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On the Rate at Which Comets Split

JUN CHEN AND DAVID JEWITT

Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822
E-mail: jchen@galileo.ifa.hawaii.edu

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We use time-resolved charge-coupled device (CCD) images to assess the frequency of splitting of comets. When blinked on a computer, the CCD images provide relatively high and uniform sensitivity to comoving companions. We find that 3 comets are split in a sample of 49, and estimate that the cometary splitting rate is $S \sim 0.01$ per year per comet or larger. This large rate suggests that splitting may be an important destructive process for the cometary nuclei. © 1994 Academic Press, Inc.

1. INTRODUCTION

A small but significant fraction of comets are observed to be multiple, the number of components ranging between 2 and 22 (in the recently discovered comet P/Shoemaker–Levy 9). Even though no comet has been observed at the moment of rupture, it is widely accepted that multiple comets are products of the splitting of single precursor nuclei. In a comprehensive review, Sekanina (1982) listed 21 split comets observed in the interval from 1846 to 1976. The characteristic separation velocity is of order 0.5 m $\sec^{-1}$ and varies weakly with heliocentric distance. Both long-period comets (orbital periods $P \gtrsim 200$ yrs) and short-period comets ($P < 200$ yrs) are known to split, with equal probabilities of splitting before and after perihelion. While splitting is sometimes associated with the close passage of a comet by the sun (e.g., Marsden 1989), it is also known to occur at heliocentric distances of up to 9 AU (comet P/Wirtanen, in 1954) in response to mechanisms which remain obscure.

Cometary splitting is potentially of great interest in the study of comets, for two reasons. First, splitting may expose interior portions of the nucleus to solar heating, providing a unique opportunity to study primitive materials at depth. Second, cometary splitting may be a major mode of disintegration for cometary nuclei (Jewitt 1992). Unfortunately, the statistics of nuclear splitting are not well known and little detailed physical information about splitting is available.

Most split comets have been discovered serendipitously by visual and photographic observers. The discoveries are naturally biased toward comets that attract the attention of observers, namely, to highly active comets at small heliocentric distances. Existing observations also include a natural bias toward secondary comets that are similar in brightness to their primaries, since faint secondaries will more easily escape detection. Furthermore, in split comets with small separation, the secondaries must be observed against a high surface brightness background due to the coma of the primary comet. Thus, it seems likely that such "embedded secondaries" will be undersampled in the split comet inventory. Indeed, if the secondary components fade on a timescale that is short compared to the timescale to move out of the coma of the primary, it would seem possible that we might be missing a large number of embedded secondaries. On the other hand, older secondaries will also be observationally underrepresented, either because of pronounced secular fading (as discussed by Sekanina 1982) or because the secondaries move out of the field of view of the detector.

The availability of highly sensitive charge-coupled device (CCD) detectors allows us to reduce some of the biases mentioned above. Very faint secondary nuclei, and those secondaries embedded in the active comae of their parent nuclei, can be sought using image processing techniques that cannot be applied to visual or photographic data. In this paper we present CCD photometry of comets observed for other purposes since 1986. Time-resolved image sequences of each comet have been blinked to identify comoving companions. Where necessary, we have digitally removed bright comae in order to search for near-nucleus companions that might otherwise be missed. The present work benefits from the high sensitivity of the CCD and from the ease with which computerized methods can be used to search for secondary companions to active comets.

2. OBSERVATIONS

For this survey, we used images taken since 1986 in the course of other programs of cometary research. The sample contains a mix of faint comets observed for near-nucleus studies with brighter objects observed for coma investigations. The observations constitute a rather het-

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TABLE I
Journal of Observations

UT Date	Telescope Diameter [m]	CCD Camera [pixel] x [pixel]	Scale ["/pixel]
1986/Mar/06,07	KPNO 2.1m	TI 3 800 x 800	0.38
1986/Oct/30,31	KPNO 2.1m	TI 2 800 x 800	0.38
1987/Mar/30	KPNO 2.1m	TI 2 800 x 800	0.38
1987/Apr/01,02,03	KPNO 2.1m	TI 2 800 x 800	0.38
1987/Sep/19,20	KPNO 2.1m	TI 2 800 x 800	0.38
1988/Feb/07,11	MDM 2.4m	RCA 164 x 256	0.60
1988/Feb/29	MDM 2.4m	MASCOT 357 x 192	0.63
1988/Jun/29	MDM 1.3m	BRICC 500 x 500	0.48
1988/Sep/06	MDM 2.4m	MK III 400 x 576	0.73
1989/May/29	UH 2.2m	TI 1 800 x 800	0.80
1989/Aug/24,25	UH 2.2m	GEC 385 x 576	0.20
1989/Sep/29	UH 2.2m	GEC 50mm 385 x 576	0.86
1990/May/12,14,15	MDM 1.3m	MK III 400 x 576	0.70
1991/Jan/14,15	UH 2.2m	GEC 385 x 576	0.20
1991/Sep/12,14,15	MDM 2.4m	MK III 400 x 576	0.73
1991/Nov/21	UH 2.2m	Tek 1024 x 1024	0.21
1992/Mar/30	UH 2.2m	Tek 1024 x 1024	0.21
1992/Aug/30	UH 2.2m	Tek 2048 x 2048	0.22
1993/Jul/15	UH 2.2m	Tek 2048 x 2048	0.22

erogeneous sample that is not strongly biased toward bright, near-sun comets. In all cases, we selected only time-resolved image sequences suitable for computer blinking. The data were obtained at Michigan–Dartmouth–MIT Observatory (MDM) and Kitt Peak National Observatory (KPNO), both on Kitt Peak in Arizona, and at Mauna Kea Observatory (MKO) in Hawaii. A majority of the photometric data were acquired through a Mould R filter since the effective wavelength ($\lambda_e \sim 6500$ Å) is close to the wavelength of peak quantum efficiency of the CCD, and atmospheric extinction and cometary gaseous emissions are less important in the R band than in others. The R band is also dominated by sunlight scattered from cometary dust, with minor contributions from resonance fluorescence in coma gas. Typical image quality was about 1.5 arcsec full width at half maximum (FWHM) in the MDM and KPNO data, and 0.8 arcsec FWHM in the MKO data. A journal of observations is provided in Table I.

The data analysis consisted of subtracting the bias from each image, and then dividing the bias-subtracted images by a "flat field" to remove pixel-to-pixel sensitivity variations. Bias (zero exposure) frames were recorded at intervals through each night or by measuring the overclock region. The flat field was typically obtained from images of the morning twilight sky. Flux calibration of the images was obtained using standard stars from the lists by Landolt (1983) and Christian *et al.* (1985). The photometric uncertainties in the comet photometry are primarily due to sky-subtraction uncertainties and zero-point errors, and are estimated to be of order ±0.05 mag.

We rapidly displayed (blinked) time-resolved image sequences of comets to search for comoving secondary companions. As a result, only those comets with at least four images in the R band could be used. Generally, a timebase of about 1 h was taken to create these four images. During this interval, the motion of a typical comet was $\sim 10''$–$40''$ relative to the fixed stars.

In order to search for potential embedded secondaries, we made a coma model according to a p^{-1} surface brightness law, where p is the impact parameter (Jewitt 1991). After convolving with a Gaussian function to simulate the atmospheric seeing, we used the model as a divisor to reduce images of comets with extensive comae. Again, the coma-removed images were blinked to search for comoving objects in the near-nucleus regions.

The cometary magnitudes were generally obtained using a synthetic circular aperture $2''$–$8''$ in radius with sky subtraction from a concentric annulus up to $8''$ wide. The angular image scales of the CCDs are listed in Table I. The integrated photometry is summarized in full in Table II (for short period comets) and Table III (for nonperiodic comets), including the geometric parameters of each comet at the time of observation. The heliocentric distance R, geocentric distance Δ, and phase angle α were obtained from an ephemeris provided by David Tholen. In comets where more than one nucleus is present, the primary nucleus is assumed to be the visually brighter

TABLE II
Geometric Parameters and Integrated Photometry of Short Period Comets

Comet	UT Date	q [AU]	R [AU]	Δ [AU]	α [deg]	m_p	m_s
P/Arend-Rigaux	1986 Mar 06	1.43	3.94	3.57	- 14.1	20.14	> 22.35
P/Ashbrook-Jackson	1988 Feb 11	2.32	4.56	3.62	4.3	20.43	> 20.62
P/2060 Chiron	1991 Jan 14	1.34	10.60	9.63	0.7	15.79	> 22.10
P/Chernykh(*)	1991 Sep 15	2.36	2.61	1.61	- 2.2	16.37	19.25
P/Ciffreo(*)	1986 Mar 06	1.71	2.09	1.71	28.2	19.06	18.27
P/Daniel	1986 Mar 06	1.65	2.52	1.63	- 12.1	19.14	> 20.30
P/d'Arrest	1989 Aug 24	1.34	2.51	2.70	- 22.0	20.59	> 21.21
P/Encke	1991 Sep 12	0.33	3.46	2.56	8.6	19.99	> 21.17
P/Faye	1991 Sep 12	1.62	1.73	0.82	- 21.0	13.24	> 21.16
P/Forbes	1987 Sep 20	1.45	2.65	1.88	- 16.8	19.95	> 22.38
P/Gehrels 2	1991 Jan 15	2.25	3.62	2.79	- 0.9	20.73	> 22.91
P/Gehrels 3	1986 Mar 06	3.43	3.55	2.57	3.1	18.58	> 21.64
P/Giacobini-Zinner	1987 Apr 02	1.04	4.80	3.98	7.5	21.57	> 22.74
P/Grigg-Skjellerup	1986 Oct 31	1.00	2.68	2.18	- 20.5	19.20	> 22.73
P/Gunn	1989 May 29	2.46	2.57	1.62	10.1	14.21	> 21.41
P/Halley	1987 Mar 30	0.59	5.39	4.56	6.4	17.08	> 19.45
P/Hartley 2	1987 Apr 01	0.95	5.12	4.15	- 2.9	20.48	> 22.49
P/Holmes	1987 Apr 02	2.18	3.36	3.62	15.9	20.04	> 22.62
P/Howell	1987 Sep 20	1.41	1.52	0.79	37.1	16.06	> 21.06
P/Kearns-Kwee	1991 Jan 14	2.20	2.25	1.29	6.3	15.77	> 21.42
P/Klemola	1987 Sep 19	1.76	1.90	0.92	- 10.4	15.23	> 20.82
P/Kojima	1986 Mar 07	2.40	2.41	1.69	19.4	18.06	> 20.80
P/Lovas 1	1989 Aug 25	1.67	1.74	1.47	- 35.4	17.05	> 21.61
P/Neujmin 1	1986 Mar 06	1.56	5.09	4.77	10.9	19.82	> 21.32
P/Russell 3	1990 May 12	2.51	2.52	1.53	- 6.1	18.76	> 25.17
P/Schwassmann-Wachmann 1	1991 Jan 14	5.76	5.81	5.71	9.8	16.80	> 21.59
P/Schwassmann-Wachmann 2	1991 Sep 14	2.07	4.58	3.69	6.4	20.64	> 21.63
P/Schwassmann-Wachmann 3	1990 May 14	0.93	0.94	0.48	- 84.3	13.24	> 16.47
P/Shajn-Schaldach	1993 Jul 15	2.34	2.49	2.03	- 4.5	18.98	> 24.78
P/Shoemaker-Levy 6	1991 Nov 21	1.14	1.24	0.32	32.4	17.83	> 21.06
P/Taylor	1991 Jan 14	1.95	1.96	0.97	2.5	16.83	> 22.89
P/Tempel 1	1988 Feb 07	1.49	3.10	2.15	6.5	18.93	> 20.30
P/Tempel 2	1988 Feb 07	1.48	2.51	2.44	- 23.0	18.80	> 20.44
P/Vaisala 1	1993 Jul 15	1.78	1.95	1.91	30.6	18.12	> 24.95
P/Van Biesbroeck	1990 May 15	2.40	3.58	2.81	12.4	18.52	> 21.57
P/Wild 2	1989 Sep 29	1.58	3.74	3.06	- 12.5	18.50	> 20.54
P/Wild 3	1987 Apr 01	2.30	2.51	1.59	- 11.8	18.64	> 22.56

Note. R is the distance from the Sun. Δ is the distance from the Earth. q is the perihelion distance. α is the phase angle. m_p is the magnitude of the comet. m_s is the magnitude of the "secondary" comet. * indicates a split comet.

one. The magnitude of the primary is denoted m_p, while the magnitude of the secondary companion, where observed, is denoted m_s. For apparently single comets, m_s is an upper limit to the allowable brightness of any secondary. Specifically, no secondary brighter than m_s could exist in the field of view of the CCD if separated from the primary by more than approximately 2 arcsec.

3. DISCUSSION

Out of 49 comets, 3 were observed to be split, corresponding to a fraction $f \sim 6\%$. With reference to Table II and Table III, they are comets P/Chernykh, P/Ciffreo, and Wilson. Comets Chernykh and Wilson are known to be split (Luu and Jewitt 1991, Meech 1988), while comet Ciffreo was noted by Larson and Klemola (1986) to have a peculiar morphology that we here recognize as the signature of a split comet. The features of these three comets are shown in Figs. 1 and 2, where arrows indicate the two components and horizontal bars indicate 10″. Of the three comets, only Wilson is dynamically new. Surprisingly, no additional split comets were found, despite our systematic and sensitive search.

In order to estimate the rate at which comets split it

TABLE III

Geometric Parameters and Integrated Photometry of Long-Period Comets

Comet	UT Date	q [AU]	R [AU]	Δ [AU]	α [deg]	m_p	m_s
(N) Austin(1989c1)	1990 May 12	0.35	0.90	0.36	- 97.2	20.31	> 24.84
(N) Bowell	1987 Sep 20	3.36	15.50	14.53	- 1.0	20.30	> 23.40
(N) Levy(1987a)	1987 Apr 02	0.92	1.96	0.98	- 9.5	18.11	> 21.48
(L) Mcnaught-Russell 91w	1991 Sep 12	6.99	7.26	6.31	2.9	17.81	> 21.17
(N) Shoemaker('84f)	1987 Sep 20	2.70	7.30	6.90	- 7.5	17.76	> 22.08
(L) Shoemaker('84r)	1987 Sep 19	5.49	9.42	8.49	2.4	14.07	> 22.48
(L) Shoemaker('86b)	1986 Oct 30	3.59	4.13	4.26	- 13.5	19.42	> 22.91
(L) Shoemaker-Holt	1988 Jun 29	1.17	2.31	2.02	- 26.1	16.47	> 20.96
(N) Shoemaker-Holt-Rodriquez	1988 Jun 29	2.47	4.35	3.57	- 9.6	15.25	> 21.10
(L) Thiele	1987 Apr 03	1.32	5.57	4.88	- 8.0	23.53	> 24.66
(N) Wilson	1986 Oct 30	1.20	2.72	2.60	21.4	13.68	> 22.68
(N) Wilson(*)	1988 Feb 29	1.20	4.21	3.56	11.0	15.22	16.40
(L) Yanaka (1988r)	1989 May 29	1.89	3.12	2.68	18.2	17.23	> 21.74

Note. R is the distance from the Sun. Δ is the distance from the Earth. q is the perihelion distance. α is the phase angle. m_p is the magnitude of comet. m_s is the magnitude of "secondary" comet. * indicates split comet. (N) indicates nonperiodic comets. (L) indicates long-period comets.

is necessary to know the observational lifetimes of the secondary components. Physically, the lifetime of a secondary will be determined by the timescale for the loss of volatiles by sublimation due to solar heating. This lifetime is a strong function of the instantaneous heliocentric distance, the size of the secondary, and the orbital characteristics of the comet. Assuming a water ice composition, and after taking into account the equilibrium sublimation equation (cf. Delsemme 1982), we obtained relations among the lifetime, the heliocentric distance and the size of the nucleus. Figure 3 shows these relations. The figure shows that even a 10-m-sized secondary made of H_2O ice could endure for a period ~1 yr (3×10^7 sec) against sublimation at 1 AU. On the other hand, the physical dimensions of the secondaries are unknown, so that it is difficult to proceed from a calculation of the sublimation rate to the lifetime of the secondary.

A strict and relatively model-independent upper limit to the observable lifetime of a secondary comet is imposed by the finite field of view of the images used in this survey. At distance $\Delta = 1$ AU, a 5-arcmin field of view corresponds to a linear distance $d \sim 2.2 \times 10^8$ m in the plane of the sky (Table I). With a mean secondary ejection velocity $v_s \sim 0.5$ m sec^{-1} (Sekanina 1982), and with a comet centered in the field of view, the approximate residence time is $t \sim d/(2v_s) \sim 2 \times 10^8$ sec, or about 6 yr. In practice, this is a strong upper limit to the residence time, since Keplerian shear between comets on adjacent orbits will cause the separation to increase at a rate greater than v_s, as will differential nongravitational accelerations due to outgassing (Sekanina 1982). A conservative estimate of the mean rate of splitting of the comets is given by $S \sim f/t$. From the values given above, we estimate

$$S \sim 0.01 \text{ year}^{-1} \text{ comet}^{-1}$$

This is a *lower* limit to S, since we have overestimated the residence time, and since many secondaries will have physical lifetimes shorter than the residence time. For example, 70% of the secondaries plotted by Sekanina (1982) have lifetimes ≤100 days of exposure to sunlight at 1 AU. Hence, we regard $S \sim 0.01$/year as a lower bound to the rate of splitting of comets in the present sample. We cannot exclude the possibility that some comets are more prone to splitting than others. The statistics of our sample are too poor to separately determine the splitting rates of short-period and long-period comets. Evidently, although it is perceived as rare by observers, splitting is statistically common among comets.

This large splitting rate is incompatible with the notion that a monolithic parent nucleus breaks repeatedly into two nearly equal fragments. For example, in the 4×10^5 yr dynamical lifetime of a short-period comet (e.g., Everhart 1973, Levison and Duncan 1994), the nucleus will split thousands of times. A comet 10 km in diameter has volume $\sim 10^{11}$ m^3. After a thousand splittings, the volume of each fragment would be $\sim 10^{11} \times 2^{-1000} \sim 10^{-290}$ m^3 if the splitting is to break up into two equal size components, and the fragments would be too small to exist as comets. Instead, the high splitting rate supports the view that each secondary contains a very minor fraction of the mass of its primary, presumably 0.1% or less. This has been described as "peel off" (Sekanina 1982), or "crust-loss" splitting (Hughes and McBride 1992), to connote the idea that part of the mantle detaches with a very unequal mass ratio between components.

The recent discovery of split comet P/Shoemaker–Levy

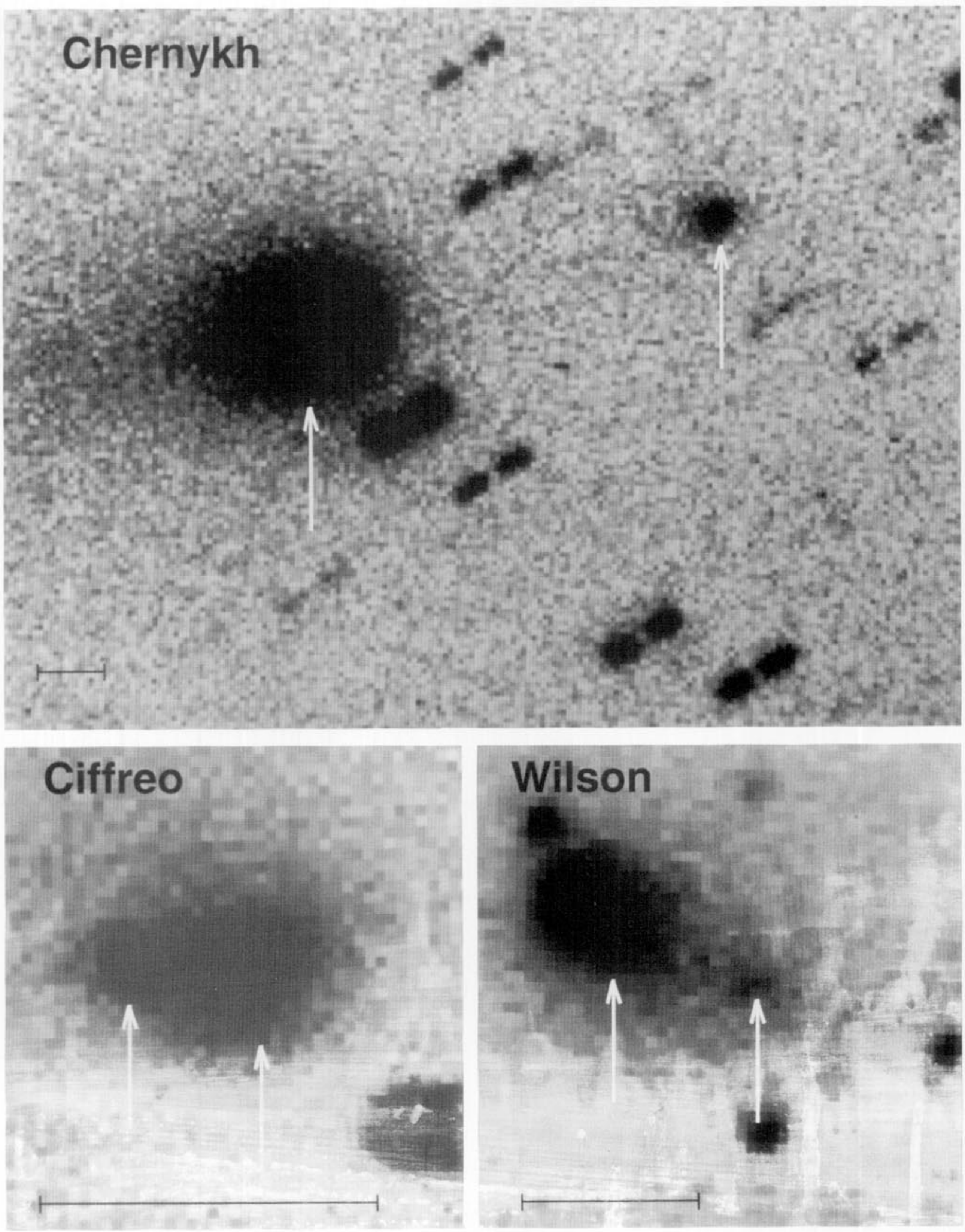

FIG. 1. Features of three split comets (North up, East left). Upper panel: P/Chernykh (UT 1991/Sep/15); lower left panel: P/Ciffreo (UT 1986/Mar/06); lower right panel: Comet Wilson (UT 1988/Feb/29). Two arrows in each panel indicate two components, where the 10″ bar for each image is given also.

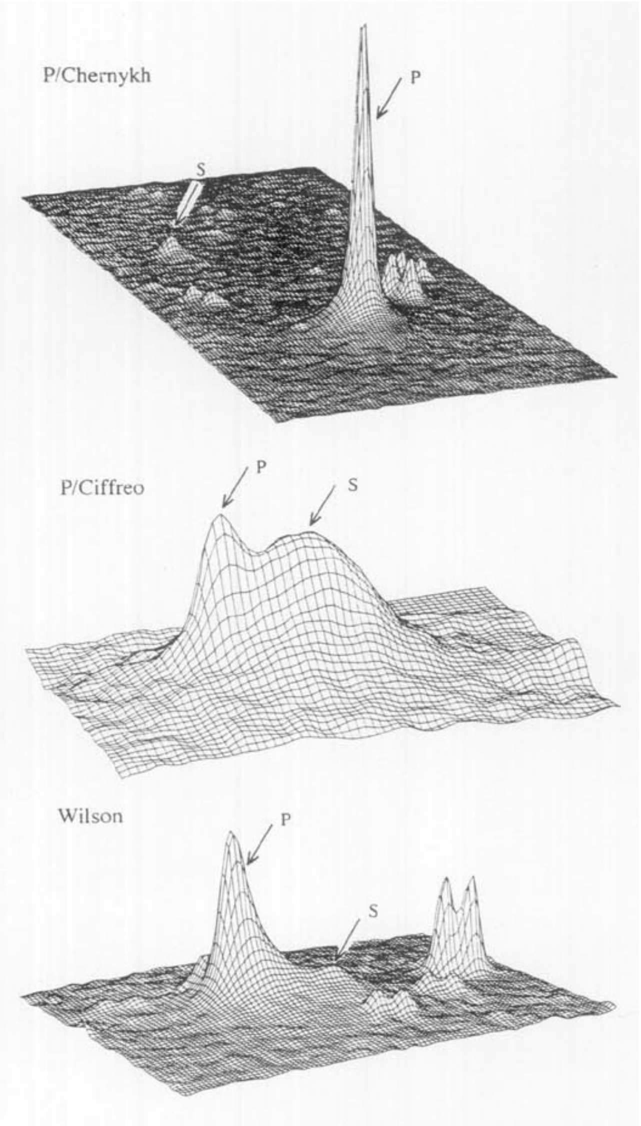

FIG. 2. Surface representations of three split comets in Fig. 1. Arrows marked "P" and "S" indicate primary and secondary components.

9 (Shoemaker *et al.* 1993) with its many components (Luu and Jewitt 1993; the countable number of its subnuclei is 22 as this paper is written) further emphasizes the significance of splitting in comets. However, because we observed this comet expressly because of its reported peculiar appearance, we cannot legitimately include it in the present observational sample without introducing an unwanted bias.

One thousand short-period comets each with 4×10^5 yr lifetime and producing one secondary per century would give approximately 4×10^6 secondaries in a swarm defined by the orbits of the parent comets. Where are they? Spacewatch observations show that Earth approachers smaller than 100 m are increasingly over-abundant compared to the magnitude–frequency distribution extrapolated from larger objects (Rabinowitz 1992, 1993). For example, at 10 m, the near-Earth flux is more than two orders of magnitude greater than a power law extrapolated from larger sizes. Tantalizing clues from spectral measurements and orbital associations suggest that some of these objects may be the debris from extinct, short-period comets (Rabinowitz 1992). More work needs to be done to determine whether or not these small objects have cometary parents, but it could be reasonably supposed that at least some of them are dead secondaries from split comets.

4. SUMMARY

From a re-examination of time-resolved sequences of CCD images of comets, we find:

(1) Three out of 49 observed comets possess secondaries.

(2) The derived splitting rate is of order $S \sim 0.01$ yr^{-1} comet^{-1} corresponding to $\sim 10^3$ splitting events in the

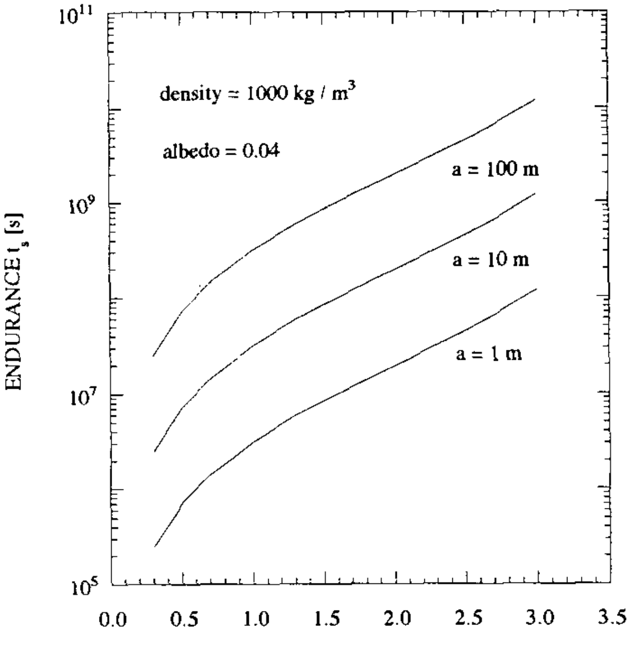

FIG. 3. Endurance of a sublimating, slowly spinning, spherical water-ice nucleus as a function of heliocentric distance. Adopted Bond albedo is 0.04. The three curves show sublimation lifetimes of objects 1 m, 10 m, and 100 m in radius.

$\sim 4 \times 10^5$ yr dynamical lifetime of each short period comet. Although perceived as rare by observers, splitting is a common occurrence in comets.

(3) Dead secondary nuclei may account for part of the excess flux of near-Earth objects reported at small sizes by Rabinowitz (1992, 1993).

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