Split Comets

H. Boehnhardt
Max-Planck-Institut für Astronomie Heidelberg

More than 40 split comets have been observed over the past 150 years. Two of the split comets have disappeared completely; another one was destroyed during its impact on Jupiter. The analysis of the postsplitting dynamics of fragments suggests that nucleus splitting can occur at large heliocentric distances (certainly beyond 50 AU) for long-period and new comets and all along the orbit for short-period comets. Various models for split comets have been proposed, but only in one peculiar case, the break-up of Comet D/1993 F2 (Shoemaker-Levy 9) around Jupiter, has a splitting mechanism been fully understood: The nucleus of D/1993 F2 was disrupted by tidal forces. The fragments of split comets seem to be subkilometer in size. It is, however, not clear whether they are cometesimals that formed during the early formation history of the planetary system or are pieces from a heavily processed surface crust of the parent body. The two basic types of comet splitting (few fragments and many fragments) may require different model interpretations. Disappearing comets may represent rare cases of complete nucleus dissolution as suggested by the prototype case, Comet C/1999 S4 (LINEAR). At least one large family of split comets exists — the Kreutz group— but other smaller clusters of comets with common parent bodies are very likely. Comet splitting seems to be an efficient process of mass loss of the nucleus and thus can play an important role in the evolution of comets toward their terminal state. The secondary nuclei behave as comets of their own (with activity, coma, and tail) exhibiting a wide range of lifetimes. However, at present it is now known whether the fragments' terminal state is "completely dissolved" or "exhausted and inactive."

1. THE PHENOMENON

Split comets appear as multiple comets with two or more components arising from the same parent and initially moving in very similar orbits. When active, the components usually display well-defined individual comae and tails that can overlap each other when the ensemble is close (see Fig. 1). Most of the components of a split comet "disappear" sooner or later; i.e., within time spans of hours to years the components become too faint to be detected even by the largest telescopes, and only one main component "survives" for a longer period of time. Activity outbursts and the appearance of coma arclets can be associated with comet splitting events. However, the ultimate proof of comet splitting is provided through the detection of at least one secondary component (also called a fragment or companion) to the primary nucleus.

The scientific interest in split comets reaches beyond the obvious questions "Why do comets split?" and "What is the sequence of events?" and focuses on the understanding of the internal structure and chemistry of the cometary nucleus as well as its overall evolution with time. The answers obtained from split comets may even provide information on the formation scenario of the solar system (for instance, the size distribution of the cometesimals, the original ice chemistry, and even the "birth place" of cometary nuclei).

1.1. Types of Split Comets

Two types of split comets are known from observations:

Type A: The split comet has a few (usually two) components. The primary fragment is the one that remains "permanent"; the secondary can be minor, short-lived, or persistent for a longer time (years to centuries). The primary is considered to be identical to the original nucleus (the parent body), while the secondary represents a smaller piece that is broken off the nucleus (typically 10–100 m in size). Type A splitting events can recur in the same object. Known cases are the comets listed in section 8 (with the exception of the ones mentioned as Type B below).

Type B: The split comet has many (more than 10) components that could arise from a single or a short sequence of fragmentation events. The fragments are short-lived (possibly of small size), and no primary component can be identified. Tertiary fragmentation of secondaries is occasionally observed. Type B events are believed to represent cases of dissolution and/or disruption of the comet and the parent body may become completely destroyed. Known cases are Comet D/1993 F2 (Shoemaker-Levy 9) and Comet C/1999 S4 (LINEAR).

In summary, observations and modeling results provide evidence for at least 42 split comets producing several hundred (>400) fragments in more than 100 splitting events.

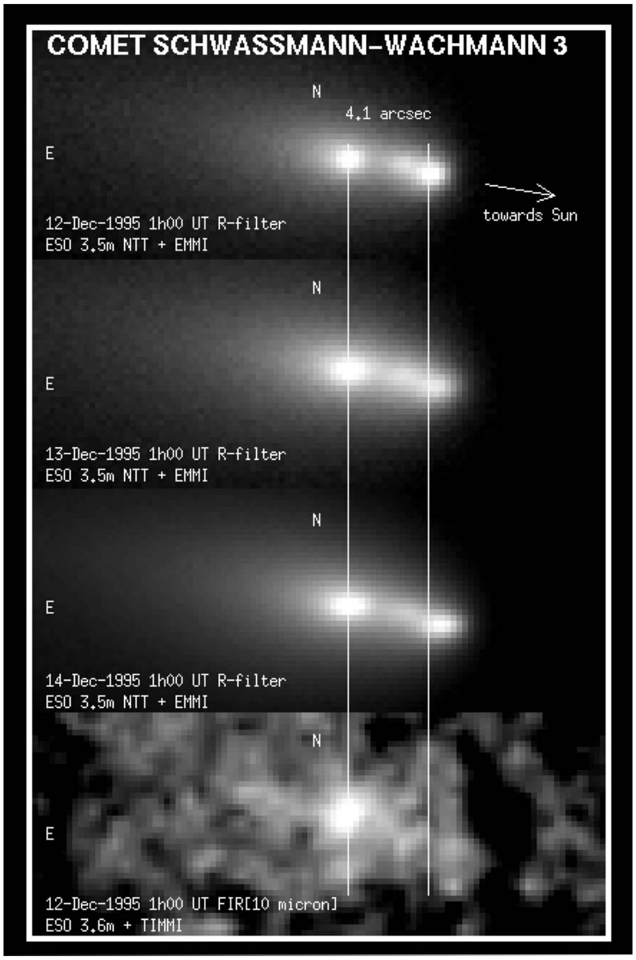

Fig. 1. Three components of split Comet 73P/Schwassmann-Wachmann 3 are detected in mid-December 1995 shortly after the splitting event of the nucleus. Each fragment has its own coma and tail that overlap. Component C (to the east) is the primary fragment, companions B (middle) and A (to the west) are secondary fragments. Fragment B is considered persistent, since it survived the subsequent perihelion passage in January 2001. Fragment A was not found upon the next return of the comet. The images are taken in the visible R-band filter (upper three panels; NTT + EMMI) and in the mid-IR N band (bottom panel; 3.6-m + TIMMI). Courtesy of the European Southern Observatory (ESO).

1.2. Designation of Fragments

In general, the fragments are denoted with the designation and name of the parent comet [given by the International Astronomical Union (IAU)], followed by upper-case letters beginning with the letter A for the component that passes perihelion first. This fragment is supposed to be the primary component. However, cases of misidentified primaries exist (for instance, 73P/Schwassmann-Wachmann 3A and C, the latter being the primary; see also Fig. 1). Indices for tertiary components that split from already denoted fragments were introduced, such as in the case of D/1993 F2 (Shoemaker-Levy 9) components P_1, etc. Widely separated components may even receive different IAU designations and names [like Comets C/1965 S1 (Ikeya-Seki) and C/1882 R1 (Great September Comet)] and are only linked *a posteriori* to a common parent body.

2. DYNAMICS OF COMET SPLITTING

As discussed in *Marsden and Sekanina* (1971), simple backward integration of the orbits of the fragments of split comets does not yield unique and well-defined "collision" points of their orbits that could be considered the places where the fragmentations of the nuclei happened. Moreover, this approach does not provide a sensible description of the dynamical aspects of the splitting event itself.

2.1. Dynamical Models for Comet Splitting

Sekanina (1977, 1978, 1979, 1982) has developed a five-parameter model to approximate the dynamics of the motion of the fragments of split comets. He and colleagues applied this model to more than 30 split comets. A similar approach was used by *Meech et al.* (1995) for Comet C/1986 P1 (Wilson). The parameters are used to constrain the fragmentation event dynamically through the time T_s when the splitting happened, the radial V_r, transverse V_t and normal V_n components of the separation velocity of the secondary fragment relative to the primary one, and the deceleration parameter Γ of the secondary relative to the primary component. V_r points in the direction of the radius vector of the comet, positive along the radius vector; V_t is perpendicular to the radius vector of the comet in the orbital plane, positive in the direction of the velocity vector of the comet; V_n is perpendicular to the orbital plane of the comet, positive toward the direction of the angular momentum. The deceleration Γ is a result of the momentum transfer between the two fragments due to their different outgassing rates and masses. It is measured in radial direction only; the two other components of the deceleration are set to zero. Γ is assumed to vary with solar distance r proportional to $1/r^2$.

The model implies a single-step, two-body fragmentation of the nucleus. Its parameters (or subsets of them) are determined by nonlinear least-squares fits of astrometric positions of the fragments. As such, the quality of the parameter solution depends very much on the accuracy, the number, and the measured arc of astrometric positions of the fragments. Moreover, at least in the case of more than two fragments, a variety of splitting sequences of the fragments are possible and need to be analyzed (*Sekanina,* 1999; *Weaver et al.,* 2001), and for events that produce many fragments like C/1999 S4 (LINEAR) a complete and unique solution becomes impossible. Also, different numerical solutions are possible even for a two-fragment case by considering various subsets of fit parameters, and the selection of the most plausible one requires a critical discussion of the physical meaning of the solutions.

Desvoivres et al. (1999) have introduced a description of the dynamics of split comets that is based on a physical outgassing model for the components. As in Sekanina's approach, this model implies a single-step two-body fragmentation scenario of the nucleus, and the many model parameters — including the size and bulk density of the fragments — are determined through a numerical fit of the motion of the fragments involving plausibility considerations on some of the fit parameters. The authors applied their model to three splitting events observed in Comet C/1996 B2 (Hyakutake) in 1996 and could indeed demonstrate that outgassing of the fragments together with the initial momentum from the splitting event provide a suitable description of the dynamics of the companions.

Neither model implies a particular physical process that causes the splitting of comets, and in each model only the separation dynamics of the fragments after breakup (and when at larger distance from each other) is described. They were successfully applied to split comets with fragments of small (a few arcseconds to a few degrees) mutual distances.

2.2. Results from the Dynamical Modeling of Comet Splitting

The results discussed below are primarily based on the work by Sekanina and collaborators over the past 25 years (*Sekanina,* 1977, 1978, 1979, 1982, 1988, 1991, 1995b, 1997a, 1998, 1999, 2001, 2002c; *Sekanina and Marsden,* 1982; *Sekanina and Yeomans,* 1985; *Sekanina and Chodas,* 2002a–d; *Sekanina et al.,* 1996, 2002; Marsden and Sekanina, personal communication). Figure 2 contains plots that illustrate the results and conclusions on the dynamical modeling of split comets. The underlying database contains 33 comets producing a total of 97 fragments in 64 splitting events (9 dynamically new comets with 22 components in 13 events, 13 long-period comets with 37 components in 24 events, and 11 short-period comets with 38 components in 28 events).

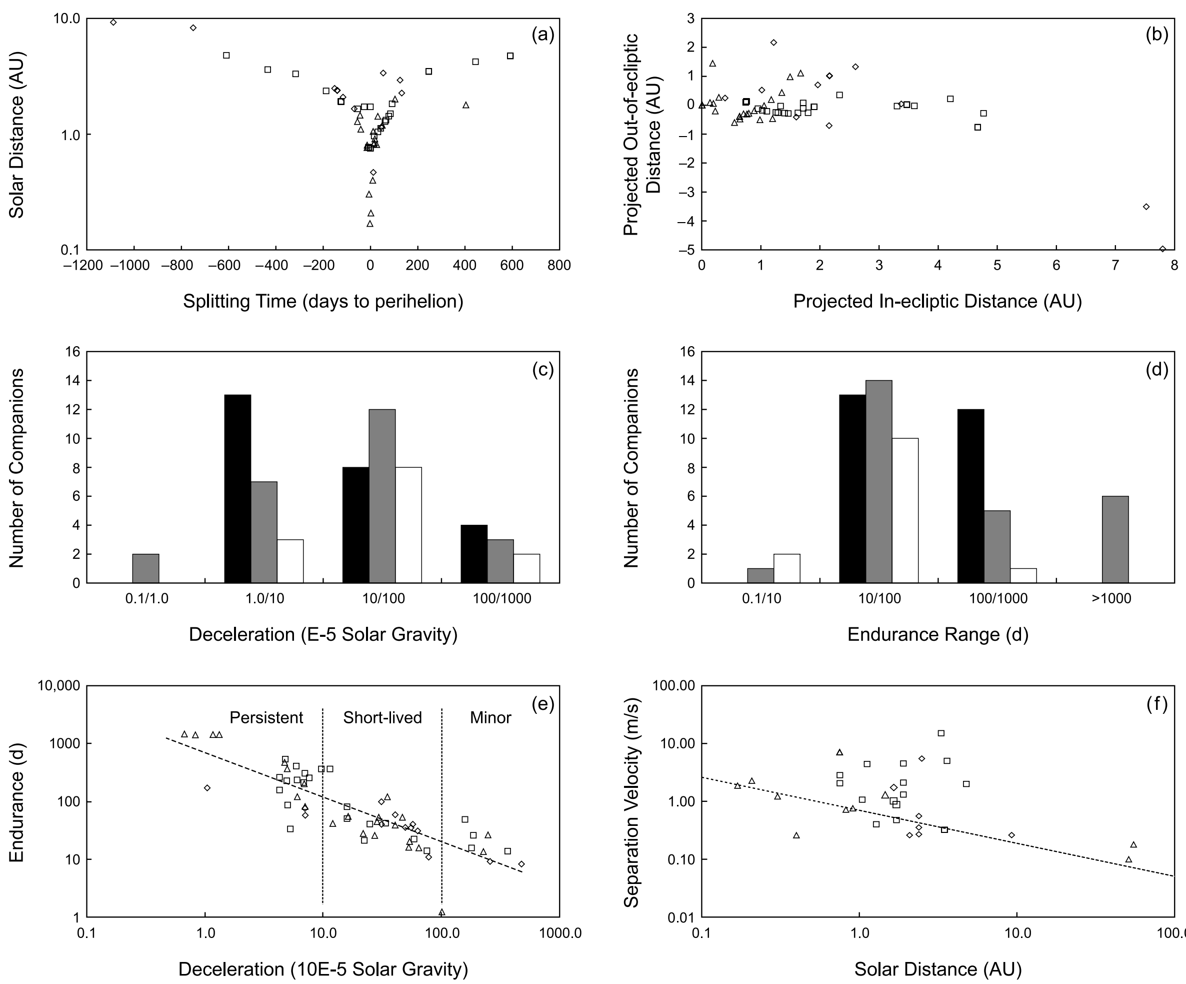

Fig. 2. Results from the dynamical modeling of comet-splitting events. **(a)** Solar distance vs. splitting time to perihelion (negative/positive before/after perihelion). **(b)** Location of splitting events: Projected out-of-ecliptic distance vs. projected in-ecliptic distance **(c)** Histogram distribution of relative deceleration of companions. **(d)** Histogram distribution of endurances of companions. **(e)** Endurance vs. deceleration of companions. **(f)** Separation velocity of the companions vs. solar distance at time of splitting. Symbols and colors used in the plots are as follows: short-period comets — squares (plots) and black (histograms); long-period comets — diamonds (plots) and gray (histograms); dynamically new comets — triangles (plots) and white (histograms). In **(e)** the three groups of companions ("persistent", "short-lived", "minor") are indicated between dotted vertical lines. The broken line in this panel shows the best fit described by equation (2) in section 2.2. The broken line in **(f)** represents the relationship obtained by *Sekanina* (1982) and described in section 2.2.

TABLE 1. Mean values for the deceleration, endurance, and separation velocity of fragments.

	New Comets	Long-Period Comets	Short-Period Comets
Deceleration (10^{-5} solar units)	86 ± 134	41 ± 43	49 ± 59
Number of fragments	13	24	25
Endurance (days)	52 ± 31	514 ± 653	161 ± 128
Number of fragments	13	26	25
Separation velocity (m/s)	1.3 ± 1.3	2.0 ± 1.9	2.7 ± 2.3
Number of fragments	7	12	16

2.2.1. Primary and "higher-order" fragments. The identification of the primary fragment of a splitting event is made purely on dynamical grounds: The primary is the companion that passes perihelion first and thus shows the smallest nongravitational force of the breakup products. For many cases one can assume that it carries the vast majority of mass of the original nucleus. "Secondaries" are believed to represent lighter pieces from the splitting event since they show higher nongravitational forces than the primaries. Tertiary fragments are produced when secondaries disintegrate further, and so on for even higher-order fragments. The presence of multiple companions requires a careful analysis of the observations in order to definitively establish the sequence of nucleus splitting events that generated the fragments.

2.2.2. Splitting time T_s. The plot "splitting time" vs. "solar distance" in Fig. 2 shows a clustering of splitting events close to perihelion, a trend that may have considerable observational bias since these events happen closer to the observers on Earth. The comet splitting is about equally likely before and after perihelion. The behavior of short-period, long-period, and dynamically new comets seems to be similar. A few early breakups (i.e., long before perihelion passage) of long-period and dynamically new comets are known. The results for T_s suggest that at least short-period comets seem to split all along their orbits.

2.2.3. Splitting location. The solar distances, where comet splitting happens, peak within about 2 AU. However, there are several cases where comets split at larger distances, even beyond 50 AU (not plotted in Fig. 2; see also section 3.1). While the splitting locations of short-period comets are naturally close to the ecliptic, such a bias does not exist for new and long-period comets that can split at large distance in and out of the orbital plane of the planets. Indications exist (*Sekanina*, 1982, 1997a, 1999) that comets may split all along the orbit even at large heliocentric distances (>5 AU) up to aphelion of long-period comets (*Sekanina and Chodas,* 2002a, 2002b; *Sekanina et al.,* 2002).

2.2.4. Deceleration parameter Γ. The deceleration parameter Γ ranges from 10^{-5} to almost 10^{-2} × solar gravity. The coarse histogram distribution in Fig. 2 suggests that long-period and new comets tend to produce fragments subject to decelerations Γ of 10^{-4}–10^{-3} × solar gravity, while the fragments of short-period comets show on the average smaller Γ values. This trend suggests that fragments of the latter comets may be parts of a more evolved surface crust, i.e., they contain more dust of higher bulk density and less sublimating ices that can contribute to the nongravitational forces on the body. The breakup products of the two other groups may contain more volatile ices since their surfaces have experienced little loss by thermal heating during the much rarer perihelion passages. The mean deceleration of fragments from new comets (Table 1) is about twice as high as for those of long- and short-period comets (all with large error bars).

2.2.5. Endurance E of the fragments. The lifetimes of split components differ by a large amount, even for the same comet. This indicates that the fragments have different reservoirs of outgassing material and they must be of different size and mass after all. *Sekanina* (1977, 1982) has introduced the so-called endurance parameter E of a fragment as a measure for the persistence of fragments. The endurance E has been defined as the time interval from the splitting event (given by T_s) to its final observation (at time T_f), normalized by the inverse-square law to a distance of 1 AU from the Sun. In other words, the endurance measures a minimum sublimation lifetime of a companion. In terms of orbital parameters, E (in days) can be written as

$$E = 1.015 * A_{sf}/[a * (1 - e^2)]^{1/2} \quad (1)$$

where A_{sf} is the length of the heliocentric arc of the orbit (in degrees) that the fragment passed through between T_s and T_f, a is the semimajor axis, and e is the eccentricity of the cometary orbit. Obviously, the endurance values of split comets are lower limits only, since T_f may be rather constrained by the visibility of the objects and telescope capabilities.

The measured endurances E cover three orders of magnitude from a few to several thousand days. In Fig. 2 the endurance E is plotted vs. the deceleration Γ for about 50 companions seen in split comets. Here, "companion" means secondary fragments, the decelerations of which were measured relative to the primary ones. The latter are to be considered the more persistent products since their lifetimes are at least as long as (and in most cases much longer than) those of the secondary ones. The conclusion of *Sekanina* (1982) that the endurance E scales with the deceleration Γ of the secondary fragments is still valid. However, the larger dataset available now suggests a steeper exponent for Γ

(correlation coefficient 0.7)

$$E \text{ (in days)} = 690\ (\pm 180) * \Gamma^{-0.77\ (\pm 0.07)} \qquad (2)$$

Based upon an anticipated clustering in the endurance vs. deceleration plot of companions, *Sekanina* (1982) has introduced a classification scheme for the fragments of split comets, i.e., persistent ($\Gamma < 10^{-4}$ solar gravity), short-lived ($10^{-4} < \Gamma < 10^{-3}$ solar gravity), and minor components ($\Gamma > 10^{-3}$ solar gravity). In the larger dataset now available (see Fig. 2) the original clustering is less obvious. Nevertheless, the "minor components" are distinguished from the merging groups of "short-lived" and "persistent" objects. Among the latter, a few fragments with very long lifetimes (E > 1000 d) have been observed. The mean values for the endurances of the three dynamical classes of comets (Table 1) suggest that new comets are on the average less persistent as long- and short-period comets, although the mean deviations of the mean endurance values are large.

2.2.6. Separation velocities. The relative speed of the fragments shortly after the fragmentation event amounts from 0.1 to 15 m/s with the majority between 0.3 and 4 m/s. In many cases the velocity components are ill-defined through the available observations, if measurable at all. In Fig. 2 only cases are plotted for which all three components of the separation velocity are estimated, thus the total amplitude V_{total} can be calculated. It is unclear whether trends with solar distance r exist as suggested by *Sekanina* (1982) based on a smaller dataset: Dynamically new comets (and less likely long-period comets as well) may follow approximately *Sekanina*'s (1982) data fit of $V_{total} \sim 0.7 * r^{-0.57}$, while a similar behavior is not obvious for the short-period comets. Instead, for the latter, a random scatter of V_{total} independent of r is found. Therefore, on the average, a slightly larger separation velocity (see Table 1) may be indicative of a different fragmentation mechanism or of higher tensile strength of the nuclei as compared to the long-period and dynamically new comets (which may be less evolved due to rarer passages close to the Sun).

3. SPLIT PAIRS, FAMILIES, AND COMET EVOLUTION

The dynamical modeling described in section 2 is preferably applied to cases where evidence for the comet splitting comes from the observations of the fragments that appear close in time and space. In fact, most of the fragments are observed within the same — narrow — field of view of the telescopes used. Linking "wider and older" pairs and clusters of split comets is a more difficult task.

3.1. Pairs and Families of Split Comets

Similarity of the dynamical (semimajor axis, eccentricity) and geometrical (inclination, ascending node, argument of perihelion) orbital elements of comets suggests a common origin of the respective nuclei despite very different times for perihelion passage and despite the failure to identify the location and time of the splitting along the orbit from simple numerical backward integration of their orbits (*Marsden and Sekanina,* 1971). Such evidence, i.e., from similarity of orbital elements, exists for several possible pairs of split comets: C/1988 F1 (Levy) and C/1988 J1 (Shoemaker-Holt) (*Bardwell,* 1988); C/1988 A1 (Liller) and C/1996 Q1 (Tabur) (*Jahn,* 1996); C/2002 C1 (Ikeya-Zhang) and C/1661 C1 (*Green,* 2002); C/2002 A1 (LINEAR) and C/2002 A2 (LINEAR) (*Sekanina et al.,* 2003), C/2002 Q2 (LINEAR) and C/2002 Q3 (LINEAR) (*Adams,* 2002). Backward integration of the orbits of periodic Comets 42P/Neujmin 3 and 53P/Van Biesbroeck suggests a good agreement of their orbits before 1850 when a very close encounter with Jupiter may have occurred (*Carusi et al.,* 1985).

Tancredi et al. (2000) have addressed the question of families of split pairs and families among short-period comets through a statistical approach. The authors analyzed the dynamical taxonomy of Jupiter-family comets and near-Earth asteroids (NEAs) using clustering of Lyapunov indicators derived from the orbital elements of the objects. A splitting hypothesis for the Jupiter-family comets, i.e., to originate from a "giant" 50-km nucleus (comparable in size to a small Kuiper belt object), is not very likely. Moreover, they found that the contribution of split comets to the population of near-Earth asteroids is small, if at all significant. The clustering of the Lyapunov indicators of Comets 42P/Neujmin 3 and 53P/van Biesbroeck with those of Comets 14P/Wolf and 121P/Shoemaker-Holt 2 is not only supporting a splitting scenario for the former pair of comets, but may even suggest the involvement of further candidates, i.e., the latter two comets.

In order to model the dynamics of splitting events over more than one orbital revolution, *Sekanina and Chodas* (2002a,b) have integrated planetary and nonrelativistic perturbations in the original approach of *Sekanina* (1982) (see section 2.1). The authors used their enhanced model to link major Sun-grazing comets as fragments of parent bodies (fitting V_r, V_t, V_n, but neglecting the deceleration parameter Γ): Comets C/1965 S1 (Ikeya-Seki) and C/1882 R1 (Great September Comet) were produced by a common parent that split in 1106 shortly after perihelion passage [this was already suggested by *Marsden* (1967)]. Moreover, the motion of Comet C/1970 K1 (White-Ortiz-Olelli) is consistent with a scenario in which the parent was an unknown third fragment of the 1106 splitting event, and the separation of C/1970 K1 (White-Ortiz-Olelli) occurred in the eighteenth century at a large heliocentric distance of about 150 AU. C/1880 C1 (Great Southern Comet) split off C/1843 D1 (Great March Comet) at 2.5–3 AU after perihelion passage in the eleventh century [also previously suggested by *Marsden* (1989), with breakup in the fifteenth century only). As a by-product, but most interesting for linking orbits of fragments over longer time intervals, *Sekanina and Chodas* (2002a) summarize the orbit perturbations of Sun-grazing comets that split since the last perihelion passage with nonzero separation velocity.

3.2. Kreutz Group and Solar and Heliospheric Observatory (SOHO) Comets

The Kreutz group comets (also called Sun-grazers) are comets that approach the Sun to a perihelion distance <2.5 solar radii. The number of discovered Sun-grazer comets has increased tremendously with the advent of coronagraphic observations from satellites, e.g., SOLWIND, Solar Maximum Mission (SMM), and in particular the Solar and Heliospheric Observatory (SOHO), which has detected several hundred new objects (*Sekanina,* 2000b). Two main families (I and II, with a further division into two subgroups for family II) are identified through statistical methods [clustering of orbital elements (*Marsden,* 1967, 1989; *Sekanina,* 2002a)]. There also exists a non-Kreutz near-Sun comet group among the SOHO comets that is characterized by similar orbital elements (*Meyer and Marsden,* 2002). Practically all smaller Sun-grazers (i.e., most of the so-called "SOHO" comets) do not survive perihelion passage (*Sekanina,* 2000a,b), but the larger (i.e., brighter) ones in the Kreutz group do.

Nucleus splitting of the Kreutz group and SOHO comets suggests the following: (1) some larger objects (*Marsden,* 1967, 1989; *Sekanina,* 2002a,b) are among the list of split comets (see Appendix); (2) there are tremdendous similarities in the orbital elements of these comets and their subgroups (*Marsden,* 1967, 1989; *Meyer and Marsden,* 2002); and (3) the SOHO comets show a significant temporal clumping since more than 15 pairs of comets were observed that appeared within less than 0.5 d in similar orbits within the field of view of the SOHO coronagraph. A dynamical analysis of the latter (*Sekanina,* 2000b) indicates that the pairs originate from fragmentation events all along the orbit, i.e., not necessarily close to the Sun, but more or less at any point along the orbit, even near aphelion. The dissolution of the smaller SOHO comets close to the Sun happens before reaching perihelion and it is frequently indicated through an activity flare at ~3 solar radii with a subsequent drop in brightness. Sekanina attributes the disappearance of these comets to an "erosion" effect of the nuclei due to the strong heating of the Sun.

Sekanina (2000b) has introduced a scenario for the formation of this group of comets involving a parent nucleus that split into two major fragments, possibly through tidal forces or at least tidally triggered, during perihelion very close to the Sun. After the break-up the two major fragments evolved into slightly different orbits, but continued to split along their paths around the Sun, generating a cascade of tertiary components of very different size that form the group and subgroups of Kreutz comets.

3.3. Nucleus Splitting and the Evolution of Comets

The role of nucleus splitting in the evolution of comets is widely unexplored. Multiplicity and persistence of fragments and recurrence of the splitting phenomenon in comets would argue for the existence of break-up families among the current population of comets. And indeed some indications are found (see sections 3.1 and 3.2). The Lyapunov indicator cluster analysis by *Tancredi et al.* (2000) suggests that break-up families are not very abundant among Jupiter-family comets. This could imply that the production of long persistent fragments by short-period comets is low and/or that the decay rate of the break-up products is fast compared to the typical dissipation timescale for the Lyapunov indicators of these class of comets (on the order of several hundreds of years).

From simple estimates on the mass loss due to recurrent nucleus splitting events it becomes clear that fragmentation may be an efficient destruction process for comets. For instance, from the current catalogue of about 160 short-period comets, 10 objects are known to have split, three of them repeatedly (16P/Brooks 2, 51P/Harrington, 141P/Machholz 2); one object (3D/Biela) disappeared completely after nucleus splitting. The observational baseline for this class of comets is on the order of 200 years, and it must be assumed that some other splitting events escaped detection. Thus, the numerical splitting rate of ~3% per century and object may only represent a lower limit for short-period comets. This rough order-of-magnitude result is consistent with the splitting rate estimate of at least 1 event per century and comet published by *Chen and Jewitt* (1994) based on observations of break-up events of comets in general. *Weissman* (1980) reports splitting rates of 1%, 4%, and 10% for short-period, long-period, and dynamically new comets based on a sample of 25 objects (of which 7 are at least questionable candidates).

Over its mean lifetime in the inner planetary system, a short-period comet may experience about 1000 splitting events. If the average mass loss in these events corresponds to a 50-m fragment, the total mass loss by nucleus splitting can amount to 500–1000-m equivalent radius over the lifetime of a comet, i.e., it is on the order of the typical size of the nuclei of short-period comets. Therefore, nucleus splitting may represent an important mass loss factor in the life of a comet and should be considered carefully in the scenarios for the evolution and "end state" of comet nuclei.

4. SECONDARY EFFECTS: OUTBURSTS AND COMA ARCLETS

The main effect of comet splitting is the appearance of one or more companions of a primary component (Type A). In a very few cases, many more fragments appear (quasi-) simultaneously and without clear indication of a primary component among them (Type B). Unfortunately, in general the existence of primary and secondary components becomes detectable in direct images only long (typically weeks) after the time when the splitting actually occurred. Activity outbursts and arclets in the coma of a comet can indicate the occurrence of a nucleus break-up event at or shortly after the time when the comet splits.

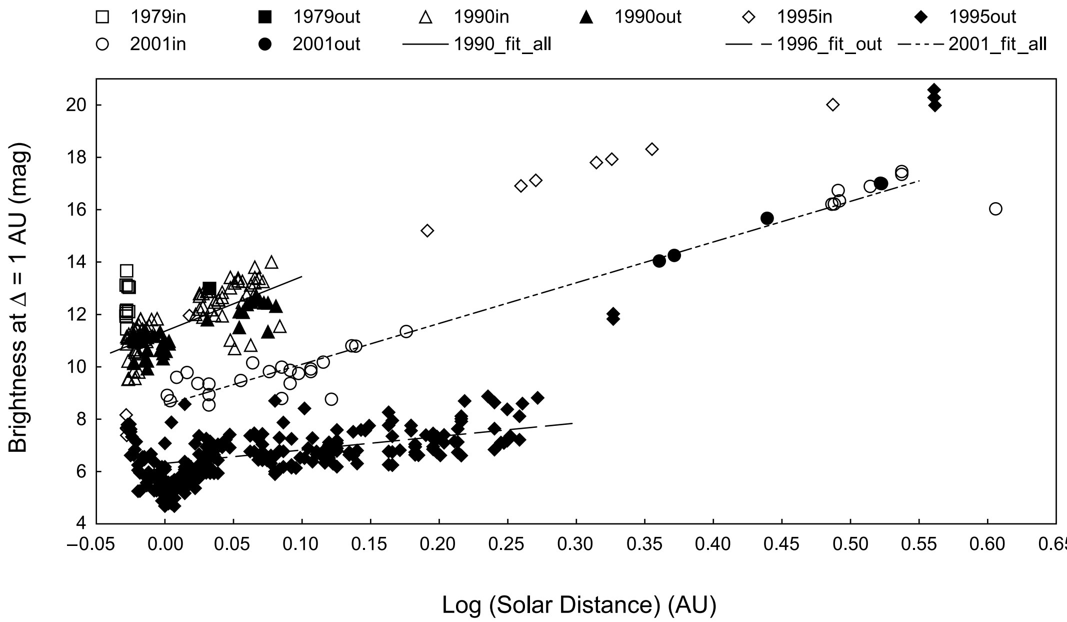

Fig. 3. Pre- and post-break-up visual lightcurve of Comet 73P/Schwassmann-Wachmann 3. The lightcurve of the total brightness estimates in the visual wavelength range over four apparitions of the comet from 1979 to 2001. Nucleus splitting happened around perihelion 1995 and shortly thereafter. Even one apparition, i.e., 4–6 years later, the brightness of the comet (component C) is still 2–3 mag above normal level before break-up. The observations obtained during the 1979, 1990, 1995–1996, and 2001 perihelion passages are marked by symbols. Least-squares fits to the various apparition lightcurves are indicated by lines. In the legend, numbers next to the symbols and lines denote the year of the comet apparition, "in" stands for inbound, "out" for outbound, "all" for all data of the apparition, "fit" for least-squares fit.

4.1. Activity Outbursts

Outbursts in the visual lightcurve of comets can indicate splitting events. There are prominent cases that demonstrate the temporal relationship between nucleus splitting and activity outbursts with amplitudes of 3 mag and more: C/1975 V1 (West), 73P/Schwassmann-Wachmann 3, and C/1999 S4 (LINEAR) as described by *Sekanina* (1982), *Sekanina et al.* (1996), and *Green* (2000). Smaller lightcurve peaks and nucleus break-ups are associated with Comets C/1899 E1 (Swift), C/1914 S1 (Campbell), C/1943 X1 (Whipple-Fedtke), C/1969 T1 (Tago-Sato-Kosaka), and C/1975 V1 (West) (see *Sekanina,* 1982); C/1986 P1 (Wilson) (see *Meech et al.,* 1995); and 73P/Schwassmann-Wachmann 3, C/1996 J1 (Evans-Drinkwater), and C/2001 A2 (LINEAR) (*Sekanina,* 1998; *Sekanina et al.,* 1996, 2002). The rise times of these outbursts, if measurable, last for a few (2–20) days. The durations of the activity outbursts have a very wide range, from a few days to months or maybe even years. Figure 3 shows the lightcurve of 73P/Schwassmann-Wachmann 3 during the past four apparitions observed: The lightcurves in 1979 and 1990, plus most of the preperihelion phase in 1995, define the (rather repetitive) normal activity level before break-up of the comet in autumn 1995. The postperihelion lightcurve in 1995–1996 is about 5 mag (factor of 100) brighter than normal due to the break-up events around perihelion and thereafter, and even during the subsequent perihelion passage the comet remains 2–3 mag brighter than before splitting.

The outbursts identified in the visual and most of the broadband brightness estimates and measurements of comets indicate a higher dust content in the coma. Most of this dust in the visible is of micrometer size (*McDonald et al.,* 1987). Most of the outbursts to which nucleus break-ups can be associated (*Sekanina,* 1982; *Sekanina et al.,* 1996, 2002) peak several days after the estimated dates of these events, suggesting that additional dust is released during or — more likely — after the splitting of the comet. The early phases of the dust expansion after break-up events are documented for C/1999 S4 (LINEAR) by *Schulz and Stüwe* (2002) and *Kidger* (2002). Outbursts in the gas production, although in smaller and short-term events difficult to observe, are also reported for split comets, e.g., 73P/Schwassmann-Wachmann 3 (*Crovisier et al.,* 1996) and C/1999 S4 (LINEAR) (*Mäkinen et al.,* 2001; *Farnham et al.,* 2001). For C/1999 S4 (LINEAR) the published measurements show a rapid decay of the gas and dust production of the comet in late July 2000. This in turn suggests that the reservoir of sublimating ice in this comet was exhausted rapidly after the complete disruption of the nucleus.

However, the relationship between outbursts in the lightcurve on one side and splitting events on the other is not "one-to-one": Not all splitting events are accompanied by noticeable outbursts (e.g., fragment E in 73P/Schwassmann-

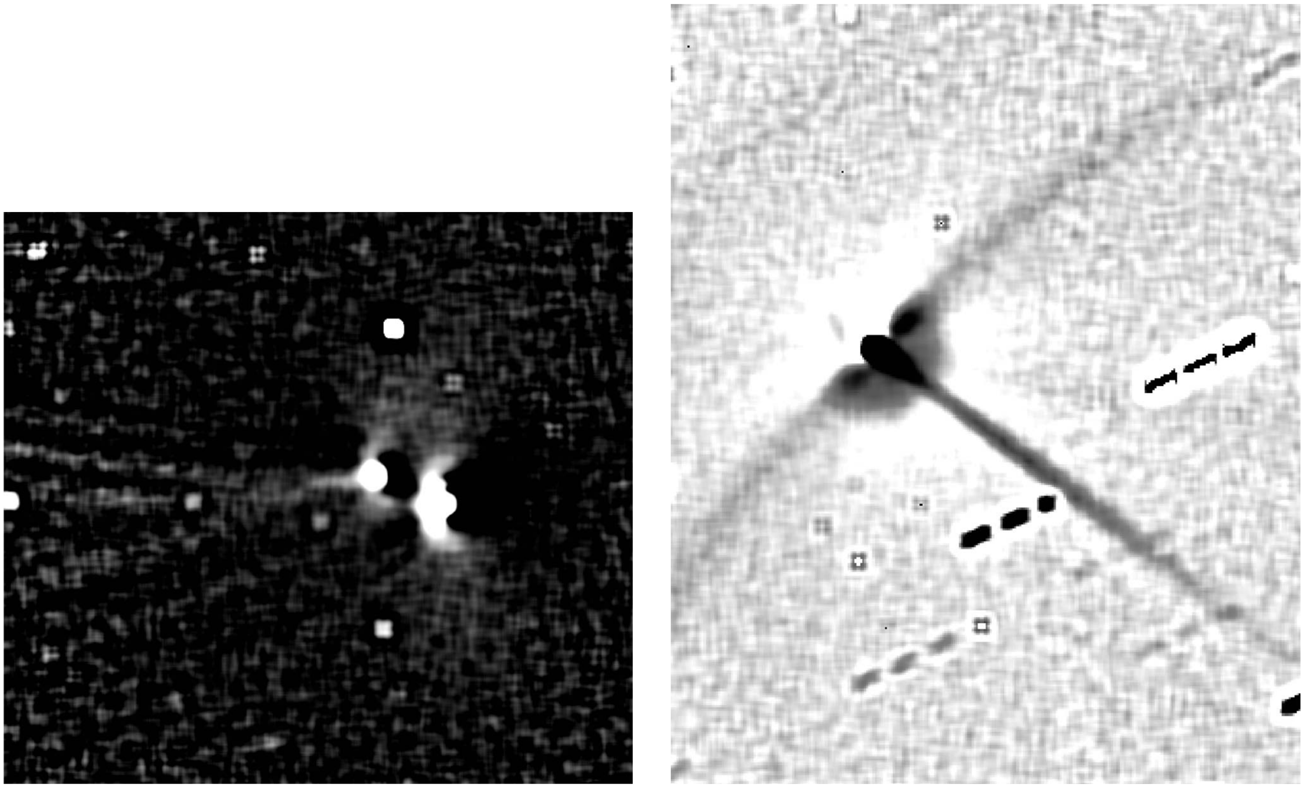

Fig. 4. Coma arclets of fragments of Comet C/2001 A2 (LINEAR). These broadband R-filter exposures of the comet show three coma arclets observed during the break-up episodes of the comet. In the left image (taken on 18 May 2001) two arclets are seen, one (to the left) between companions B and C (both not directly visible in the image) and another one (to the right) close to fragment A. The former arclets seem to be associated with the splitting of component C from B on 10 May 2001, while for the latter case no companion of fragment A is reported. The right image (taken on 13 July 2001) shows another very wide arclet around component B. Apart from the main component no further fragments could be identified. However, the straight tail-like extension away from the Sun may represent dust released by the invisible fragment(s) that might have split off fragment B a few days before the image was taken. The images are taken with the New Technology Telescope (NTT) and the Very Large Telescope (VLT) of the European Southern Observatory (ESO), respectively. North is up and east to the left; field of view is 2.5×1.9 arcmin^2 in the left and 1.0×1.2 arcmin^2 in the right panel. Image courtesy of E. Jehin et al., ESO Chile.

Wachmann 3) and not all outbursts indicate splitting events that produce detectable companions (e.g., the 10-mag outburst of Comet 52P/Harrington-Abell observed from July 1998 to February 1999). Outbursts of smaller amplitude (1–3 mag) may also occur as episodes of enhanced activity of the comet without obvious splitting of the nucleus (see *Prialnik et al.,* 2004; *Meech et al.,* 2004). Activity outbursts of splitting events start around the estimated time of the nucleus break-up and they usually reach peak brightness a short time (order of days) thereafter. However, it is not clear whether brightness outbursts are associated with the actual cause of the break-up or are more a consequence of the nucleus splitting.

The visual and broadband filter lightcurves of companions in split comets show a systematic decay in brightness and intrinsic short-term variability of the fragments (*Sekanina,* 1982, 1998; *Sekanina et al.,* 1996, 1998). Both phenomena seem to be due to outgassing behavior of fresh material from the interior of the original nucleus that may be exposed to sunlight for the first time since the formation of the comet. The measurements of lightcurves for individual components usually suffer from the overlap of the comae shortly after the splitting event such that the measured magnitudes are contaminated by light from the neighboring coma(e).

4.2. Coma Arclets

Coma arclets, also called "coma wings" because of their bird-shaped appearance, have been seen in three comets shortly after splitting events that produced short-lived companions of the primary nuclei, i.e., in Comets C/1996 B2 (Hyakutake) (*Harris et al.,* 1997; *Rodionov et al.,* 1998), C/1999 S4 (LINEAR) (*Farnham et al.,* 2001), and C/2001 A2 (LINEAR) (*Jehin et al.,* 2002). They show up easily when some simple structure enhancement (like wavelet or adaptive Laplace filtering or radial renormalization) is applied to the flat-fielded images. Figure 4 shows examples of arclets observed during break-up of Comet C/2001 A2 (LINEAR).

The arclet structure appears to be located in between two split companions. The observed arcs are almost perpendicular to the connecting line of the fragments, rather symmetric on both sides and preferably — but not exclusively — with tailward curvature. The observed arclets extended over 1000 to 10,000 km on both sides and intersected the connecting line of the fragments at a few 100 to a few 1000 km projected distance. They appeared soon (within 10 d) after the fragmentation event of the nucleus and faded away within 3–5 d after first appearance. From narrow and broadband imaging in the visible and near-IR (*Harris et al.,* 1997), it is clear that the coma arclets are made of gas (OH, CN, and C_2 gas was identified). Dust does not participate in their formation. Nevertheless, arclets are also detectable in broadband images taken in visible wavelengths if their gas content is large enough and covered by the filter bandpasses. Thus far, coma arclets have only been reported in split comets close to quadrature position and at distances close to Earth. The importance of both conditions on the visibility of the phenomenon is presently unclear.

Three physical interpretations of the coma arclets are published. *Harris et al.* (1997) proposed an arc model involving gas release from the primary nucleus plus an extended source located on the connecting line toward the secondary component. The extended source is claimed to be a train of boulders produced during the splitting event and emitted in the same direction as the major secondary fragment. No shock wave of gas is predicted in this model, but the main contribution to the arclets should come from the gas released by the boulder train. Indeed, in the case of Comet C/1996 B2 (Hyakutake) a straight spike of diffuse light, typical for dust streamers, was seen along the connecting line of the two fragments at the time when the arclets occurred. A similar phenomenon was found for one of several arclets observed in Comet C/2001 (LINEAR), although in this particular case no fragment could be detected (*Jehin et al.,* 2002). *Rodionov et al.* (1998) model the arclets of Comet C/1996 B2 (Hyakutake) through a two-source (the two fragments) outflow of rarefied supersonic gases that produce shock waves in the region between the two components. The shock waves are best visible edge-on (i.e., close to quadrature geometry of the comet). This model involves activity on the night side of the primary nucleus — otherwise no shock front is formed. *Farnham et al.* (2001) interpret the arclets seen in Comet C/1999 S4 (LINEAR) before the major break-up of the nucleus in July 2001 as a dust jet from an active region close to the equator of a fast rotating nucleus. According to this scenario, the rotation axis should point toward the Sun. This scenario certainly has some difficulties in explaining the many arclets of gaseous origin seen in the other two comets.

Even though the physical nature of coma arclets in split comets is not yet clearly understood, there is no doubt that they can be considered as early tracers of nucleus break-up events.

5. PHYSICO-CHEMICAL PROPERTIES OF SPLIT COMETS AND THEIR FRAGMENTS

The observations of split comets, and in particular the measurements of the fragments of Comet C/1999 S4 (LINEAR) (*Weaver et al.,* 2001), suggest that "solid" secondary bodies are produced by fragmentation of a primary nucleus. If one assumes that the fragments are the original building blocks of cometary nuclei, the break-up of Comet C/1999 S4 (LINEAR) provides indications of the typical size distribution of cometesimals, at least for the (yet unknown) region of the planetary disk where its nucleus was formed. The former assumption, however, can be questioned, at least for comets coming from the Kuiper belt region [such as the short-period comets (*Farinella and Davis,* 1996)] if one considers the collision environment of the belt that may have created the population of comet-size bodies through collisional break-ups of larger objects over the lifetime of the solar system. The impact energy induced in a Kuiper belt body through long-term bombardment is of an amount that could potentially modify the constitution of the whole body or at least a major part of it.

Size estimates of nuclei before or during the fragmentation episode exist only for two comets, 73P/Schwassmann-Wachmann 3 [radius 1.1 km (*Boehnhardt et al.,* 1999)] and C/1996 B2 (Hyakutake) [radius 2.4 km (*Lisse et al.,* 1999)]. Photometric measurements of fragment sizes are published for C/1999 S4 (LINEAR) [50–100 m for 4% albedo (*Weaver et al.,* 2001)]; a few more size estimates of fragments or upper limits were derived from the dynamical models of the splitting event (*Sekanina,* 1982; *Sekanina et al.,* 1996; *Desvoivres et al.,* 1999; *Boehnhardt et al.,* 2002), from the brightness evolution of Sun-grazer and SOHO comets [50 km to 5 m (*Sekanina,* 2000b, 2002a,b)] and from the break-up of Comet D/1993 F2 (Shoemaker-Levy 9) (*Sekanina,* 1995a; *Asphaug and Benz,* 1996). Lower limits of the fragment's sizes were also derived from the explosion blankets produced during the impacts of the split Comet D/1993 F2 (Shoemaker-Levy 9) on Jupiter (see, e.g., *Ortiz et al.,* 1995). Mass estimates of the fragments are provided by the authors assuming a bulk density for the nucleus material. A size distribution function N(R) for the fragments of C/1999 S4 (LINEAR) was derived by *Mäkinen et al.* (2001): $N(R) \sim R^{-2.7}$ (R for the radius of the fragment). However, the overall size or mass budget of split comets (before and after break-up) remains unknown since it was not yet measured for individual objects.

As mentioned in section 2, some of the fragments of split comets are "persistent" and endure for several years. It seems likely that independent and long-lived cometary nuclei may evolve. Other fragments have very short lifetimes of only a few days to weeks. The fragments of C/1999 S4 (LINEAR) survived intact after the nucleus disruption for about 2–3 weeks (see Fig. 5). Thereafter, they disappeared quickly — and "collectively" — within a few days. Exactly what happens to the short- and long-lived

Fig. 5. Many short-lived fragments of Comet C/1999 S4 (LINEAR). This R-filter image taken in early August 2000 at the ESO VLT shows at least 16 short-lived fragments that were produced in the break-up of the nucleus between 21 and 24 July 2000. The fragments are embedded in a diffuse coma of which a long dust-tail streamer extends away from the Sun. Image processing is used to increase the contrast of the fragments on the diffuse coma background. North is up and east to the left; field of view is 3.4 × 2.5 arcmin^2. Image courtesy of European Southern Observatory (ESO).

fragments when they disappear is not known: Do they dissolve into even smaller pieces, or do they become inactive?

From the 10 split comets (4 short-period and 6 long-period) that are classified taxonomically, 7 comets [16P/Brooks 2, 69P/Taylor, 101P/Chernykh, 108P/Ciffreo, C/1975 V1 (West), C/1986 P1 (Wilson) (see *A'Hearn et al.,* 1995), and C/1999 S4 (LINEAR) (see *Mumma et al.,* 2001)] belong to the group of carbon-depleted objects, and 3 comets [C/1988 A1 (Liller) (see *A'Hearn et al.,* 1995), C/1996 B2 (Hyakutake) (*Schleicher and Osip,* 2002), and C/2001 A2 (LINEAR) (see *Jehin et al.,* 2002)] appear to be "typical" in their carbon content. A link between this taxonomic parameter and the splitting behavior of the nucleus is not obvious. The chemical composition of fragments is known even less, and not even a single fragment has measured production rates of gas and/or dust. *Bockelée-Morvan et al.* (2001) have inferred from gas production rates of the coma of C/1999 S4 (LINEAR) before and after the fatal splitting in July 2001 that the nucleus of this comet may have had a rather homogeneous chemistry. This conclusion would support the (unproven) scenario that this nucleus may have contained cometesimals that were formed in the same region of the planetary formation disk.

6. FRAGMENTATION MECHANISMS

Several fragmentation mechanisms are used to explain the splitting of cometary nuclei. Thus far, the success of these scenarios in the understanding of these events is limited, presumably since (1) the most important parameters of comet nuclei (such as internal structure, nucleus/surface stratification, material types, tensile and shear strengths, size, and rotation) used in these models are not at all or not very well known, and (2) the available observations do not constrain well the actual event sequence and the physical properties of the parent and daughter components of split comets. Not surprisingly, only for one split comet, D/1993 F2 (Shoemaker-Levy 9), do modelers seem to agree on the fragmentation scenario (i.e., tidal splitting close to Jupiter), although with significant differences in the details of interpretation and conclusion.

6.1. Scenarios

6.1.1. Tidal splitting. Tidal splitting of a body (comet nucleus) in the neighborhood of a large mass (a planet or the Sun) is induced when the differential gravitational "pull" of the large mass throughout the small body exceeds the forces of self-gravity and material strength (tensile and/or shear) of the latter. A simplified condition for tidal disruption of spherical bodies was published by *Whipple* (1963)

$$\sigma < GM_o\rho R^2/\Delta^3 \qquad (3)$$

The parameter σ is the tensile strength of the material, G is the gravitational constant, M_o is the mass of the large body, ρ and R are the bulk density and radius of the sphere, and Δ is the distance between the two bodies. A rigorous theoretical treatment of the problem for spheres and biaxial ellipsoids can be found in *Davidsson* (1999, 2001).

The models predict that the break-up should start from the center of the nucleus and that it should affect the body as a whole. The products of tidal splitting should be larger pieces in the center of the nucleus and smaller ones toward the surface of the body. This latter prediction, however, may depend on the internal structure of the nucleus as well. Obviously, this scenario works only in the neighborhood of heavy bodies. Tidal forces, even if not causing the nucleus splitting, can be responsible for major cracks in the body that weaken its structural strength such that it may split later as the result of another process (e.g., thermal or rotational splitting).

6.1.2. Rotational splitting. Splitting of a rotating nucleus happens when the centrifugal force exceeds self-gravity and material strength inside the body. A simplified expression for the condition of disruption of a rotating sphere is given by *Sekanina* (1982)

$$\sigma < 2\pi^2\rho R^2/P^2 = 1/2\rho V_{rot}^2 \qquad (4)$$

with σ, ρ, and R as explained above; P is the rotation period and V_{rot} is the rotation velocity at the equator of the sphere. A comprehensive theoretical model for centrifugal forces in rotating spheres and biaxial ellipsoids is presented by *Davidsson* (1999, 2001). The acceleration of the rotation speed of the nucleus can be caused by reaction forces due to outgassing (see *Jorda and Gutiérrez,* 2002).

The prediction of the model is that "dense" nuclei with nonnegligible material strength should break up from the body center, while strengthless nuclei should loosen fragments from the surface. The properties of the fragmentation products are case dependent, i.e., larger pieces in the center and smaller fragments at the surface for the case of "dense" nuclei or — more likely — only smaller pieces for strengthless bodies. Rotational splitting depends mainly on the rotation motion of the nucleus and can happen at any distance from the Sun. Due to changes of the rotational state of the nucleus by reaction forces from comet activity and modification of the properties of surface material by the mass loss of the nucleus when active, the occurrence of rotational splitting may in principle happen randomly along the orbit, but clearly with a preference for solar distances where the comet is active.

6.1.3. Splitting by thermal stress. Due to their variable distances to the Sun, comet nuclei are exposed to diffusion of heat waves penetrating into their interior during orbital revolutions. Thus thermal stress is induced in the body and, if the material strength is exceeded, nucleus splitting may occur. *Tauber and Kührt* (1987) have considered both homogeneous bodies (water ice) and nuclei with material inhomogeneities (water ice with inclusions of CO_2 and silicates). In both cases cracks due to thermal stress can form on the surface and, subsequently, minor pieces could split from the comet. *Shestakova and Tambostseva* (1997) and *Tambostseva and Shestakova* (1999) have presented model calculations for comet splitting by thermal stress. A number of cases are distinguishable depending on nucleus size and solar distance: Break-up may occur for larger bodies due to compression stress, splitting of subkilometer-sized bodies due to radial stress may happen closer than 40 AU from the Sun, and thermal splitting in general should be efficient — provided that tensile strength of the body material is low — when the object is closer than 5 AU to the Sun.

The fragmentation products should depend on the cause. The extend to which the body is affected by thermal stress splitting depends on the depth of the heat wave penetration and thus also on the size of the nucleus: Smaller bodies (subkilometer-sized) can split as a whole, while the break-up of surface fragments is more likely for larger bodies. Thermal stress splitting clearly is a scenario that may be able to produce fragments even at larger distances (several 10 AU) from the Sun.

6.1.4. Splitting by internal gas pressure. High gas pressure in the nucleus can be caused by sublimation of subsurface pockets of supervolatile ices (e.g., CO) when the comet approaches the Sun and the heat wave from the increasing solar illumination reaches the depths of these ice pockets. If the gas pressure cannot be released through surface activity, the tensile strength of the nucleus material can be exceeded and fragmentation of the comet occurs. *Kührt and Keller* (1994) present models for crust formation and the buildup of vapor pressure underneath. They conclude that a purely gravitationally bound crust is unstable and will be blown off the nucleus during perihelion passage. However, a crust of porous material held together by cohesive forces can withstand internal gas pressure up to the tensile strength estimated for cometary nuclei (see section 6.2).

Two different scenarios for comet break-up by internal gas pressure have been proposed: (1) an explosive blow-off of localized surface areas (possibly covered by an impermeable crust) as described by *Whipple* (1978), *Brin and Mendis* (1979), and *Brin* (1980); or (2) a complete disruption of the nucleus as suggested by *Samarasinha* (2001). The latter case imposes additional "requirements" on the internal structure of the nucleus and its surface: It should allow gas diffusion throughout the whole body via a system of connecting voids in the nucleus, and before splitting, the surface does not outgas enough to efficiently reduce the gas pressure inside the nucleus. Since both scenarios are based on comet activity, they are restricted to orbit arcs not far from the Sun, even though sublimation of supervolatile ices such as CO and N_2 can occur up to ~50 AU solar distance (*Delsemme,* 1982). *Prialnik and Bar-Nun* (1992) have proposed crystallization of amorphous ice to explain the outburst activity of Comet 1P/Halley at 14 AU outbound. This scenario could also potentially work to produce internal gas pressure that may cause the fragmentation of cometary nuclei.

6.1.5. Impact-induced comet splitting. During their orbital revolution around the Sun, comet nuclei can experience (hypervelocity) impacts by other solar system bodies such as asteroids. Since comets are small, such an impact, if it happens, will most likely destroy the whole nucleus, even if the impactor is a small (subkilometer-sized) body itself. *Toth* (2001) considered asteroid impacts for the disruption of Comet C/1999 S4 (LINEAR). Impact probabilities and the range of impact energies due to meter-sized impactors from the asteroid belt on short-period comets are estimated by *Beech and Gauer* (2002).

A "modification" of this scenario is comet splitting by impacts of larger boulders produced by the comet itself. Such pieces may exist, and it is feasible that they can travel "aside" the comet in its orbit around the Sun. Impact may occur at intersection points of their orbits, e.g., near aphelion for boulders produced near perihelion. As for most of the other scenarios described in this section, no detailed analysis and prediction of observable effects are available.

6.2. Observational Facts and Constraints

6.2.1. Comet D/1993 F2 (Shoemaker-Levy-9). Comet D/1993 F2 (Shoemaker-Levy 9) broke up in 1992 during a close approach with Jupiter (<20,000 km above the cloud level of the giant planet) (Fig. 6). Modelers (*Sekanina,* 1994; *Asphaug and Benz,* 1996; and references contained therein) of this event agree that the tidal forces of Jupiter have caused the cracking of the nucleus structure of this comet. However, according to *Sekanina* (1994) the separation of the fragments started only 3 h after the time of closest approach to Jupiter, i.e., after the tidal forces reached maximum amplitude. Apparently, the largest fragments traveled

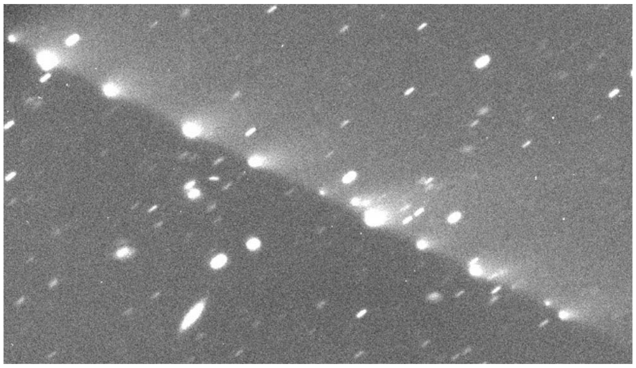

Fig. 6. Tidally disrupted chain of fragments in Comet D/1993 F2 (Shoemaker-Levy 9). This R-filter exposure taken on 5 May 1994 at the Calar Alto 3.5-m telescope shows fragments F to W of the broken comet. The fragments' chain extends diagonally across the image. Each fragment is surrounded by its own coma while their diffuse and wider dust tails overlap, causing a brighter background above the image diagonal. North is up and east to the left; field of view is 4.3 × 2.5 $arcmin^2$. Image courtesy of K. Birkle, Max-Planck-Institut für Astronomie, Heidelberg.

in the middle of the "chain" of the known 23 Shoemaker-Levy 9 components, as inferred from the size estimates and the impact explosions at Jupiter in July 1994. This picture would be in agreement with the tidal break-up model, which expects larger fragments to be created in the center of the splitting body, while lighter and smaller ones, i.e., the fragments at the leading and trailing end of the Shoemaker-Levy 9 chain, arose closer to the surface. Similar signatures are also seen in some peculiar crater chains at the surface of the jovian moons Callisto and Ganymede (*Schenk et al.,* 1996). The crater chains in the icy crust of these satellites are believed to be caused by impacts of narrow ensembles of fragments from tidally split comets after close encounters with Jupiter. In Comet Shoemaker-Levy 9, tertiary splitting occurred in some of the fragments, in all cases for unknown reasons (and certainly not due to tidal forces), but clearly suggesting that the split components may have had intrinsic substructure (*Sekanina,* 1995a).

Tidal splitting at Jupiter or the Sun is claimed to be involved in the break-up of Comets 16P/Brooks 2 (*Sekanina and Yeomans,* 1985) and the Sun-grazer Comets C/1882 R1 (Great September Comet), C/1963 R1 (Pereyra) and C/1965 S1 (Ikeya-Seki) (*Sekanina,* 1997a). The break-up mechanisms of all other split comets remain unknown, even though one may favor rotational break-up for the short-period comets because of the range of observed separation velocities and their independence from the heliocentric distance of the splitting event. Comet C/1999 S4 (LINEAR) has certainly experienced a nucleus splitting of a somewhat unique nature, since its nucleus disrupted in many pieces that disappeared after a lifetime of a few weeks (see also section 7.1). Nucleus splitting at very large heliocentric distances [beyond ~100 AU as suggested for Comet C/1970 K1 (White-Ortiz-Olelli) (*Sekanina and Chodas,* 2002b)] excludes all activity driven models as the fragmentation mechanism.

6.2.2. Tensile strength. Thus far, the tensile strength of a cometary nucleus is less constrained by actual observations and modeling of splitting events than by comets that do not split. The large size of Comet C/1995 O1 (Hale-Bopp) together with its fast rotation of 11.5 h puts a lower limit of 10^4–10^5 dyn/cm^2 on the tensile strength of its nucleus (assuming a bulk density of 0.5–1 g/cm^3). Assuming a similar tensile strength for the nuclei of comets for which reliable size *and* rotation period estimates exist, it is clear that these comets are — at present — "safe" against rotational break-up. On the other hand, if rotational break-up is involved in the splitting of short-period comets, a similar range for the tensile strength as for Comet Hale-Bopp would follow from the observed separation velocities of the fragments (see section 2.2). Unless one assumes a special nature for the bodies of split comets, it is obvious from the existence of fragments that the nuclei of split comets are not strengthless and they have an intrinsic substructure or at least nonuniform tensile strength.

7. RELATED PHENOMENA: DISAPPEARING COMETS AND DUST-TAIL STRIAE

7.1. Disappearing Comets

Comets can disappear in front of the "eyes" of the observers without obvious indication of a dramatic nucleus fragmentation event: C/1988 P1 (Machholz), Comets C/1996 Q1 (Tabur), C/2000 W1 (Utsunomiya-Jones) (see Fig. 7), C/2002 O4 (Hönig), and C/2002 O6 (SWAN) are some of the more recent cases. Leftovers of these disappearing comets are diffuse and fading comae and so-called "truncated" dust tails in which the synchrones are only populated to a certain start time at the nucleus and no "younger" grains are found in the dust tails. Two scenarios should be mentioned that could explain the observations: (1) the complete disintegration of the nucleus similar to Comet C/1999 S4 (LINEAR) (see below) and (2) an evolved, very crusty nucleus with one or only a few active regions that become "suddenly" dormant due to shadowing from solar illumination when the comet moves along its orbit. Both scenarios imply that disappearing comets are to be considered within the terminal phase of cometary evolution. It may be noteworthy that gas jets, perpendicular and symmetric to the Sun-comet line and without counterparts in the dust, were observed in Comet C/1996 Q1 (Tabur) before disappearance of the comet (*Schulz,* 2000). These jets very much resemble the arclets seen during splitting events in other comets (see section 4.2). Since C/1996 Q1 (Tabur) together with Comet C/1988 A1 (Liller) is most likely a product of a splitting event during an earlier apparition (*Jahn,* 1996), it is feasible that the former comet has experienced further splitting events that may have culminated in an — unobserved — complete dissolution of the nucleus during its last return to the Sun. The disappear-

Fig. 7. Comet C/2000 W1 (Utsunomiya-Jones), which disappeared in early 2001. This R-filter image, taken on 19 February 2001 at the 3.5-m Telescopio Nazionale Galileo (TNG) at the Roque de los Muchachos Observatory in La Palma, shows only a very weak and diffuse dust cloud without central condensation at the position of the comet (center and uppermost part of the image). North is up and east to the left; field of view is 3.0 × 2.6 arcmin^2. Image courtesy of J. L. Ortiz, Instituto Astrofisico de Andalucia, Granada.

ance together with the later perihelion passage of C/1996 Q1 (Tabur) to C/1988 A1 (Liller) also supports the interpretation of C/1996 Q1 being the fragment of C/1988 A1.

After some smaller splitting events before perihelion, Comet C/1999 S4 (LINEAR) broke apart completely in the second half of July 2000 close to perihelion (see Fig. 5). More than 20 fragments, but no "dominant" primary fragment, were observed (*Weaver et al.,* 2001). About three weeks after the disruptive splitting event the fragments could not be detected, and it is assumed they disappeared, more or less collectively, either by further fragmentation or by becoming undetectable due to exhaustion of sublimation activity. The rapid decay of water gas production after break-up (*Mäkinen et al.,* 2001) supports the scenario that this comet disappeared completely in a diffusing and fading cloud of previous dust release. This splitting comet can be considered the prototype (since best studied) of a disappearing comet.

7.2. Dust-Tail Striae and Comet Splitting

The origin of striae in the dust tail of some bright comets, e.g., C/1975 V1 (West) and C/1995 O1 (Hale-Bopp) (see Fig. 8), suggest secondary fragmentation of house-sized boulders (*Sekanina and Farrell,* 1980). The previous two-step model scenario introduced by *Sekanina and Farrell* (1980) involved relatively large pieces with very high solar radiation pressure parameter β (>0.1) as "parents" of striae that split off the cometary nucleus weeks before disruption. The new interpretation, proposed by Z. Sekanina and H. Boehnhardt at the Cometary Dust Workshop 2000 held in Canterbury, implies much earlier separation times of the parent fragments from the main nucleus, i.e., the boulders are produced by the cometary nucleus far away from the Sun and drift slowly away from the primary nucleus (hence no need for a high β) to the distance where, during approach of the comet to the Sun, the secondary fragmentation occurs in the region of the dust tail. This secondary disintegration is a process of short duration (on the order of one day or less) that may affect a boulder as a whole, i.e., it may become completely dissolved. An interesting candidate mechanism for the fragmentation of boulders is gas and dust emission activity when boulders approach the Sun. The proposed striae fragmentation hy-

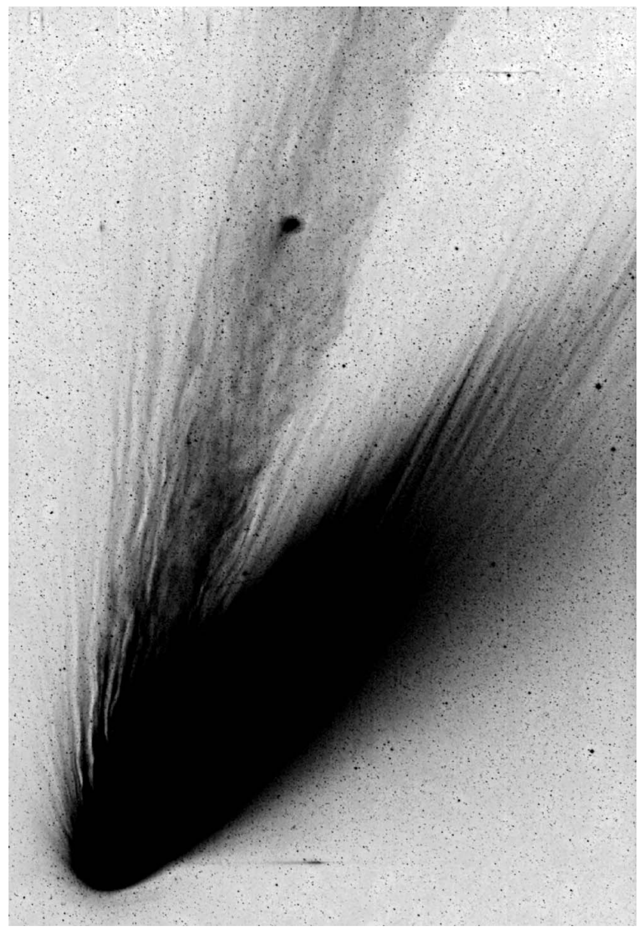

Fig. 8. Striated dust tail of Comet C/1995 O1 (Hale-Bopp). In March and April 1996 the diffuse dust tail (right part of the image) of Comet C/1995 O1 (Hale-Bopp) contained many striae. In the image the striae are best visible as narrow straight bands to the outer edge of the dust tail. The striae are not coinciding with dust synchrones pointing toward the nucleus in the coma (lower left, overexposed), which indicates that the striae dust is not released directly from the nucleus. The prominent structured ion tail points away from the direction of the Sun. North is up and east to the left; field of view is 3.0 × 4.5 deg^2. Image courtesy of K. Birkle, Max-Planck-Institut für Astronomie, Heidelberg.

TABLE A1. List of split comets, likely split pairs, and families of split comets.

Tidally split comets	
C/1882 R1 (Great September Comet)*	16P/Brooks 2 (1889 + 1995)*
C/1963 R1 (Pereyra)*	C/1965 S1 (Ikeya-Seki)*
D/1993 F2 (Shoemaker-Levy 9)†	
Comets split for unknown reasons	
3D/Biela (1840)	C/1860 D1 (Liais)
C/1888 D1 (Sawerthal)	C/1889 O1 (Davidson)
D/1896 R2 (Giacobini)	C/1899 E1 (Swift)
C/1906 E1 (Kopff)	C/1914 S1 (Campbell)
C/1915 C1 (Mellish)	69P/Taylor (1915)
C/1942 X1 (Whipple-Fedtke)	C/1947 X1 (Southern Comet)
C/1955 O1 (Honda)	C/1956 F1 (Wirtanen)
C/1968 U1 (Wild)	C/1969 O1 (Kohoutek)
C/1969 T1 (Tago-Sato-Kosaka)	C/1975 V1 (West)
79P/du-Toit-Hartley (1982)	108P/Ciffreo (1985)
C/1986 P1 (Wilson)	101P/Chernykh (1991)
C/1994 G1 (Takamizawa-Levy)	141P/Machholz 2 (1987 + 1989)
51P/Harrington (1994 + 2001)	73P/Schwassmann-Wachmann 3 (1995/1996 + 2001)
C/1996 B2 (Hyakutake)	C/1996 J1 (Evans-Drinkwater)
C/1999 S4 (LINEAR)	C/2001 A2 (LINEAR)
57P/du-Toit-Neujmin-Delporte (2002)	
Likely split pairs	
C/1988 F1 (Levy) and C/1988 J1 (Shoemaker-Holt)	
C/1988 A1 (Liller) and C/1996 Q1 (Tabur)	
C/2002 C1 (Ikeya-Zhang) and C/1661 C1	
C/2002 A1 (LINEAR) and C/2002 A2 (LINEAR)	
C/2002 Q2 (LINEAR) and C/2002 Q3 (LINEAR)	
Likely split families	
42P/Neujmin 3 and 53P/Van Biesbroeck and 14P/Wolf‡ and 121P/Shoemaker-Holt 2‡	
C/1965 S1 (Ikeya-Seki) and C/1882 R1 (Great September Comet) and C/1970 K1 (White-Ortiz-Olelli)	
C/1880 C1 (Great Southern Comet) and C/1843 D1 (Great March Comet)	
Kreutz group and SOHO comets	

*Likely scenario.
†The only secure case of a tidally split comet.
‡Uncertain member.

pothesis somehow implies that striae should predominantly appear in comets before reaching perihelion.

8. APPENDIX: LIST OF SPLIT COMETS

Here we compile a list of split comets, likely pairs, and families of split comets as reported in the literature (Table A1). For periodic comets the year of the splitting event is given in parenthesis. Comet C/1995 O1 (Hale-Bopp) is not listed as split comet below even though indications exist that this comet may have displayed double or multiple nuclei (*Sekanina,* 1997b; *Marchis et al.,* 1999) and several companion comae (*Boehnhardt et al.,* 2003). It is also noted that *McBride et al.* (1997) favor the existence of a major boulder in the coma of Comet 26P/Grigg-Skjellerup from the *Giotto* flyby measurements at the comet. The detection of fragments (several hundred meters in size) around this comet is not confirmed by other observations (*Boehnhardt et al.,* 1999). Since the fragmentation products reported for both comets are to be considered uncertain for the time being, we do not include 26P/Grigg-Skjellerup and C/1995 O1 (Hale-Bopp) in the list below. Based on the clustering of dust impacts during the *Giotto* encounter, the existence of fragmenting boulder-sized pieces in the coma of Comet 1P/Halley (see *Boehnhardt,* 2002, and references therein) is also the subject of speculation.

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