrovnikoff and Beyer photometric data for more than 100 comets have been analyzed for intrinsic brightness variations, *before* and *after* perihelion, according to the r^{-n} law, where r is solar distance. The Oort and Schmidt classification of comet 'age' has been extended and applied with Marsden's new determinations of inverse semi-major axis, $1/a$, original. All classes of comets with $P > 25$ yr show statistically the same value of n *after* perihelion. New comets approach perihelion with smaller values of n and older comets with increasingly larger values (Table II). For comets of $P < 25$ yr, n is larger and erratic.

A physical interpretation involves the quick loss of a frosting of super-volatile materials from new comets; then, for all comets, the development of an insulating crust after perihelion. The crust also includes 'globs' of meteoroidal and icy material. The crust tends to be purged near perihelion but generally to grow in a spotty fashion with cometary age. The orientation of the axes of rotating comets is shown to be an important unknown factor in cometary brightness variations. A speculation is made concerning the axis of rotation for C/Kohoutek, 1973 XII.

1. Introduction

The purpose of this paper is to refine the statistical observational relationships between comet 'ages', in the Oort (1950) sense, and their luminosity variations with solar distance, *before* and *after* perihelion separately. From these new observational correlations some qualitative understanding of the changes in the surface structures with cometary age emerges. Attention is also given to certain photometric effects that may be expected from the orientation of the rotation axes of cometary nuclei. A relevant suggestion is made with regard to the rotation axis and photometric behavior of C/Kohoutek, 1973 XII. Specifically, the marked difference in the intrinsic light curve of this 'new' comet compared to that of 'old' P/Halley is shown in Figure 1.

It becomes clear that many questions about comets and their origin must await a space mission, particularly a rendezvous mission, to a comet.

Oort (1950) first classified comets by means of their 'original' orbits, at great heliocentric distances before they enter the planetary regions. He designated 'new' comets as those that make their first entrance into the inner solar system from the great solar-bound cloud. From Schmidt's (1950) study of cometary brightness variations, Oort and Schmidt (1950) then found that 'new' comets show a less rapid increase of

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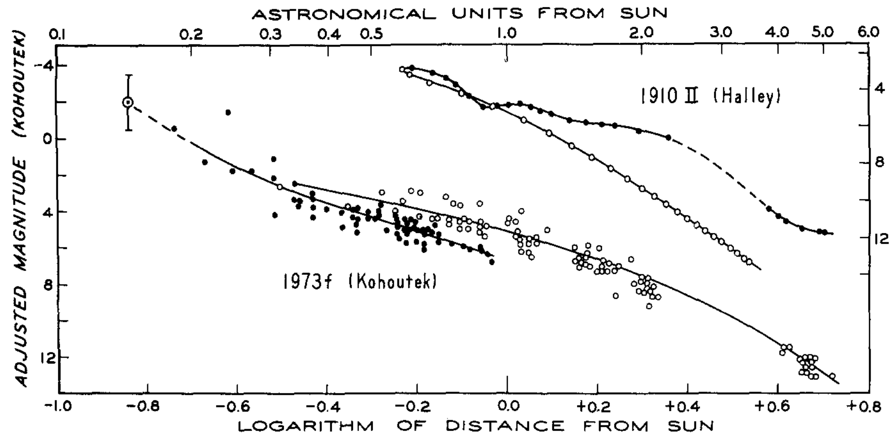

Fig. 1. Magnitudes of P/Halley and C/Kohoutek corrected to Earth-distance, $\Delta = 1.0$ AU, by Luigi G. Jacchia; *circles*, before perihelion; *dots*, after perihelion. Courtesy *Sky and Telescope Magazine*.

intrinsic brightness with decreasing heliocentric distance than older comets. They also found that new comets are statistically more dusty, showing a stronger continuous to band spectrum ratio than older and shorter-period comets while simultaneously displaying tails of different types.

Regarding the physical nature of comets, Oort and Schmidt concluded that newer comets show a more rapid rate of deterioration than older comets and that they must contain more volatile gases. Hruška and Vanýsek (1958) extended the photometric studies of comets both on the basis of Levin's photometric parameters and also with the classical parameters, 'absolute' magnitude H and the exponent n of the solar radius vector r, coupled with an inverse square law of geocentric distance Δ, all related by

$$H_0 = H + 5 \log \Delta + 2.5n \log r, \tag{1}$$

where H_0 is the observed magnitude.

Hruška and Vanýsek found, consistent with the results of Oort and Schmidt, that the average value of n decreases by nearly 50% from short-period comets to very long-period comets and that comets showing a significant continuous spectrum exhibit an even smaller average value of n. Furthermore, the average value of n reaches a peak between 1 and 2 AU. For comets of semi-major axis, $a \geqslant 500$ AU, the peak value of $\bar{n}$ is reached with $1.5 < r < 2.0$ AU before perihelion, while after perihelion it is reached in the range $1.0 < r < 1.5$ AU. For $r > 2$ AU, $\bar{n}$ is generally smaller after perihelion than before. Hruška and Vanýsek then applied a dust–gas model of a comet in which the dust observed in a comet with a continuous spectrum is the order of 10^{11} g and in which the observed dust/gas ratio increases with heliocentric distance.

In a more recent and more complete study, Meisel and Morris (1976) find no correlation of n with q but point out an effect of q on H_0, caused by telescope aperture.

They list a set of well documented warnings concerning the use of the comet magnitude derived by various photometric techniques and instruments. Because of these problems inherent in comet photometry, I have limited the present study to the observations treated by Bobrovnikoff (1942) and the observations made by Beyer (1933–1972). Generally the corrections made by Bobrovnikoff for telescope aperture are accepted by the major workers in this field and, as such, set a standard that I have adopted. Empirically I find that the values of n derived from Beyer's observations agree well with those by Bobrovnikoff if multiplied by a factor of 0.7. Meisel and Morris apply a corresponding correction of 1.5 units to Beyer's determinations of n.

My goal is to concentrate on comparative values of n *before* and *after* the perihelion passages of comets. Hence, homogeneity in long series of data is most important. The compilation by Schmidt contains very few pre-perihelion measures and so is not included. A very much greater effort would be required to utilize effectively the much larger mass of material now available.

2. The Basic Data

After the pioneering effort by Oort and Schmidt, the systematic and intensive orbit calculations by Marsden (1975 and private communication), Marsden and Sekanina (1973) and Everhart (1968) have established the 'original' values of $1/a$ for long-period comets nearly to the limit of possible precision, set by the observations. Hence it is now possible to classify almost all the well observed comets with confidence. I have followed the principles of the Oort and Schmidt classification for the 'age' of comets but redefined the limits and added Class V of short-period comets, essentially the Jupiter family.

The class definitions based on the 'original' value of $1/a$, well beyond the planets, are as follows:

Class I:	$1/a < 50 \times 10^{-6}\,\mathrm{AU}^{-1}$ (Per. $> 2.8 \times 10^6$ yr),
Class II:	$50 \times 10^{-6} < 1/a < 2154 \times 10^{-6}\,\mathrm{AU}^{-1}$ ($10^4 <$ Per. $< 2.8 \times 10^6$ yr),
Class III:	$2154 \times 10^{-6} < 1/a < 10^{-2}\,\mathrm{AU}^{-1}$ ($10^3 <$ Per. $< 10^4$ yr),
Class IV:	$25 <$ Per. $< 10^3$ yr (osculating orbits),
Class V:	Per. < 25 yr (osculating orbits),
Parabolic:	Excluded.

The effects of non-gravitational forces reduce the inherent accuracy of $1/a$ for comets with moderate to small perihelion distances, as pointed out by Marsden and Sekanina (1973). Hence the limit of $1/a < 50 \times 10^{-6}\,\mathrm{AU}^{-1}$ does not guarantee that a comet is entering the inner solar system for the first time, a truly *new* comet in the Oort sense. On the other hand, because there appears to be a low frequency of true $1/a$ values in the range $50 < 1/a < 100 \times 10^{-6}\,\mathrm{AU}^{-1}$, the dilution by second or third apparition comets in Class I is probably small. More likely the 'new' comets dilute Class II.

Because the average perturbation in $1/a$ by a passage through the inner solar system to 1 AU is the order of $500 \times 10^{-6}\,\mathrm{AU}^{-1}$ (Fayet, 1910; Van Woerkom, 1948) the

Class II comets, as defined above, will mostly have made a few previous returns. Everhart (1972) places the number in the range 2 to 10. The establishment of Class II orbits is essentially a buffer between new comets and those that have made a considerable number of returns, Class III.

The distinction between Class III and Class IV orbits is arbitrary and possibly artificial. From Everhart's studies (1972) the statistical fluctuations in the number of returns among comets in this long range of period is enormous. The number of returns may well range from ten to many thousands. We shall find, however, a trend in $\bar{n}$ with class.

Parabolas are excluded from discussion here, for two reasons. For comets where Marsden has not been able to determine $1/a$ with reasonable accuracy, the spread in the possible values of $1/a$ range from Class I well into Class III or even Class IV. Thus any dependence of $1/a$ upon class is completely blanketed. Furthermore, parabolas represent comets that were observed inadequately for position and also for magnitude. Of eleven studied, none gave reliable values of n before perihelion. Hence, parabolic comets could not contribute to the solution of the major problem of this paper.

With regard to the basic magnitudes of comets the data are all from Bobrovnikoff and Beyer. Recalculations of H and n via a least squares solution from Equation (1) were made whenever the original calculations included observations through perihelion. In a few cases the number of observations or the range in r were inadequate for a meaningful solution, but were kept for completeness.

Tables Ia to Ie contain the basic data and calculated values of H and $\bar{n}$. The format of Tables Ia to Ie, corresponding to Classes I to V, respectively, is as follows:

Col. 1. Comet designation.
2. Perihelion distance, q, in AU.
3. Inclination to the ecliptic (1950.0) i, deg.
4. $1/a \times 10^{+6}\,\mathrm{AU}^{-1}$ (or, in Table Ie and Id, period in year osculating).
5. Behavior at perihelion: B = Brightening, F = Fading, Sp = Split, O = Flat.
6. Before (−) or after (+) perihelion.
7. Solar distance: r_1 first observation; r_2 last observation.
8. Absolute magnitude, H by Equation (1).
9. Standard deviation in H.
10. Exponent of r (Equation (1)), n.
11. Standard deviation in n.
12. Calculated by: Bo = Bobrovnikoff, Be = Beyer, W = Whipple.

The observational data of Bobrovnikoff are included in the upper part of each table and of Beyer in the lower part.

Notes to comets are indicated by an asterisk and listed at the bottom of each table. In the analysis, comets 1951 IV and 1962 V (P/Tuttle–Giacobini–Kresák) and comets

TABLE Ia

Class I comets, Per. $> 2.8 \times 10^6$ yr $1/a$ (orig.) $< 50 \times 10^{-6}$ (AU)$^{-1}$

Comet	q (AU)	i	$1/a \times 10^{+6}$	At q	±	r_1 (AU)	r_2 (AU)	H mag.	$\pm\sigma$	n	$\pm\sigma$	C
1886 IX	0.66	102	46	B	−	1.14	0.68	4.8	0.2	2.4	0.9	W
1899 I	0.33	146	−109	B	+	0.72	1.78	6.2	0.3	4.5	0.9	W
1902 III	0.40	156	27	—	−	1.74	0.58	6.8	0.1	2.6	0.1	Bo
1903 IV	0.33	85	33	—	−	1.51	0.39	6.5	0.1	2.4	0.1	Bo
1912 II	0.72	79	45	—	+	0.72	2.04	6.3	0.1	3.2	0.2	Bo
1914 V	1.10	68	29	F*	−	3.74	1.11	1.9	0.1	2.9	0.3	W
					+	1.10	2.52	2.2	0.1	3.0	0.2	W
1917 III	1.69	26	17	B	−	2.02	1.69	11.0	1.6	−2.3	2.4	W
					+	1.69	2.25	7.8	0.7	2.8	1.0	W
1921 II	1.01	132	18	O	−	1.17	1.01	6.9	0.1	5.6	1.1	W
					+	1.01	1.12	7.0	0.1	8.5	2.9	W
1925 I	1.11	100	40	—	+	1.01	1.12	5.9	0.3	3.3	0.6	Bo
1932 VI	2.31	125	45	—	+	1.16	1.79	5.1	0.8	2.5	0.6	Bo
1941 I	0.37	50	44	—	−	1.76	0.52	5.8	0.0	2.0	0.1	Be
1942 IV	1.44	79	16	—*	−	1.78	1.45	5.9*	—	—	—	Be
1946 VI	1.14	57	44	—	−	1.69	1.42	4.0	1.1	5.1	2.5	W
					+	2.77	3.21	4.1	1.1	4.5	0.9	W
1947 I	2.41	108	−1	F	−	2.62	2.41	3.6	1.4	5.0	1.5	W
					+	2.40	3.62	3.6	0.5	5.4	0.4	W
1948 I	0.75	141	26	—	+	0.97	2.14	6.3	0.1	3.0	0.2	Be
1948 II	1.50	78	28	F	−	1.69	1.53	17.0	3.0	−17.0	7.0	W
					+	1.60	1.70	10.7	0.8	−0.5	1.4	W
1948 V	2.11	100	35	O	−	2.20	2.11	−10.0	3.0	21.0	4.0	W
					+	2.11	3.82	4.6	0.1	4.3	0.1	W
1951 I	2.57	144	38	—	−	3.43	3.03	6.6	0.9	1.9	0.7	W
1952 VI	1.20	46	1	B	+	1.20	1.40	8.9	0.4	5.7	1.3	Be
1954 VIII	0.68	116	49	—	+	1.71	2.25	3.9	0.4	8.4	0.6	Be
1954 XII	0.75	89	36	—*	+	1.35	1.78	6.3	0.7	11.0	1.8	W
1955 V	0.88	108	−727	Sp*	+	0.92	2.03	6.8	0.3	4.7	0.7	Be
1955 VI	3.87	100	42	O	−	4.15	3.94	3.6	4.0	4.0	2.6	W
					+	3.88	4.39	3.0	1.0	4.4	0.6	W
1957 III	0.32	120	−98	—	−	2.56	1.39	5.6	0.1	3.9	0.2	W
					+	0.55	2.77	5.1	0.1	4.3	0.1	W
1960 II	0.50	160	−135	F*	−	1.19	0.51	8.3	0.2	4.3	0.5	W
					+	0.54	1.48	7.7	0.1	3.8	0.4	W
1962 III	0.03	65	25	—	−	1.49	0.60	6.2	0.1	2.3	0.2	Be
					+	0.38	1.43	5.1	0.1	3.6	0.2	Be
1968 VI	1.70	129	−82	F	−	1.26	1.16	6.3	0.2	−0.2	1.3	W
					+	1.16	1.78	6.0	0.1	3.5	0.2	W

Notes:

1914 V	Br. $\sim 0^{\mathrm{m}}.5$ near $r = 1.8$ AU before q.
1942 IV	Max. rel. mag. near March 13. Faded to April 20. $T =$ April 30.8.
1954 XII	Faded badly after q.
1955 V	After q Br. $0^{\mathrm{m}}.7$ at $r = 1.0$/AU. 2nd Burst at $r = 1.21$ AU then seen double 2^{d} later.
1960 II	Faded $> 1^{\mathrm{m}}.1$ at $r = 1.2$ AU after q.

TABLE Ib

Class II comets (1.0×10^4 yr < Per. < 2.8×10^6 yr) ($50 \times 10^{-6} < 1/a < 2154 \times 10^{-6}$ AU^{-1})

Comet	q (AU)	i	$1/a \times 10^{+6}$	At q	±	r_1 (AU)	r_2 (AU)	H mag.	±σ	n	±σ	C
1886 II	0.48	84	332	O	−	1.71	1.05	6.7	0.1	2.0	0.1	W
1890 II	1.91	121	89	B	+	1.91	3.30	5.3	0.9	2.6	1.0	W
1893 II	0.68	160	987	—	+	0.68	0.97	6.4	0.3	2.2	1.0	Bo
1900 II	1.02	62	610	O	+	1.02	1.34	8.7	0.1	6.3	0.5	W
1904 I	2.71	125	227	—	+	2.75	3.90	3.4	0.5	3.4	0.4	Bo
1908 III	0.94	140	174	*	−	1.95	1.02	4.0	0.2	5.0	0.5	Bo
1914 II	1.20	24	126	O	−	1.42	1.20	10.6	0.4	−0.5	1.5	W
					+	1.21	1.37	10.1	0.3	1.3	1.2	W
1915 II	1.00	54	75	F!*	−	2.46	1.38	5.6	0.6	1.7	0.5	Bo
				Sp	+	1.43	2.60	6.2	0.8	3.0	0.5	Bo
1930 II	0.67	125	1524	F	−	0.92	0.68	8.4	0.2	4.6	0.5	W
1937 IV	1.73	42	62	F*	−	2.33	1.74	5.9	0.5	3.4	0.8	W
					+	1.74	2.02	6.3	0.3	3.6	0.4	W
1937 V	0.86	143	124	F	−	1.14	0.86	6.2	0.0	1.2	0.3	W
					+	0.86	0.96	6.4	0.1	1.1	0.7	W
1941 VIII	0.88	94	79	O	−	1.49	0.88	6.9	0.1	3.3	0.3	W
					+	0.88	1.53	7.0	0.0	3.3	0.1	W
1948 IV	0.21	23	612	—	+	0.81	2.20	7.5	0.1	5.4	0.2	Be
1948 XI	0.14	23	1297	*	+	0.58	3.06	5.4	0.5	3.7	0.5	Be
1949 IV	2.06	106	736	—	−	2.34	2.06	5.4	0.4	5.7	0.4	W
					+	2.06	2.60	8.0	0.6	3.2	0.6	W
1950 I	2.55	131	268	—	+	2.55	2.84	4.9	1.3	5.4	1.2	Be
1952 I	0.74	152	1340	—	+	0.96	1.37	8.9	0.2	4.3	0.7	Be
1954 X	0.97	53	70	—*	−	2.96	1.05	5.9	0.1	3.6	0.1	Be
1957 V	0.36	94	2001	—	−	0.45	1.44	3.6	0.0	2.2	0.1	Be
1958 III	1.32	16	256	B	+	1.32	1.62	6.4	0.4	7.8	0.9	W
1959 I	1.63	61	76	O	−	1.88	1.63	6.6	0.4	5.8	0.7	W
					+	1.63	1.80	7.5	0.4	4.1	0.6	W
1959 IV	1.15	48	593	—	+	1.17	1.22	9.4	1.0	4.3	5.1	Be
1963 III	1.54	86	1281	B*	−	1.65	1.54	~5.0		~3.0		Be
					+	1.54	1.67	*				Be
1964 IX	1.26	68	2121	B*	+	1.29	1.70	6.1	0.3	6.6	0.7	Be
1966 II	2.02	29	643	—	+	2.54	2.74	14.2	4.5	−4.0	4.0	W
1966 V	2.38	40	79	F	−	2.53	2.38	−0.5	1.3	9.1	1.4	W
1968 I	1.70	129	842	O	−	1.82	1.70	4.4	1.0	3.7	1.7	W
					+	1.74	2.13	2.6	0.3	6.6	0.4	W
1969 IX	0.47	76	507	—	+	0.47	2.46	6.4	0.1	3.1	0.2	Be
1970 III	1.72	86	549	O	−	2.91	1.72	6.7	0.1	3.5	0.1	W
					+	1.72	1.91	8.9	2.0	0.1	3.2	W
1970 XV	1.11	127	283	F	−	1.90	1.11	5.6	0.1	2.6	0.2	Be

Notes:

1908 III	Br. > $0\overset{\mathrm{m}}{.}5$ at $r = 1.7$ before q.
1915 II	Faded ~$0\overset{\mathrm{m}}{.}4$ at $r = 1.6$ before q.
1937 IV	Faded near $r = 1.7$ before q.
1948 XI	Faded $0\overset{\mathrm{m}}{.}8$ near $r = 2.4$ after q.
1954 X	Faded ~$0\overset{\mathrm{m}}{.}5$ near $r = 1.22$ before q.
1963 III	1^{m} Burst after q, $r = 1.55$ AU. Then $2\overset{\mathrm{m}}{.}4$ burst, $r = 1.57$. Decay 0.25 day^{-1}.
1964 IX	Br. > 1^{m} just after q.

TABLE Ic

Class III comets (10^3 yr < Per. < 10^4 yr) ($2154 \times 10^{-6} < 1/a < 10^4 \times 10^{-6}$ AU^{-1})

Comet	q (AU)	i	$1/a \times 10^{+6}$	At q	±	r_1 (AU)	r_2 (AU)	H mag.	$\pm\sigma$	n	$\pm\sigma$	C
1858 VI	0.58	117	6370	F	−	0.81	0.59	3.4	0.7	3.5	0.7	Bo
					+	0.58	0.85	4.3	0.2	4.5	0.2	Bo
1874 III	0.68	11	3206	B!	−	1.00	0.68	6.2	0.1	4.2	0.3	W
1881 III	0.74	63	5461	B	+	0.77	2.20	5.6	0.1	2.4	0.2	Bo
1907 IV	0.51	9	2650	B*	−	1.63	0.53	4.5	0.1	4.1	0.3	W
					+	0.53	2.31	4.1	0.3	3.1	0.4	W
1911 II	0.68	148	7467	*	+	0.71	1.16	7.9	0.2	4.3	0.9	Bo
1911 V	0.49	34	6280	O	−	1.90	0.51	5.6	0.1	3.6	0.1	W
					+	0.49	1.30	5.6	0.1	3.0	0.3	W
1911 VI	0.79	108	2491	B	−	1.20	0.79	6.3	0.1	3.6	0.5	Bo
1913 II	1.46	152	3422	O	+	1.47	1.52	6.0	6.0	8.9	14.0	Bo
1913 IV	1.36	144	2542	F	+	1.37	1.53	6.5	1.4	7.8	3.7	W
1936 II	1.10	79	8294	B	−	1.33	1.10	6.7	0.1	6.6	0.6	W
					+	1.10	1.27	7.1	0.1	1.3	0.5	W
1939 III	0.53	138	3135	—	+	0.58	1.03	6.4	0.1	3.1	0.3	Be
1943 I	1.35	20	7310	B!	−	1.48	1.36	−1.8	1.0	23.0	3.0	W
					+	1.34	2.09	4.2	0.2	4.1	0.4	W
1948 X	1.27	88	2633	—	+	1.38	2.19	6.0	0.5	6.5	0.7	Be
1953 I	1.66	59	3277	?	−	2.00	1.68	0.4	0.9	14.1	1.4	W
					+	1.67	1.83	11.1	8.7	−6.0	14.0	W
1953 III	1.02	94	2983	F?	−	1.11	1.03	7.3	0.2	13.7	1.8	W
1955 IV	1.43	50	4355	—	+	1.44	2.33	4.8	0.4	7.2	0.6	Be
1961 V	0.04	24	2209	—	+	0.31	1.41	9.2	0.6	6.0	1.0	Be
1962 VIII	2.13	153	4935	—	−	5.00	2.28	2.1	0.1	3.5	0.1	Be
1968 IV	0.68	102	7014	O	+	1.03	1.30	11.3	0.6	5.5	1.7	W
1970 II	0.54	90	7346	B	+	0.64	3.84	3.4	0.0	4.4	0.1	Be

Notes:

1907 IV	Br. well after q.
1911 II	Br. well after q.

1952 III and 1960 III (P/Schaumasse) of Table Ie are all treated as separate comets while the four returns of P/Encke are treated as one only.

3. Summary of Numerical Results

From a comparison of mean values of n by Bobrovnikoff and Beyer, a correction factor of 0.7 is applied to n for the Beyer data in Tables Ia–Ie, to reduce to Bobrovnikoff's system. In averaging values of n for comets of the same class, the standard deviation of a single determination of n ranges from ±1.0 to ±1.4 for Classes I and II, from ±1.1 to 2.2 for Class III and above 2.2 for Classes IV and V. On the assumption that these variations are more representative of cometary vagaries than observational errors, the weighting system is simplified to the following in terms of the data in

TABLE Id

Class IV comets ($25 < P < 10^3$ yr)

Comet	q (AU)	i_0	Per. (yr)	At q	±	r_1 (AU)	r_2 (AU)	H mag. ± σ		$n \pm \sigma$		C
1861 II	0.82	85	362	*	+	1.12	1.53	5.1	0.1	0.5	0.6	Bo
1862 III	0.96	114	120	F	–	1.08	0.96	5.3	0.1	9.6	1.3	W
					+	0.96	1.08	5.4	0.1	5.6	2.1	W
1884 I	0.78	74	72	F	–	2.14	0.81	5.2	0.1	3.1	0.2	Bo
1898 I	1.10	73	398	—	+	1.11	1.69	4.6	0.4	5.9	1.2	Bo
1906 VII	1.22	56	583	O	+	1.22	1.28	7.6	0.2	6.9	0.8	Bo
1910 II	0.59	162	76	B?	–	2.74	1.06	5.3	0.2	5.5	0.3	W
					+	0.59	1.49	5.1	0.1	2.2	0.4	W
1913 VI	1.25	41	62	*	–	1.51	1.34	14.6	1.1	–11.0	2.8	Bo
1919 III	0.48	19	72	—	–	1.17	0.62	10.4	0.1	5.8	0.5	Bo
1930 III	0.48	67	452	B	+	0.49	1.45	8.7	0.1	4.7	0.2	Bo
1932 V	1.04	72	287	O	–	1.09	1.04	7.2	0.1	11.3	1.1	W
					+	1.04	1.18	7.2	0.2	14.0	1.8	W
1932 X	1.13	25	260	B	+	1.14	1.40	8.1	0.3	5.4	1.2	W
1935 I	0.81	65	894	B	–	0.95	0.81	10.2	0.2	4.4	1.4	W
					+	0.81	1.09	9.7	0.1	2.9	0.4	W
1937 II	0.62	26	589	—	+	0.68	1.47	10.2	0.1	3.7	0.3	Bo
1941 II	0.94	26	372	—	+	0.94	1.36	10.9	0.1	2.1	0.7	Be
1952 V	1.28	112	590	F	–	1.32	1.29	5.9	1.1	10.8	3.9	W
					+	1.28	1.40	7.8	1.2	6.9	3.6	W
1954 VII	0.77	74	71	—*	–	3.38	0.87	4.7	0.1	4.3	0.2	Be
1955 III	0.53	86	356	—	+	0.61	0.95	6.8	0.1	5.2	0.1	Be
1956 IV	1.18	45	69	B!	–	1.95	1.18	4.7	0.1	6.4	0.2	Be
					+	1.19	1.85	5.0	0.1	3.9	0.2	Be
1961 II	1.06	151	932	O	–	1.16	1.06	6.5	0.1	9.2	1.1	W
1963 I	0.63	161	823	—	–	1.59	0.63	6.3	0.2	4.7	0.5	Be
					+	0.63	2.99	5.4	0.3	3.6	0.3	Be

Notes:

1861 II	Fading after q.
1913 VI	C/Westphal. Faded out before q.
1954 VII	Br. $> 0\overset{\text{m}}{.}5$ before q, $r = 1.33$ AU.

Tables Ia–Ie: values of n with $\sigma_n < 1.0$ for Bo and $\sigma_n < 1.3$ for Be receive weight 1.0; values of n for $1.0 \leqslant \sigma_n \leqslant 2.0$ for Bo and $1.3 \leqslant \sigma_n \leqslant 2.6$ for Be receive weight 0.5; other values of n are ignored in the solutions for $\bar{n}$.

Table II presents the mean values of n for 103 comets, 55 cases before and 74 cases after perihelion. The five classes of comets are represented in successive lines of Table II and the mean, both before and after perihelion. In each of the latter sections the number of comets and the sum of the weights ( ) are given in the first column, values of $\bar{n}$ in the second with standard deviation, σ, in the third. The overall mean value of $\bar{n}$, 3.62, appears in the last line, agreeing with $\bar{n} = 3.6$ obtained by Meisel and Morris (1976).

From Table II we see that $\bar{n}$ is smaller before perihelion than after for comet Classes

TABLE Ie

Class V comets (Per. < 25 yr)

Comet	q (AU)	i_0	Per. (yr)	At q	±	r_1 (AU)	r_2 (AU)	H mag.	$\pm\sigma$	n	$\pm\sigma$	C
1947 II	0.85	18	4.90	—	+	0.97	1.04	12.9	0.1	3.6	1.7	W
1947 VII	1.87	7	6.59	—	+	1.88	2.03	10.8	1.6	3.0	2.2	Be
1948 IX	2.31	12	7.48	F	−	2.33	2.32	11.1	0.5	−0.7	0.5	W
					+	2.32	2.40	13.2	5.0	−2.7	5.4	W
1950 VII	1.39	17	6.71	—	+	1.50	1.64	8.9	0.9	8.6	1.8	Be
1951 IV	1.12	14	5.47	B	+	1.12	1.26	9.8	0.4	13.2	2.3	W
1952 III	1.19	12	8.17	O*	−	1.24	1.20	6.6	0.5	11.6	2.2	W
					+	1.20	1.81	7.0	0.2	7.3	0.4	W
1954 III	0.56	13	5.21	—	+	0.64	1.10	12.8	1.5	6.1	1.3	Be
1959 VIII	0.94	31	6.42	—	−	1.24	0.94	10.2	0.0	9.4	0.1	Be
1960 III	1.20	12	8.18	O*	−	1.42	1.20	8.0	0.2	10.2	0.8	W
					+	1.20	1.30	7.9	0.4	9.8	2.0	W
1962 V	1.12	14	5.49	B*	−	1.36	1.12	11.5	0.3	11.9	1.5	Be
					+	1.12	1.27	11.5	0.2	12.0	1.2	Be
1963 VIII	2.21	9	8.95	B!	+	2.21	2.44	9.2	0.8	2.0	0.8	Be
1969 VI	1.62	9	7.41	—	+	1.66	1.89	10.2	0.5	2.6	0.9	Be
						P/Encke						
1937 VI	0.33	12	3.29	—	−	1.30	0.75	10.0	0.1	6.0	0.2	Be
1948 XI	0.34	12	3.30	—	−	1.49	0.73	9.9	0.1	6.3	0.4	Be
1951 III	0.34	12	3.30	—	−	1.11	0.43	9.8	0.1	2.7	0.1	Be
1961 I	0.34	12	3.30	—	−	0.84	0.55	10.2	0.2	3.5	0.3	Be
1971 II	0.34	10	3.30	—	−	1.12	0.57	10.8	0.1	5.1	0.3	Be
Mean	Encke	—	—	—	−	1.17	0.61	10.1	0.2	4.7	0.7	W

Notes:

1952 III Br. $0^{m}3$ after q, $r = 1.24$.
1960 III Uncertain mag. after q.
1962 V Br. $1^{m}1$ at q.

I and II, the new and nearly new comets, while the reverse is true for all the older classes of comets. On the other hand, $\bar{n}$ is essentially the same for Classes I to IV after perihelion and probably increases for Class V, the 'Jupiter family'. Hence the systematic increase of $\bar{n}$ with comet age found by earlier investigators arises largely from the increase of *pre-perihelion* $\bar{n}$ with age. Furthermore, the scatter in σ increases markedly for the older comets in Classes IV and V.

As further confirmation of the trends in $\bar{n}$ derived from Table II, the sense of the changes in n from before to after perihelion is presented in Table III. In Case A the number of changes in n from Tables I for comets observed both before and after perihelion are listed as increases or decreases when the change exceeds the sum of the σ's of the respective n's. In Case B, similarly, the numbers of increases or decreases in n are listed regardless of the values of the σ's.

TABLE II

Mean values of n for 103 comets

Type	Before perihelion			After perihelion		
	Number	$\bar{n}$	$\pm\sigma$	Number	$\bar{n}$	$\pm\sigma$
I	14 (11.5)	2.44	0.30	19 (17.5)	3.35	0.27
II	16 (14.5)	2.82	0.38	19 (17.5)	3.31	0.31
III	9 (8.0)	4.72	0.78	13 (12.5)	3.39	0.31
IV	10 (8.5)	5.21	0.76	13 (11.5)	3.82	0.80
V	6 (5.0)	5.0	1.4	10 (7.0)	4.61	0.91
Mean	55 (47.5)	3.71		75 (66.0)	3.56	
Mean (all)	130 (113.5)	3.62				

The data of the upper part of Table III can be treated by Fisher's classical test of significance. The numbers are arranged in sets of four, Increase vs Decrease and Class vs Class. The second part of Table III lists these probabilities for the combinations from the first column. The least probable combination is Class I compared to Classes III+IV+V combined, definitely below the 1% level of significance for both Cases A and B. As expected, Class II comets appear to represent a mixture of new and returned comets whereas Classes I, III and IV seem to be relatively 'pure', new or old.

It is important to note that the correlations derived above can be derived separately by the use of either Bobrovnikoff's or Beyer's data alone but, naturally, with less reliability than with the combined data.

The tendency of comets to brighten or fade as they pass perihelion can be studied from the data of column 5 in Tables Ia–Id. Table IV lists the numbers of comets that

TABLE III

Sense of change in n from before to after perihelion

	A. Change in n exceeds sum of σ's		B. Change in n regardless of σ's	
	Increase	Decrease	Increase	Decrease
Class I	6	0	9	3
Class II	2	2	4	4
Class III	1	5	1	5
Class IV	0	4	1	6
Class V	0	1	1	3
Probabilities				
I vs III	0.015		0.030	
I vs IV	0.005		0.017	
I vs III+IV+V	0.0006		0.003	
I+II vs III+IV+V	0.002		0.004	

TABLE IV

Tendency of comets to brighten or fade at perihelion

	Class				
	I	II	III	IV	V
No. brightening	4	4	7	5	3
No. fading	6	6	3	3	1

tend to brighten or fade in each class. The Fisher test for Classes I+II vs Classes III+IV+V yields a probability just at the 5% level, significant but not strongly convincing, particularly as the observation itself is somewhat subjective and uncertain. Nevertheless, the result tends to support the derived and strongly reliable changes in $\bar{n}$ before and after perihelion as a function of class.

I find no significant correlation of n with perihelion distance q.

4. Physical Interpretation of the Results

Only a qualitative interpretation will be attempted. A typical bright new comet of Class I, such as Kohoutek, 1973 XII, brightens rapidly at great solar distances and then slowly near perihelion. A typical 'mature' comet of Class III or IV, such as P/Halley, brightens more rapidly near perihelion. Both types fade at about the same rate after perihelion.

The behavior of new comets at great solar distances supports the conclusion of Oort and Schmidt (1950), viz. that new comets contain more volatile gases than older comets. On the basis of the icy conglomerate model (Whipple, 1950, 1951) this statement implies the occurrence of more volatile *ices* in the new comet. Furthermore, the reduced rate of brightening of the new comet before perihelion implies that the supply of super volatile ices has been exhausted before perihelion is reached. Marsden and Sekanina (1973) reach these same conclusions on the basis of the dearth of discoveries of older comets with large q. They conclude that because returning comets are fainter than they were on their first apparition, they are not detected because of the severe telescopic limitations in finding relatively inactive comets of large q.

A possible explanation for a thin extremely volatile outer layer, the *frosting*, in new comets is activation by cosmic rays over some 4.6×10^9 yr in the Oort cloud. As Donn (1976) and Whipple (1976) have shown, the outer layers receive ionization damage amounting to some 80 times the heat of vaporization of H_2O ice in this time.

Whatever the source of the quickly removed super active frosting on new comets, they show statistically the same luminosity loss rate after perihelion as much older comets, $n \cong 3.4$, and then return with much larger values of n ($\sim$4.7). I suggest this change of n after perihelion arises for all comets from the building up of an insulating crust of meteoritic material, and, at larger solar distances also of H_2O ice. This layer is almost certainly spotty, the spots consisting of small cometesimals leaving cores on the surface. I visualize the main outer body or *mantle* of a comet as being highly irregular in structure. The irregularities must have arisen during formation by the agglomeration of small cometesimals, many of these having cores of H_2O ice and meteoroidal material more cohesive and probably less volatile than the matrix material.

Only new comets, then, are free from such an insulating layer on their way to perihelion after they lose their superactive frosting, if q is not too large, $< \sim 4$. The value $n = 2.4$ can perhaps be taken as representing the average 'true' value of cometary activity for average mantle material, typical of all but the oldest comets. As soon as the solar heating begins to decrease, the insulating spotted crust begins to form. It continues to grow with increasing solar distance and, for most comets, finally reduces the activity to an unobservably low level.

On returning towards perihelion, the cometary activity grows as the crust is removed. The total sublimation rate increases as the crust is blown away. The major 'purging' of the surface then occurs in the general neighborhood of perihelion. Thus, statistically at least, all comets act similarly after their first perihelion passage until eventually they disappear or, if large enough, develop a thick crust that curtails their activity severely at all times.

The oldest short-period comets tend to be extremely erratic in their luminosity behavior, sometimes being seriously choked up by their thick insulating crusts. Possibly some finally lose their cometary character entirely, becoming unobservable as comets but conceivably as asteroids.

Among the short-period comets Kresák (1973) finds two that were much more active immediately after their perihelion distances were reduced by Jupiter perturbations than they were on subsequent returns. He infers high and then decreasing albedos for comets approaching the Sun within $r = 3.2$ AU for the first time. I would ascribe the effect to a purging of insulating crust followed by a re-establishment of an equilibrium crustal condition on subsequent returns.

That the short-period comets are relatively inactive or else extremely small compared to newer comets is evidenced from the mean absolute magnitudes from Tables Ia–Ie. For Classes I, II and III, $\bar{H} = 6\overset{\mathrm{m}}{.}0$. For Class IV, $\bar{H} = 7\overset{\mathrm{m}}{.}4$, and for Class V, $\bar{H} = 10.3$. If this difference of $4\overset{\mathrm{m}}{.}3$ between the first three and fifth class is caused only by size, the mean radius ratio is 7.5 times. The ratio in area or albedo is then 52 times. For ten short-period comets of $\bar{H} = 10.4$ ($n = 4$), Kresák (1973) finds a mean radius of 1.6 km from absolute magnitudes and various albedos depending upon the observed distance of each comet. Similarly, Whipple (1976) derives a mean radius of 1.3 km for ten short-period comets of $H_{10} = 12\overset{\mathrm{m}}{.}2$, on the basis of albedos of 0.15 and 0.33. The values of albedos and radii are supported by measured non-gravitational radial accelerations. These comets are the brighter and probably the larger among those of short-period.

For comparison, Delsemme and Rud (1973) have determined the radius, R, and albedo, A, of a Class III comet, 1970 II, Bennett, and one of Class II, 1969 IX, with

$H = 3.4$ and 6.4, respectively (Tables Ic, Ib). The determinations depend upon the measured production of H_2O and the magnitude at great solar distances. The radii derived are 3.76 ± 0.08 km for 1970 II and 2.20 ± 0.05 km for 1969 IX with $A \sim 0.6$. Similarly, O'Dell (1976) finds for Class I, C/Kohoutek, 1973 XII, $R = 2.1$ km ($H \sim 6^{\mathrm{m}}$). For P/Halley I find (unpublished) from the non-gravitational acceleration $R \sim 2.9$ km ($H = 5^{\mathrm{m}}.2$, Table Id).

If we reduce all the absolute magnitudes in the previous two paragraphs to comets of $R = 1$ km, the four of Classes I–IV give $H(1\text{ km}) = 7^{\mathrm{m}}.4$ and the 20 of Class V gives $H(1\text{ km}) = 12^{\mathrm{m}}.0$, a difference of $4^{\mathrm{m}}.6$ or 69 times in brightness. After a generous correction factor for albedo, we find that the basic activity of the more active Class V short-period comets is statistically about an order of magnitude less than that of younger classes.

Differences in the observed spectral compositions of the short-period comets from those of longer period consist almost entirely in the tendency of the latter to show a continuous spectrum more strongly and frequently. Hence, we confirm our conclusion that the nuclei of short-period comets statistically are covered with an insulating and probably dark layer, over some 90% of their surfaces.

My suggestion that the younger comets tend to purge their surfaces near perihelion requires a time-delay mechanism in the deterioration process for the insulating material. For a uniform crust one would expect a strong correlation of the $\bar{n}$'s with perihelion distance. Solar heat alone at smaller q's should be adequate, so that the effect of purging should be apparent only for comets with q above some sizeable minimum value where H_2O ice does not sublimate readily. The concept of dark clumps or volumes imbedded in comets provide some possible basis for a time-delayed mechanism of deterioration. Let us call them *globs*. If the globs are more coherent physically and less volatile than the matrix material, particularly if the meteoritic material contributes even a weak tensile strength to them, we find a physical basis for delay in sublimation. P/Encke, for example, does indeed provide larger meteoroids in the fireball class (Whipple, 1940) while many fireballs observed in the Prairie Network (Ceplecha and McCrosky, 1976) come from sizeable weak structures, almost certainly of cometary origin. The globs, exposed on the surface of a comet, would develop into mounds or even rough columns, wasting away irregularly with time as they are sculptured by the escaping gases and dust from surrounding areas. With time their mean densities would decrease as the various ices would escape slowly and, of course, their dimensions would decrease. Many would finally be carried away while others would become unstable and crumble, to suffer the same fate.

Some limits on the dimensions of the globs can be guessed, based on the requirement that they play a significant role in delaying surface sublimation but still can be removed to a considerable extent on the way to perihelion. From effective initiation of some sublimation, the icy halo of Delsemme and Wenger (1970), at $r \sim 7$ AU, the integrated solar heat for a parabola to $q = 1$ AU is equivalent to 0.27 yr continuous exposure normal to the Sun at 1 AU. For $q = 3$ AU, it is 0.11 yr and to $q = 0.5$ AU, 0.41 yr equivalent. For an albedo of 0.6, 0.25 time effective exposure at normal incidence, and latent heat of 640 cal g^{-1} for H_2O ice, the equivalent thickness removed at density unity is 165 cm for 1 yr equivalent exposure at 1 AU. The average surface material of a comet may well range from $\ll 0.1$ g cm^{-3} for Classes I and II to >0.5 for Classes III and IV. Let us adopt 0.4 as density for cometary surfaces and 0.5 for globs. The thickness removed to $q = 1$ AU would then be <110 cm. A structured weak glob of the order of 1 m in diameter could thus be undermined and largely removed on the way to perihelion and also accumulate on the way out. A spherical glob of diameter 1 m and density 0.5 has a mass of 0.26 ton, rare but occasionally observed by the Prairie Network. Undoubtedly a hierarchy of glob dimensions, densities, structures and cohesions must exist. Detailed knowledge of the globs must await a rendezvous space mission to a comet such as P/Halley.

I find it difficult to visualize a qualitatively different structure for the surfaces of cometary nuclei, in view of cometary luminosity behavior and our general knowledge of cometary meteoroids. More quantitative knowledge about the globs would provide vital information about the conditions, particularly the temperature sequence, during the original freezing out and/or accumulation of comets. Their existence probably implies some cooling during comet formation, starting from a rather low initial temperature. They might well be formed in the process envisioned by Alfvén and Arrhenius (1976), the Trulsen jet-stream process, if conditions were idealized in actuality.

5. Effects of Rotation on Cometary Behavior

Our limited knowledge concerning the rotation of cometary nuclei is summarized in the following three paragraphs.

The sense of rotation is statistically random with respect to the sense of revolution about the Sun for 34 periodic comets in Marsden's (1975) catalogue, measured by the sign of the non-gravitational term in the period of revolution. His A_2 is positive in 15 cases and negative in 19. This leads to the strong presumption that the poles of rotation are randomly oriented with respect to the poles of revolution.

Fay and Wisniewski (1976) find photometric evidence that P/D'Arrest was rotating with a period of 5.11 ± 0.0 h in August 1976.

Several percent of the known comets have been observed to split. Although we have no proof that comet splitting, when not induced tidally, is caused by spin-up, I find this explanation the most likely. Indeed, the possibility gave me early confidence in the icy conglomerate model of comets (Whipple, 1950). In a current investigation I find theoretical evidence that spin-up can be systematically induced in roughly contoured comets if one makes certain assumptions about the time-lag in heat conduction. Unusual cometary bursts may often be caused by very rapid rotation.

I will not belabor this discussion by including the arguments that most comets probably rotate with periods less than a day, but it does seem safe to assume that the period of rotation is generally very much shorter than the period of revolution. With this assumption and that of randomness in the orientation of the pole let us now speculate concerning the possible effect of rotation on C/Kohoutek, 1973 XII.

The intrinsic brightness of C/Kohoutek (see Figure 1) rose rapidly near discovery, at $r \sim 4.0$ AU, and leveled off to a relatively small value of n (in the r^{-n} law of brightness) at $r \sim 1.0$ AU. From $r \sim 0.3$ AU to $r = 0.14$ AU at perihelion the brightness rose very rapidly, later perhaps dropping slightly below its average descending curve near $r = 0.4$ AU.

To account for the trends of this brightness behavior let us accept that a comet will be intrinsically brighter at a given solar distance if the subsolar point lies nearer to the pole than to the equator of the rotating nucleus. On average, the illuminated area receives twice the solar radiation when the Sun shines from a pole than from the equator. This corresponds to a reduction in solar distance by a factor $1/\sqrt{2}$, particularly important at great solar distances where sublimation rates are minimal and time-lags great.

So let us now postulate that the pole of rotation of C/Kohoutek lay fairly close to the plane of revolution, say within 20° (i.e., more than 70° from the pole of revolution). The probability of this orientation is just over 1/3 (i.e., sin 20°).

Furthermore, suppose specifically that the axis of one pole, P_1, lay closest to the Sun at true anomaly, $v = -163°$ at $r = 6.5$ AU. Little change in orientation would take place to $v = -158°$, near discovery. This situation maximizes the heating of the P_1 hemisphere of the nucleus to account for the early discovery and the rapid rate of brightening observed shortly after discovery.

Much the same region of the comet was illuminated at $v = -118°$, 45° later, at $r = 0.54$ AU. The other pole, P_2, indeed received no radiation until a few days before perihelion. But remember that the region near P_2 consisted of superactive frosting characteristic of new comets. It was suddenly exposed just before $q = 0.14$ AU and received maximum radiation at $v = +17°$ only 0.003 AU farther away. This, I propose, accounts for the sudden brightening of C/Kohoutek near perihelion.

By the time $v = +107°$ at $r = 0.40$ AU, the equator of the comet passed through the Sun, thus accounting for the slight relative drop in brightness at that time. This is the reason for choosing $v = -163°$ as the time of nearest alignment of P_1 to the Sun.

It is interesting to consider the probable thickness of the frosting on the surface of this new comet. From the assumed beginning of significant sublimation, taken at $r = 7.0$ AU and $v = -163.^{\circ}6$, to $r = 1.0$ AU and $v = -136°$, when the light curve appears to have leveled off, the total radiation on the comet is equivalent to 0.154 yr at 1 AU. For an albedo of 0.6 and an average surface exposure of 0.5, the equivalent total heat is 0.031 yr at 1 AU. If composed of H_2O ice, the thickness of the layer of unit density is 51 cm. Probably the frosting had a lower heat of vaporization and carried with it a considerable additional mass of H_2O ice grains, so that the frosting was perhaps a metre or two in thickness at unit density. The actual density was undoubtedly very much lower and the physical thickness much greater. It is interesting that the ionization by cosmic rays in 4.6×10^9 yr drops to less than 0.5 its maximum (near the surface) at a depth of 200 g cm^{-2} and below 0.1 at 600 g cm^{-2}.

Incidentally, O'Dell (1976) calculates that the total mass loss for C/Kohoutek was about 1×10^{14} g or a thickness of about 2 m of H_2O ice equivalent, the dust mass being ~ 0.8 the H_2O ice mass. My calculations above would give somewhat higher values.

The moral of this section of this paper is that the orientation of the rotation axes can produce large effects in the intrinsic light curves of comets, particularly of new comets, but also significantly of old ones. For half of the comets the polar axis will lie within 30° of the orbital plane. Hence polar effects can become significant as a comet swings from $v = -45°$ to $+45°$ about perihelion. Unfortunately, the verification of a polar axis orientation is impossible for almost all comets at the moment. There may be several comets at large solar distances where the direction of the icy halo will give a clue. P/Schwassmann–Wachmann I is such a case. I am now studying it with this end in view.

6. A Caveat

The reader should constantly bear in mind that this paper concerns the statistically average comet. Hence the conclusions should be applied to an individual comet with great care. For example, C/Stearns, 1927 IV (Class II), was observed as a diffuse object to $r > 11.5$ AU and showed Swan bands even though $q = 3.7$ AU. It, like a few other young comets, must have had an extraordinarily thick frosting of superactive material. A glance at the deviant comets in Tables Ia–Id shows how badly some comets can behave.

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