Kreutz Sungrazers: The ultimate case of cometary fragmentation and disintegration?

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The history and dynamical evolution of the Kreutz group of sungrazing comets can be investigated by modeling the observed temporal and spatial distributions of the group's members, more than 250 of which were known by the end of 2000. This paper presents the results of an early phase of this modeling effort, which is based on (i) a long-standing consensus that all comets belonging to the Kreutz group are fragments of one original, massive comet; and (ii) a breakthrough in the understanding of the sungrazers' pairs and tight clusters detected in large numbers with the coronagraphs onboard the *Solar and Heliospheric Observatory (SOHO)*. All these objects are products of progressive fragmentation that typically begins with a tidally-triggered (or tidally-assisted) breakup near perihelion, in the immediate proximity of the Sun. However, instead of terminating at that point — as postulated in all previous hypotheses — the process is shown to continue in a cascading fashion throughout the orbit about the Sun. Isolated, nontidal fragmentation episodes occur essentially spontaneously, with very low separation velocities (~meters per second) and at large heliocentric distances (Sekanina 2000a). Each event yields a new generation of ever smaller fragments.

Besides its own merits, this scenario is strongly corroborated by parallel evidence on the now defunct comet Shoemaker-Levy 9 (D/1993 F2). In fact, this object can serve as an analogue for the Kreutz comet group because it, too, continued to fragment long after its extremely close approach to Jupiter in July 1992 (Sekanina, Chodas, and Yeomans 1998).

One of the most critical points in modeling the Kreutz group's history and evolution is to explain the existence of two subgroups, which are particularly prominent among the brightest members. It is believed that the subgroups date back to an early breakup of the progenitor comet into two major fragments, perhaps the two "supercomets," C/1882 R1 (a member of one of the two subgroups) and C/1843 D1 (a member of the other subgroup). This event may have taken place only two revolutions about the Sun ago and it did not occur near perihelion.

Any breakup gives rise to a broad mass (and size) distribution of fragments, with extensive fissures and cracks in their interior facilitating more fragmentation. This process results in a complex hierarchy of its products, depending critically on the relationship among the *major* members of the group. *Minor* fragments acquire enough extra momentum during each of the episodes that their motions carry no "memory" of these events other than the most recent one. Thus, a population of these minor fragments — such as the *SOHO* sungrazers never surviving their perihelion passage intact — can be modeled by Monte Carlo methods to match the orbital distributions and the correlations among the orbital elements. The results of this investigation contribute significantly to our understanding of the formation, structure, mechanical strength, activity, and disintegration of cometary nuclei, and of the role of comets in the solar system evolution.

1 Kreutz comet group: Highlights of past research

1.1 Basic Orbital Information

The Kreutz group comets move about the Sun in a truly unique set of orbits. At perihelion they graze the Sun (hence, sungrazers), passing often only a small fraction of the solar radius above the photosphere. Collisions with the Sun are in principle possible, but are *de facto* quite rare because most of these objects disintegrate before they reach perihelion (Sec. 3.1).

The aphelion distances of the Kreutz group comets differ from case to case, but they are known to amount generally to between 130 and 200 AU, corresponding to orbital periods of some 500–1000 years. The rate of insolation at the subsolar point on the nucleus of a sungrazing comet varies between perihelion and aphelion by more than a factor of a hundred million, for some of these objects by more than a billion.

Another consequence of the sungrazers' peculiar orbits is the huge contrast between the orbital velocity at perihelion, which is near 600 km s^{-1}, and at aphelion, where it drops down to between 15 and 40 *meters* per second. The first value is just below the velocity of escape from the Sun, the second value is only moderately greater than typical rotational velocities of cometary nuclei, the facts that turn out to be highly relevant for modeling the orbital distribution of fragmentation products.

The orbital planes of the bright Kreutz group comets are inclined to the plane of the ecliptic by 35° to 41° and the motions are retrograde. The lines of apsides make an angle of some 60° to 90° with the nodal lines, the perihelion points being concentrated, within a few tenths of a degree, in a direction with the following ecliptical coordinates (equinox 2000.0): longitude $L = 282^\circ.7$, latitude $B = +35^\circ.2$. As a result, the comets approach the Sun from the south and, if they survive, recede also to the south; close encounters with any planet are ruled out and the orbits are affected only by indirect perturbations of the planets.

1.2 Ground-Based Discoveries and Early Studies

The comet nowadays recognized as the first undisputed member of this sungrazing group was discovered in 1843 and is now designated as C/1843 D1. Additional members, detected between 1880 and 1887 (C/1880 C1, Tewfik, C/1882 R1, and C/1887 B1), prompted Kreutz (1888, 1891, 1901) to undertake a series of major orbital investigations of the group. Following a 75-year long drought, during which only one member was discovered (C/1945 X1 = du Toit), three more sungrazers arrived in succession between 1963 and 1970. These are the comets C/1963 R1 = Pereyra, C/1965 S1 = Ikeya-Seki, and C/1970 K1 = White-Ortiz-Bolelli.

Although the possible existence of comet groups was discussed in the early literature, Kreutz (1891) appears to be the first to postulate that the members of the sungrazing group were products of a progenitor comet that had broken up repeatedly *near perihelion*, just as the discrete postperihelion nuclei of comet C/1882 R1 were obviously products of the comet's single mass observed prior to perihelion. Evidence shows that the individual secondary nuclei had a tendency to lining up along the orbit and that their revolution periods differed typically by ~100 years or more. A simple calculation indicates that components of comet C/1882 R1 separating from each other at perihelion at a rate of 1 m/s (typical for comet rotation velocities) along the direction of motion, would have orbital periods differing by ~115 years. Thus, a very minor impulse acquired by a fragment during the breakup at perihelion results in a major change in the time of its next return to perihelion. However, except for this effect, the orbits along which the individual fragments leave the Sun are virtually identical.

In the 1960s, the understanding of the orbital evolution of the Kreutz group was greatly advanced by Marsden (1967). He showed that the indirect perturbations of the planets, especially Jupiter, can significantly change the orbital elements of the sungrazers from return to next return: the nodal line by up to 4°.2, the argument of perihelion by up to 3°.2, the inclination by up to 0°.8, and the perihelion distance by up to 0.2 $R_\odot$. On the other hand, the orientation of the line of apsides remains almost unaffected.

The two subgroups, whose existence was proposed by others in 1966, were extensively discussed by Marsden in his 1967 paper. The differences in the orbital elements between Subgroup I (encompassing the comets of 1843, 1880, 1887, and 1963) and Subgroup II (the comets of 1882, 1945, and 1965) are about one order of magnitude greater than is the scatter among the individual comets within either subgroup. For example, the subgroups differ by ~20° in the longitude of the nodal line, whereas within either subgroup the scatter is not more than about ±2°. (The comet of 1970, discovered after the publication of Marsden's first paper, was classified as Subgroup IIa in his second paper, published in 1989.)

Comparison of the indirect planetary perturbations with the orbital distribution of the Kreutz sungrazers indicates that the perturbations are approximately of the same magnitude as is the scatter among the orbital elements of the individual comets within either subgroup but that they are much smaller than the differences between the subgroups (including those between II and IIa). However, Marsden did show that the orbits of the 1882 and 1965 comets (but not the 1843 and 1963 comets) can be matched extremely well after they have been corrected for the indirect perturbations.

The understanding of the spatial and temporal distributions of the orbits has been the clue in all efforts aimed at developing a working hypothesis for the Kreutz comet group. In the 1960s, both Marsden and the author (Sekanina 1967a,b) searched independently for a solution to match the orbital distribution. In an attempt to explain the subgroups, Marsden considered the progenitor comet's splitting at perihelion some 10–20 revolutions (or ∼5000–20,000 years) ago, with only two fragments consistently surviving. He speculated about other scenarios, including very high separation velocities (up to 100 km/s), but expressed no preference for any of these. The author found no more attractive hypothesis than a collisionally-triggered breakup, a mechanism rejected by Marsden. Interestingly, both Marsden and the author remarked briefly in their papers on the possibility of explaining the observed orbital scatter by a separation velocity as low as a few meters per second, if the breakup should occur near aphelion. However, Marsden complained that the required perturbation would represent some 20 percent of the orbital velocity, while the author argued that no noncollisional mechanism was known at the time to accomplish a breakup that far from the Sun.

1.3 Entering the Era of Space-Based Discoveries and Intensified Research

A new era in the investigation of the Kreutz group commenced in 1979 with the first discovery from space. By the end of 1989, the number of known sungrazers was tripled, with 16 new ones detected with either the *SOLWIND* coronagraph onboard the *P78-1* satellite or the coronagraph flown on the *Solar Maximum Mission (SMM)*. Fifteen of these 16 comets, together with the sungrazers observed previously from the ground, were investigated by Marsden (1989) in his second paper, based again on the assumption of progressive fragmentation at perihelion. He remarked that the *SOLWIND* and *SMM* discoveries suggest a possibly continuous influx of the sungrazers, although none of the space-coronagraph comets appears to have survived the perihelion passage. Marsden also noticed a tendency for apparent clumping among the *SMM* objects, some arriving less than two weeks apart. As shown in Sec. 3.2, the issue of clumping has played a major role in the recent development of a new model for the Kreutz group.

In his 1989 paper, Marsden accounted for the planetary perturbations by calculating the differences between the so-called *original* and *future* orbits of a sungrazer, referred to the barycenter of the solar system when the comet is far from the Sun (∼100 AU). He showed that aphelion-to-aphelion changes caused by the indirect planetary perturbations are asymmetric, with non-zero averages over the time intervals of several decades. In the nodal line, for example, these changes can reach up to 7° in the orbit of comet Ikeya-Seki and up to 9° in the orbit of comet Pereyra. By direct orbital integration, Marsden showed that the comets of 1843 and 1880 can be as closely related to each other as the comets of 1882 and 1965, provided that the orbital period of the comet of 1843 is about 370 years, or $\sim \frac{1}{2}$ the orbital period of the comet of 1882. He also indicated a possible relationship between comet Pereyra and the parent of the comets of 1843 and 1880. By further extending this line of reasoning and postulating a repeatedly favorable timing for returns to the Sun, Marsden was able to describe a hypothetical process, whereby the progenitors of the two subgroups could have separated from each other in the fourth century BC, at a time that approximately coincides with that of the apparent observation, by the Greeks, of an exceptionally bright comet (∼371 BC).

Marsden's 1989 paper is likely to represent the culmination of the efforts aimed at explaining the evolution of the Kreutz comet group as a product of only two effects: recurring fragmentation at perihelion and indirect planetary perturbations. A remarkable event in 1993–94 and unexpected results of a space project, starting in the late 1990s and ostensibly unrelated to comets, provided evidence that turned out to be not only relevant to the Kreutz sungrazers, but also instrumental in opening up a new line of attack in our quest for solving the mystery of their existence.

2 Comet Shoemaker-Levy 9 (D/1993 F2): An analogue for the Kreutz comet group

When it became clear in 1993 that comet Shoemaker-Levy 9 had passed only $\frac{1}{3}$ the jovian radius above the planet on July 7, 1992; broke up into more than 20 major fragments; and would collide with the planet in late July 1994, an extraordinary international effort was set in motion to monitor this remarkable comet. Thanks to an extensive astrometric database that resulted from this effort, it was possible to un-

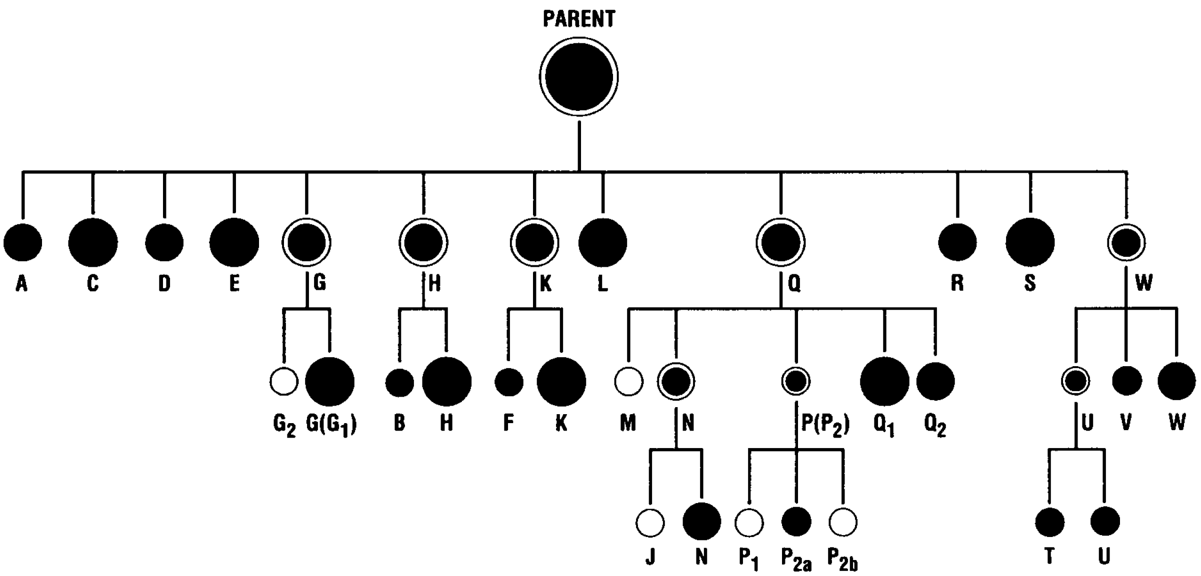

Fig. 1: Derived fragmentation hierarchy of comet Shoemaker-Levy 9. The size of the symbols is crudely proportional to the prominence of the fragments, labeled by the letters from A through W. Solid symbols refer to the fragments that remained visible until collision with Jupiter in July 1994, open symbols to the fragments that disappeared earlier, and circled symbols to the parent comet and to the fragments that had broken up before the comet was discovered. (After Sekanina, Chodas, and Yeomans 1998.)

dertake a major investigation of the relative motions of the various fragment nuclei, to determine the sequence of nuclear splitting, and to establish the fragmentation hierarchy of this comet (Sekanina, Chodas, and Yeomans 1998; also Fig. 1.3). It was concluded that the jovian tidal forces inflicted extensive cracks throughout the interior of the original nucleus but did not split it apart. The initial disruption, a rapid sequence of tidally-triggered breakup episodes, was apparently achieved by stresses exerted on the fractured parent nucleus by its fast rotation shortly after perijove, resulting in the formation of 12 of the 25 fragments. The remaining 13 subnuclei were products of isolated, spontaneous events of *secondary fragmentation*, which occurred at various times long after the encounter and represented conspicuous manifestations of the continuing stochastic process of progressive disintegration. The separation velocities involved in these episodes ranged from 0.3 to 1.7 m/s and their vectorial distribution was diagnostic of the approximately conserved angular momentum of the parent comet.

Thus, the behavior of comet Shoemaker-Levy 9 provided us with the first instance of compelling evidence for a tidally-triggered fragmentation event that did not terminate with a breakup or a rapid sequence of breakups in close proximity of the perturbing body. Rather, the process continued, apparently at a slowly decreasing rate, as a cascading series of isolated, nontidal fragmentation episodes long after the comet's close encounter with Jupiter.

3 *SOHO* Sungrazers, their pairs and clusters, and fragmentation at large heliocentric distance

3.1 Comparison of *SOHO* Sungrazers with other Kreutz comets

Following the launch of the *Solar and Heliospheric Observatory (SOHO)* on December 2, 1995, the number of newly discovered sungrazers began to skyrocket, reaching nearly 250 by the end of 2000. The spacecraft is positioned at the L_1 libration point, about 0.01 AU sunward of the Earth, with uninterrupted view of the Sun and its environment. With very few exceptions, the *SOHO* sungrazers have only been detected with the C2 and C3 coronagraphs of the *Large Angle and Spectrometric Coronagraph (LASCO)* experiment, operated by the *LASCO* consortium. The C2 camera has a field of view of 6 $R_\odot$ in radius, the occulter is about 1.5 times the size of the Sun, and each pixel is 11.4 arcsec on a side; the respective parameters for the C3 coronagraph are 32 $R_\odot$, 3.7 $R_\odot$, and 56 arcsec. The discovery, confirmation, astrometric measurement and reduction, and orbit determination of the *SOHO* comets are a collaborative effort, in which D. A. Biesecker is in charge of discovery confirmation and measurement, while Marsden is responsible for both the positional reduction and orbit determination. Although the astrometric accuracy (and therefore the quality of the orbits) is substantially better than that for the *SOLWIND* and *SMM* sungrazers, it does not reach the level of perfection achieved for the Kreutz members that were observed extensively from the ground. As a result, only parabolic elements could be computed for all *SOHO* sungrazers.

Most of the *SOHO* sungrazers are intrinsically fainter than the *SOLWIND* and *SMM* comets, fading away on their approach to the Sun and never surviving the perihelion passage intact. Thus, their existence as fragmentation products cannot predate the previous perihelion passage (e.g., Sekanina 2000b). In this respect, the *SOHO* (as well as the *SOLWIND* and *SMM*) sungrazers differ from the six intrinsically bright comets of the Kreutz group that were observed from the ground after perihelion.

3.2 Pairs and clusters of the *SOHO* Sungrazers

Biesecker (2000), who maintains an updated list of all *SOHO* comets (more than 90 percent of which belong to the Kreutz group), called attention to a large number of *pairs* among the sungrazers: two objects arriving at the Sun almost simultaneously. In Table 1, the *SOHO* pairs are sorted out by an increasing difference in the perihelion time, ΔT. The list shows that by the end of 2000 there were 37 pairs with $\Delta T < 0.75$ day, a limit that is a factor of >15 tighter than the degree of clumping among the *SMM* sungrazers noticed by Marsden (1989).

As recently noted by the author (Sekanina 2000a), comparison of the ΔT intervals with an expected random distribution suggests that the pairs are not fortuitous groupings, and there must be a physical reason for their existence. The pairs cannot be explained by fragmentation about the time of the previous perihelion passage, which is known (Sec. 1.2) to entail scatter that exceeds the ΔT values for the pairs by many orders of magnitude. Most pairs show sizable differences in the fragments' other four elements, likewise inconsistent with near-perihelion splitting. And since the comets that make up a pair arrive at the Sun at essentially the same time, the indirect planetary perturbations should exert no differential effects on their orbits. Yet, as illustrated by a composite image of the pair C/1998 K9 and C/1998 K15 in Fig. 2, the sungrazers that make up a pair usually arrive at the Sun in distinctly different trajectories.

Another property of the pairs that further underlines the complex temporal distribution of the *SOHO* sungrazers is the fact that 11 objects listed in Table 1 — C/1997 K4, C/1997 T7, C/1997 V6, C/1997 X3, C/1998 G6, C/1998 K15, C/1998 L5, C/1998 L6, C/1998 X6, C/1999 K9, and C/1999 L6 — belong to two different pairs. Thus, the pairs are unquestion-

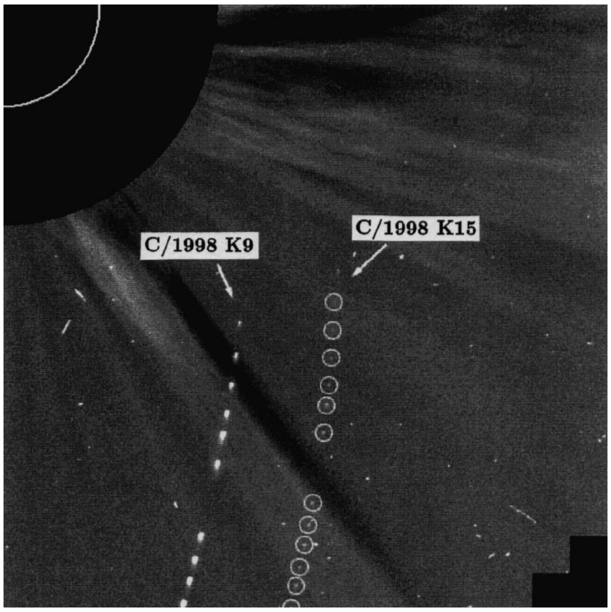

Fig. 2: A composite image of several exposures of the occulted Sun, the solar corona, and a pair of sungrazing comets, {C/1998 K9, C/1998 K15}, taken with the C2 coronagraph onboard the *SOHO* spacecraft shortly before the comets were to pass through perihelion on May 29, 1998. They were shown to be fragments of a common parent that split before its previous aphelion, at a heliocentric distance of probably more than 100 AU (Sekanina 2000a). Neither piece survived long enough to reach perihelion. The field of view is ~1°.5 on a side; the north is up, the east is to the left. (From URL posted by M. Oates, http://www.ph.u-net.com/comets/sungrazers.htm.)

TABLE 1
ORBITAL DIFFERENCES[a] IN PAIRS OF *SOHO* SUNGRAZERS ($\Delta T < 0.75$ DAY)

Pair No.	*SOHO* sungrazers	ΔT (day)	$\Delta\omega$	$\Delta\Omega$ (Equinox 2000.0)	Δi	Δq ($R_\odot$)	Date(s) (UT) of arrival
1	C/1997 U5 C/1997 U6	0.01	+0°.01	−0°.75	+0°.72	0.00	1997 Oct 27
2	C/1998 K9 C/1998 K15	0.04	+2.22	+2.90	−0.70	+0.47	1998 May 29
3	C/1997 X3 C/1997 X4	0.07	+5.49	+5.86	−1.64	−0.02	1997 Dec 3
4	C/1997 J3 C/1997 J4	0.09	+28.64	+48.73	−7.90	+0.19	1997 May 10
5	C/2000 T1 C/2000 T3	0.16	+8.73	+3.15	+1.18	+0.02	2000 Oct 11
6	C/1998 K10 C/1998 K11	0.18	+3.66	+4.47	+0.53	−0.17	1998 Jun 1–2
7	C/1999 K9 C/1999 K13	0.20	−32.54	−45.37	−4.26	+0.21	1999 May 24
8	C/1998 X6 C/1998 X7	0.21	+8.60	+7.94	−1.05	−0.04	1998 Dec 10
9	C/1999 O1 C/1999 O3	0.24	+10.80	+10.72	−0.98	+0.02	1999 Aug 1
10	C/2000 L2 C/2000 L3	0.27	−22.15	−24.36	+1.99	−0.04	2000 Jun 10
11	C/1999 L6 C/1999 L4	0.32	+13.01	+16.22	−7.70	+0.60	1999 Jun 1–2
12	C/1997 V5 C/1997 V6	0.33	+12.29	+13.88	+6.03	−0.67	1997 Nov 8–9
13	C/1997 V6 C/1997 V2	0.33	+6.13	+9.56	−0.48	+0.28	1997 Nov 9
14	C/1997 K4 C/1997 K1	0.34	−8.47	−11.00	+0.83	+0.04	1997 Jun 1
15	C/1999 K10 C/1999 L6	0.35	−26.36	−33.02	+0.76	−0.11	1999 Jun 1
16	C/1999 J8 C/1999 J1	0.37	−0.60	+0.10	+0.71	+0.13	1999 May 8
17	C/1997 G4 C/1997 G5	0.38	+0.94	−0.02	−0.26	−0.02	1997 Apr 5–6
18	C/1997 T7 C/1997 T8	0.38	−2.91	−0.85	−2.37	+0.02	1997 Oct 8–9
19	C/2000 M1 C/2000 M2	0.40	+6.11	+7.43	−0.95	−0.06	2000 Jun 18

TABLE 1 (CONTINUED)

Pair No.	*SOHO* sungrazers	ΔT (day)	$\Delta\omega$	$\Delta\Omega$ (Equinox 2000.0)	Δi	Δq ($R_\odot$)	Date(s) (UT) of arrival
20	C/1998 L5 C/1998 L6	0.41	$+9^\circ.75$	$+12^\circ.20$	$-2^\circ.24$	+0.04	1998 Jun 5–6
21	C/1999 S5 C/1999 S6	0.41	+8.24	+5.64	−0.15	0.00	1999 Sept 21
22	C/1998 G5 C/1998 G6	0.43	+6.95	+7.82	+0.42	+0.06	1998 Apr 6–7
23	C/1997 X1 C/1997 X3	0.44	+0.54	+1.22	+0.66	+0.09	1997 Dec 2–3
24	C/1998 L4 C/1998 L5	0.45	−7.83	−9.26	+1.18	+0.06	1998 Jun 5
25	C/1999 K12 C/1999 K9	0.50	+45.03	+56.91	−3.26	0.00	1999 May 23–24
26	C/1997 Y1 C/1997 Y2	0.52	+6.02	+5.97	+1.49	0.00	1997 Dec 21
27	C/1998 X5 C/1998 X6	0.52	−6.10	−4.83	+0.04	+0.06	1998 Dec 9–10
28	C/1998 L2 C/1998 L3	0.53	−12.39	−16.44	+4.02	−0.04	1998 Jun 4
29	C/1999 R3 C/1999 R4	0.54	+3.27	+1.64	−0.46	−0.04	1999 Sept 6
30	C/2000 U3 C/2000 U4	0.56	+15.64	+4.22	+7.58	−1.16	2000 Oct 24–25
31	C/1999 Q1 C/1999 Q2	0.63	−16.90	−15.26	+2.39	−0.06	1999 Aug 24–25
32	C/1997 T5 C/1997 T7	0.67	+5.60	+4.39	+0.97	0.00	1997 Oct 7–8
33	C/1998 L6 C/1998 L7	0.68	−38.15	−48.20	−11.15	+0.58	1998 Jun 6
34	C/1997 K6 C/1997 K4	0.70	+2.68	+3.72	−0.44	−0.02	1997 May 31–Jun 1
35	C/1998 K15 C/1998 K16	0.70	+3.08	+6.11	−2.99	−0.43	1998 May 29
36	C/1996 X1 C/1996 X2	0.71	−6.37	−9.41	−0.11	−0.21	1996 Dec 12
37	C/1998 G6 C/1998 G7	0.74	−9.07	−11.08	−1.30	+0.56	1998 Apr 7

[a] The differences in the orbital elements listed in columns 3–7 are from B. G. Marsden's computations and refer, respectively: to the time of perihelion passage, T; to the argument of perihelion, ω; to the longitude of ascending node, Ω; to the inclination, i; and to the perihelion distance, q.

ably parts of greater clusters and widespread clumping is indeed an inherent property of the *SOHO* sungrazer population.

3.3 Orbital Solutions for Three Pairs

The conclusion that the pairs (and clusters) are not random groupings and, at the same time, are not products of primary, near-perihelion breakups leaves only one possibility: *they are products of post-tidal, secondary fragmentation events at large heliocentric distances*. Even though compelling evidence for this kind of fragmentation was provided by comet Shoemaker-Levy 9 (Sec. 2) at 5 AU from the Sun, the ultimate proof for the Kreutz comet group should come from analysis of the sungrazers themselves.

To show that two comets moving alongside each other are fragments of a common parent and to calculate the time of separation and other relevant information, one needs to start from the offsets (in, say, right ascension and declination) of the two objects imaged in the same set of frames and to apply the standard model for split comets (Sekanina 1982). Unfortunately, such offsets could be derived for only four pairs and the resulting solution for one of these was indeterminate (orbital arcs too short). For the three pairs, C/1998 K10, C/1998 K11, C/1998 K9, C/1998 K15, and C/1999 O1, C/1999 O3, successful solutions were obtained (Sekanina 2000a), showing that the point of separation was always located more than 40 AU from the Sun, on the way to aphelion in two cases, after aphelion in one. The exact solutions depend to some extent on the value adopted for the orbital period of the pair, which is unknown (Sec. 3.1), but similar results were obtained regardless of the assumption employed. The separation velocities came out to be in a range of 2.6 to 6.4 m/s, comparable with those for other split comets (Sekanina 1982) and rather typical for nuclear rotational velocities.

The direct orbit determinations for these fragment pairs prove that fragmentation of sungrazing comets does indeed occur at large heliocentric distances, a breakthrough finding that serves as the basis for developing a conceptually new model for the Kreutz group. The orbital perturbations due to fragmentation events can be calculated as a function of the separation velocity vector and the breakup's location in the orbit. Some sampling data are examined in Sec. 4.2.

4 Model scenario for the formation and evolution of the Kreutz group by cascading fragmentation

4.1 The Conceptual Model

The assumption that the proposed model shares with all previous hypotheses is that of the source of the Kreutz group: a single, very massive original comet that continued to break up over and over again, thus producing an ever greater number of generations of ever smaller fragments. Although the objective of this research is not to determine the manner in which the progenitor got into its sungrazing orbit, the only process that is reasonably satisfactory is a capture of this ancestor comet during a close encounter with Jupiter into an orbit that was neither sungrazing nor having its line of apsides oriented like it is today. The inclination could have been near 90°. The requirement of a small perihelion distance (a few tens of solar radii) for the postcapture orbit means that the argument of perihelion should have been close to 0° or 180°, the former being preferred because of the current value (smaller than 90°). The subsequent rotation of the line of apsides and the gradual decrease in the perihelion distance could have been achieved by the same kind of indirect planetary perturbations that were employed by Marsden in his studies of the sungrazing orbits (Secs. 1.2–1.3). If this scenario did not work, the early stage of the orbital evolution remains unexplained.

One of the most critical points in modeling the formation and evolution of the Kreutz group is to explain the existence of the two subgroups. Although the boundary between the subgroups appears to be somewhat smeared among the *SOHO* sungrazers, it is very sharp among the bright members, discovered from the ground. This fact suggests that, in addition to a contribution from observational uncertainties, the orbital smear among the faint fragments is due in part to a cumulative effect of minor momentum changes that these fragments acquired during the large number of fragmentation events they and their parent fragments were involved in. The major fragments are generally much less susceptible to this kind of orbital-velocity perturbations.

Intuitively, therefore, the birth of the two subgroups should have been the result of an early breakup of the progenitor comet. To be more specific, one may suggest as a working hypothesis that the two primary products of this early fragmentation episode were the intrinsically brightest known members of the Kreutz group: C/1882 R1 (Subgroup II) and C/1843 D1 (Subgroup I). The orbital differences between these two "supercomets" leave no doubt whatsoever that their separation could not have taken place near perihelion. Even though the fragmentation process would in this scenario be initiated by a seemingly nontidal event, the Sun's tidal forces were probably still involved as a trigger, only less manifestly so. If the progenitor's perihelion distance was indeed slowly decreasing with time, internal fracturing of the nucleus due to the tidal stresses could have been spreading very gradually, always perihelion after perihelion. However, other stresses, such as those due to rotation, were acting throughout the orbit as the nucleus was getting structurally weaker, so the timing of its eventual yielding was largely a matter of coincidence, statistically favoring large heliocentric distances. And, of course, one can never completely rule out the possibility that the birth of the comets of 1843 and 1882 was not the result of the earliest event after all and that it was preceded by one or more splittings near perihelion, whose fragments have remained undetected to this time.

The stress that a tidal force of a massive body exerts on an approaching object varies as the square of the interloper's size and inversely as the cube of the relative distance between the two bodies. Thus, all else being equal, it is actually easier for the Sun to break up tidally a large comet than a small one. Significantly, of the six sungrazers observed after perihelion, only one emerged with more than two nuclei: C/1882 R1, the intrinsically brightest and obviously the largest one, even though its perihelion distance was substantially greater than that of at least two other sungrazing comets (C/1843 D1 and C/1880 C1) that were never under suspicion of having exhibited multiple nuclei.

It is thus apparent that while we cannot be absolutely *certain* that the postulated breakup of the progenitor into the comets of 1843 and 1882 was *the* primary event that was at the root of the wholesale fragmentation process, this is a *plausible* scenario worthy of close examination. It is also apparent that if one succeeds in modeling the two subgroups, one should be able to explain the observed spatial and temporal distributions of the entire Kreutz group. With a full account of the planetary perturbations, one can describe in detail the fragmentation scheme that involves the major members, while the evolution of the population of the *SOHO* sungrazers is most appropriately analyzed by Monte Carlo methods.

4.2 Effects of Breakup Location in the Orbit and Velocity of Separation on Fragments' Orbital Elements

The dependence of the orbital elements of a detached fragment on the circumstances that prevailed at the time of separation from its parent object should first be understood quantitatively. Since it is customary to refer the orbit of the less massive fragment to that of the more massive component, the extra momentum acquired by the minor fragment during a breakup is described as a perturbation of the presplit motion (Sekanina 1982) either in the heliocentric or the barycentric coordinate system.

To start with, it is assumed that the parent comet undergoes only one breakup between its two consecutive passages through perihelion and that this event yields only two discrete fragments. Although the major differences between the effects of primary and secondary fragmentation on the orbital elements were mentioned in Secs. 3.2–3.3, the dependence of the orbital momentum changes on the location of a breakup episode in the orbit is examined quantitatively in this section. These changes are products of net forces that either fragment is subjected to during and/or after separation. In general, the extra momentum acquired at splitting is expressed in terms of a velocity of separation, whereas the perturbations from the net forces after splitting can be accounted for by a differential nongravitational acceleration. The separation velocity vector is described by its components in the three cardinal directions defined by the parent's heliocentric (or barycentric) orbit: radial (away from the Sun or the barycenter), transverse, and normal of the right-handed RTN coordinate system.

To illustrate the magnitude of these effects, the results for a particular case, described by the reference barycentric orbit of a parent sungrazer in Table 2, are presented in Tables 3–5. No planetary perturbations and no nongravitational acceleration have been introduced. The time of separation is varied throughout the orbit, from the previous perihelion through aphelion to the next perihelion. The separation velocity is kept constant at 5 m/s (cf. Sec. 3.3). To identify asymmetries, effects of both the positive and negative velocity components are explored in each cardinal direction.

Table 3 lists the perturbations of the three angular elements: the argument of perihelion ω, the longitude of the ascending node Ω, and the orbital inclination i. There is no contribution from the radial component of the separation velocity to ω or from the radial and transverse components to Ω and i. Thus, the velocity's normal component accounts for the entire effects in Ω and i and for much of the effect in ω. The perturbations of ω and Ω have always the same sign, whereas the perturbation of i has the same sign as

TABLE 2
MODEL BARYCENTRIC ORBIT (EQUINOX 2000.0) FOR *SOHO* SUNGRAZERS (SUBGROUP I)

PRIMARY ELEMENTS	
Argument of Perihelion, ω	84°.0
Longitude of Ascending Node, Ω	4°.0
Orbit Inclination, i	144°.5
Perihelion Distance, q (AU)	0.0051
Orbit Eccentricity, e	0.99994
DERIVED INFORMATION	
Perihelion Distance, q ($R_\odot$)	1.096
Semimajor Axis, a (AU)	85.0
Aphelion Distance, Q (AU)	169.9949
Orbital Period, P (years)	783.66
Ecliptical Longitude of Perihelion, L	281°.4
Ecliptical Latitude of Perihelion, B	+35°.3
Orbital Velocity at Perihelion (km/s)	590
Orbital Velocity at Aphelion (km/s)	0.0177

ω and Ω only when the normal velocity component is positive (that is, points in the general direction of the north orbital pole). A negative normal component can cause a perturbation of either sign, depending on the location of the point of separation in the orbit. The perturbations of ω and Ω are very approximately symmetrical relative to aphelion, whereas the perturbations of i are generally asymmetrical.

It is encouraging to see that the near-aphelion perturbations of all three angular elements in Table 3 are comparable with, or larger than, the differences between the two subgroups of the Kreutz sungrazers (Sec. 1.2). Also, the *SOHO* pairs listed in Table 1 show a great deal of correspondence with the results in Table 3, especially in terms of the correlation between ω and Ω and the magnitude of the differences.

Table 4 summarizes information on the perturbations of the time of perihelion passage T and of the orbital period P. The contributions are now due to the radial and transverse components of the separation velocity, the normal component's effect being negligible. With its contribution to P symmetrical relative to aphelion, the transverse component of +5 m/s can extend the orbital period by up to ~3.5 times the parent's orbital period, while that of −5 m/s can shorten it by ~50 percent.

It is obvious from Table 4 that the condition $\Delta T \simeq 0$ for the *SOHO* pairs can easily be achieved by a fragmentation event at *any* large heliocentric distance, if the radial component has an opposite sign and is much smaller than the transverse component. For preaphelion events, however, this balance is achieved with increasing difficulty as the point of separation is moved further back in time toward the previous perihelion.

Table 5 presents the perturbations of the perihelion distance q and the reciprocal semimajor axis $1/a$, a measure of the orbital energy. Since changes in $1/a$ are correlated with changes in P, the profiles of the perturbation curves of these two elements have similar features. The perturbations of q, on the other hand, are similar to those of ω in that the contributing separation velocity components are the transverse and normal ones, except that their roles are reversed, with the transverse component dominating the changes in q. At aphelion, this component's contribution to q peaks, while its contribution to ω vanishes. Most significantly, a transverse component of −5 m/s (that is, against the direction of the orbital motion) can then decrease the perihelion distance of a fragment by one half the solar radius, an effect that would cause any member of Subgroup I to plunge into the Sun. Thus, a major conclusion from inspection of Table 5 is that *collisions of the Kreutz group comets with the Sun can by no means be ruled out.*

Because the perturbations of q on the one hand and those of ω and Ω on the other hand are dominated by different separation velocity components, all combinations of increasing/decreasing perihelion distance with advancing/regressing line of apsides and nodal line are possible, in conformity with evidence from Table 1.

TABLE 3
EFFECTS OF SEPARATION VELOCITY ON FRAGMENT'S ARGUMENT OF PERIHELION, LONGITUDE OF ASCENDING NODE, AND ORBIT INCLINATION AS FUNCTION OF BREAKUP LOCATION ALONG PARENT'S ORBIT

Point of separation		Effects (Equinox 2000.0) of separation-velocity component on							
Parent's distance from Sun (AU)	Time from parent's peri-helion	argument of perihelion, ω				ascend. node, Ω		inclination, i	
		transverse		normal		normal		normal	
		+5 m/s	−5 m/s	+5 m/s	−5 m/s	+5 m/s	−5 m/s	+5 m/s	−5 m/s
0.0051[a]	–	–	–	–	–	–	–	–	–
0.0055	12.4 min	–	–	–	–	–	–	–	–
0.01	55.6 min	–	–	–	–	–	–	–	–
0.02	2.4 hr	–	–	–	–	–	–	–	–
0.1	22.3 hr	–	–	−0°.01	+0°.01	−0°.01	+0°.01	−0°.01	+0°.01
1	27.6 day	+0°.01	−0°.01	−0.13	+0.13	−0.16	+0.16	−0.02	+0.02
10	2.4 yr	+0.04	−0.04	−1.31	+1.33	−1.61	+1.63	−0.15	+0.13
90	78.8 yr	+0.09	−0.09	−11.30	+11.99	−14.02	+14.68	−1.82	+0.09
150	224.1 yr	+0.06	−0.06	−17.84	+19.46	−22.34	+23.91	−3.72	−0.87
169.99[b]	391.8 yr	0.00	0.00	−19.84	+21.74	−24.91	+26.77	−4.42	−1.37
150	559.5 yr	−0.06	+0.06	−17.93	+19.40	−22.41	+23.87	−3.62	−0.98
90	704.9 yr	−0.09	+0.09	−11.39	+11.94	−14.11	+14.65	−1.65	−0.08
10	781.2 yr	−0.04	+0.04	−1.33	+1.33	−1.63	+1.64	−0.07	+0.05
1	783.6 yr	−0.01	+0.01	−0.13	+0.13	−0.16	+0.16	–	–
0.1	783.6_5 yr	–	–	−0.01	+0.01	−0.02	+0.02	–	–

[a]Perihelion of parent fragment.
[b]Aphelion of parent fragment.

A summary of the orbital perturbations due to a separation velocity of ~5 m/s acquired by fragments relative to their parent during a *single* event of nucleus breakup is presented in Table 6. It should be emphasized that the traditional hypothesis of tidally-triggered near-perihelion fragmentation is by no means in conflict with the new conceptual model: it has in fact become its integral part.

4.3 Simulation of the orbital distribution of the *SOHO* Sungrazers

Combined with the fully incorporated planetary perturbations, the described procedure can be used to investigate the fragmentation sequence and the hierarchy of the major members of the Kreutz group. Although believed to be incorrect in a majority of realistic scenarios, the premise of one fragmentation per orbital period is deemed acceptable for very massive fragments, because their motions experience only very small perturbations during their shedding of minor fragments, such as the *SOHO* sungrazers. The exception, of course, is splitting into two or more major, nearly equally massive fragments.

The premise of one breakup episode per orbital period is inapplicable in modeling the evolution of a minor fragment that is involved (via many generations of its parents) in more than one such episode between two consecutive perihelion passages. This is so, because a minor fragment's motion at the time of observation carries no "memory" of the past fragmentation events other than the *most recent* one. Consequently, one cannot trace individually the history of small pieces back in time to the previous perihelion, nor can one identify all the generations of their parents. Instead, it is prudent in this situation to apply a Monte Carlo approach in an effort to match the *SOHO* sungrazer population's observed orbital distributions and to explain the correlations among the orbital elements, examples of which are shown in Fig. 3.

The fragmentation scenario can thus be envisaged as a sequence of discrete breakup events. At the outset, a single massive parent comet undergoes an episode of tidally-triggered (or tidally-assisted) splitting that gives rise to an initial mass (and size) distribution of fragments, the interiors of most of them riddled with numerous fractures and cracks. Nearly spontaneous, post-tidal fragmentation of most of these first-generation products sets off, apparently aided by stresses from residual outgassing, rotation, and temperature gradients, but no longer from the solar tides. This process proceeds as a succession of temporally isolated episodes, that is, in a cascading fashion, each

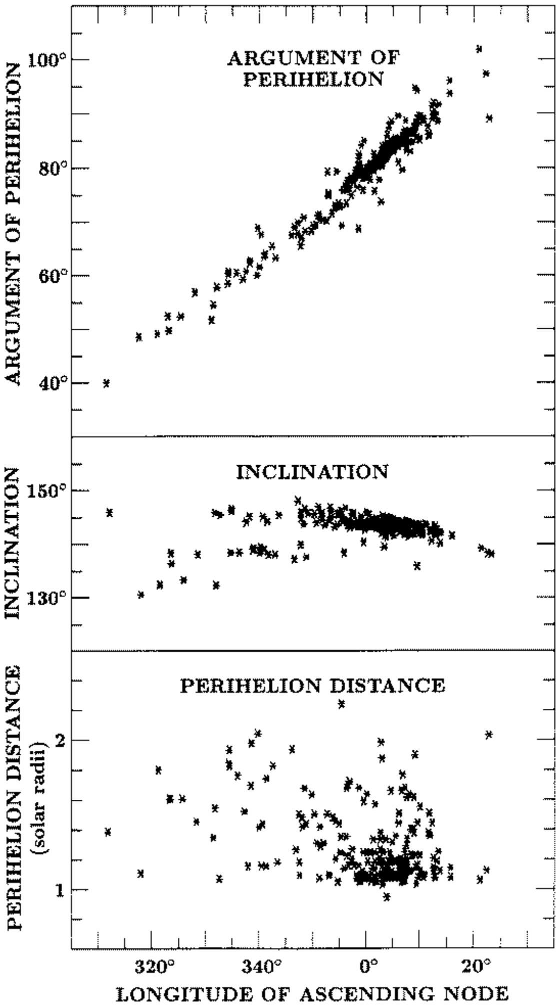

Fig. 3: Correlations between the longitude of ascending node and three other elements compiled from Marsden's orbital determinations for 232 *SOHO* sungrazing comets. Upper panel: correlation with argument of perihelion. Middle panel: correlation with orbit inclination. Lower panel: correlation with perihelion distance.

Table 4
Effects of Separation Velocity on Fragment's Time of Perihelion Passage and Orbital Period As Function of Breakup Location Along Parent's Orbit

Point of separation		Effects of separation-velocity component on							
		time of perihelion passage, T (yr)				orbital period, P (yr)			
		radial		transverse		radial		transverse	
Parent's distance from Sun (AU)	Time from parent's peri-helion	+5 m/s	−5 m/s	+5 m/s	−5 m/s	+5 m/s	−5 m/s	+5 m/s	−5 m/s
0.0051[a]	–	–	–	+1945.48	−383.29	–	–	+1945.48	−383.29
0.0055	12.4 min	+210.47	−145.43	+1600.20	−366.99	+210.47	−145.43	+1600.20	−366.99
0.01	55.6 min	+505.26	−243.98	+520.80	−247.56	+505.26	−243.98	+520.80	−247.56
0.02	2.4 hr	+413.61	−220.31	+205.87	−143.21	+413.61	−220.31	+205.87	−143.21
0.1	22.3 hr	+172.49	−126.22	+35.12	−32.67	+172.49	−126.22	+35.12	−32.67
1	27.6 day	+49.63	−44.89	+3.40	−3.37	+49.63	−44.89	+3.40	−3.37
10	2.4 yr	+14.77	−14.32	+0.34	−0.34	+14.77	−14.32	+0.34	−0.34
90	78.8 yr	+3.51	−3.48	+0.04	−0.03	+3.44	−3.41	+0.04	−0.03
150	224.1 yr	+1.63	−1.62	+0.02	−0.02	+1.33	−1.32	+0.03	−0.02
169.99[b]	391.8 yr	+0.77	−0.77	+0.01	−0.01	0.00	0.00	+0.02	−0.02
150	559.5 yr	+0.30	−0.30	+0.01	–	−1.32	+1.33	+0.03	−0.02
90	704.9 yr	+0.06	−0.06	–	–	−3.41	+3.44	+0.04	−0.03
10	781.2 yr	–	–	–	–	−14.32	+14.77	+0.34	−0.34
1	783.6 yr	–	–	–	–	−44.89	+49.63	+3.40	−3.37
0.1	783.6_5 yr	–	–	–	–	−126.22	+172.49	+35.12	−32.67

[a] Perihelion of parent fragment.
[b] Aphelion of parent fragment.

TABLE 5
EFFECTS OF SEPARATION VELOCITY ON FRAGMENT'S PERIHELION DISTANCE AND RECIPROCAL SEMIMAJOR AXIS (ORBITAL ENERGY) AS FUNCTION OF BREAKUP LOCATION ALONG PARENT'S ORBIT

Point of separation		Effects of separation-velocity component on							
		perihelion distance, q ($R_\odot$)				orbital energy, $1/a$ (10^{-6} AU^{-1})			
Parent's distance from Sun (AU)	Time from parent's peri-helion	transverse		normal		radial		transverse	
		+5 m/s	−5 m/s	+5 m/s	−5 m/s	+5 m/s	−5 m/s	+5 m/s	−5 m/s
0.0051[a]	–	–	–	–	–	–	–	−6644	+6644
0.0055	12.4 min	–	–	–	–	−1725	+1725	−6161	+6161
0.01	55.6 min	–	–	–	–	−3321	+3321	−3389	+3389
0.02	2.4 hr	–	–	–	–	−2896	+2896	−1694	+1694
0.1	22.3 hr	–	–	–	–	−1461	+1461	−339	+339
1	27.6 day	–	–	–	–	−472	+472	−34	+34
10	2.4 yr	+0.04	−0.04	–	–	−146	+146	−3	+3
90	78.8 yr	+0.35	−0.30	+0.02	+0.02	−34	+34	0	0
150	224.1 yr	+0.61	−0.48	+0.07	+0.07	−13	+13	0	0
169.99[b]	391.8 yr	+0.71	−0.53	+0.09	+0.09	0	0	0	0
150	559.5 yr	+0.61	−0.48	+0.07	+0.07	+13	−13	0	0
90	704.9 yr	+0.35	−0.30	+0.02	+0.02	+34	−34	0	0
10	781.2 yr	+0.04	−0.04	–	–	+146	−146	−3	+3
1	783.6 yr	–	–	–	–	+472	−472	−34	+34
0.1	783.6_5 yr	–	–	–	–	+1461	−1461	−339	+339

[a] Perihelion of parent fragment.
[b] Aphelion of parent fragment.

TABLE 6
OVERVIEW OF PERTURBATIONS OF ORBITAL ELEMENTS OF FRAGMENTS DUE TO SEPARATION VELOCITY OF ~5 M/S

Fragments that are products of a breakup ...	... Reach next perihelion ...	... In orbits that are ...
at or shortly after perihelion	at vastly different times (up to 2 millennia apart)	identical in ω, Ω, i, and q, but very different in P
near 1 AU after perihelion	less than 1 century apart	slightly different in ω, Ω, i ($\ll 1°$), and q ($<0.01\ R_\odot$), but moderately different in P
at a heliocentric distance of tens of AU after perihelion	tens of years apart	somewhat different in ω, Ω (both up to a few deg), i (up to $\sim 1°$), q (up to $\sim 0.1\ R_\odot$), but fairly similar in P
at a very large heliocentric distance preaphelion	several years apart	significantly different in ω, Ω (both $\sim 10°$), i (a few deg), and q (up to $\sim 0.5\ R_\odot$), but only slightly different in P
in the general proximity of aphelion	1 year or less apart	very different in ω, Ω, i, and q, but nearly identical in P
after aphelion	nearly simultaneously, not more than some weeks apart	determined by approximate symmetry of perturbations relative to aphelion, except for those in perihelion time

event releasing a new generation of fragments. Thus, an ever increasing number of fragments of ever decreasing sizes populates orbits that are generally similar near the Sun, but differ substantially at large heliocentric distances. Neglecting in the first approximation the nongravitational force that may affect the motion of the separated fragments, the rate of their drifting apart from the breakup location is described by their separation velocity. In the RTN coordinate system (Sec. 4.2), the radial component of this velocity introduces perturbations of the orbital period, the eccentricity, and the time of the next perihelion passage. The transverse component affects, in addition, the perihelion distance and the argument of perihelion. The normal component perceptibly influences all three angular elements, but only insignificantly the orbital period and the time of the next perihelion passage.

To model the evolution of the minor members of the Kreutz group that survive a number of secondary fragmentation events since the previous perihelion of their "initial" parent fragments, one needs to adopt a plausible law to express the progression of such episodes. In the absence of information that would allow one to introduce a more sophisticated paradigm, a simple scheme can be suggested as follows.

Let $T = 0$ be the time of perihelion passage of a "parent" fragment, $\mathcal{F}$, a sungrazing comet that is the source of *all* the "daughter" fragments that are considered below. Let this parent undergo a tidally-triggered fragmentation into N_0 fragments of the first generation, $\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_{N_0}$ $(N_0 \geq 2)$, and let the separation of $\mathcal{F}_1$ and $\mathcal{F}_2$ occur at time t_0 (reckoned from T). It is assumed that most, if not all, of these fragments undergo subsequent episodes of secondary (nontidal) fragmentation, so that they break up into numerous fragments of the second generation. Let, specifically, fragment $\mathcal{F}_1$ break up into N_1 fragments, $\mathcal{F}_{1,1}, \mathcal{F}_{1,2}, \ldots, \mathcal{F}_{1,N_1}$ $(N_1 \geq 2)$, and let the separation of $\mathcal{F}_{1,1}$ and $\mathcal{F}_{1,2}$ take place at time t_1, where

$$t_1 = t_0 + \Delta t_1. \tag{1}$$

Similarly, let fragment $\mathcal{F}_{1,1}$ of the second generation break up into N_2 fragments of the third generation, $\mathcal{F}_{1,1,1}, \mathcal{F}_{1,1,2}, \ldots, \mathcal{F}_{1,1,N_2}$ $(N_2 \geq 2)$, with the separation of $\mathcal{F}_{1,1,1}$ and $\mathcal{F}_{1,1,2}$ taking place at time t_2, where

$$t_2 = t_1 + \Delta t_2, \tag{2}$$

etc. Eventually, let fragment $\mathcal{F}_{1,1,\ldots,1}$ of the nth generation break up into N_n fragments of the $(n+1)$st generation $(N_n \geq 2)$, with the separation of the first two of these fragments taking place at time t_n, where

$$t_n = t_{n-1} + \Delta t_n. \tag{3}$$

This is the last episode along that particular fragmentation branch, as the fragments are now assumed either to reach perihelion or completely to disintegrate before they could split again.

The simplest law for a temporal spacing of a fragmentation sequence is keeping the interval between two consecutive events constant, $\Delta t_1 = \Delta t_2 = \Delta t_3 = \ldots = \Delta t_n \equiv \Delta t$, in which case the time of an nth event of secondary fragmentation is obviously

$$t_n = t_0 + n\Delta t. \tag{4}$$

If P is the orbital period of the leading fragment, the number of events of secondary fragmentation is given by the largest integer n that satisfies the condition

$$n < \frac{P - t_0}{\Delta t}. \tag{5}$$

Since there is an indication from the experience with comet Shoemaker-Levy 9 that the secondary fragmentation events had a tendency toward tapering off (Sec. 2), a better approximation appears to be the adoption of a geometric progression:

$$\begin{aligned}
\Delta t_1 &= \Delta t, \\
\Delta t_2 &= k\Delta t_1 &&= k\Delta t, \\
\Delta t_3 &= k\Delta t_2 &&= k^2\Delta t, \\
&\ldots\ldots\ldots\ldots\ldots\ldots \\
\Delta t_n &= k\Delta t_{n-1} &&= k^{n-1}\Delta t,
\end{aligned} \tag{6}$$

where Δt is the initial interval of secondary fragmentation and $k > 1$ is a constant describing the rate of fragmentation slowdown. In this case, the time of an nth event of secondary fragmentation is

$$t_n = t_0 + \frac{k^n - 1}{k - 1}\Delta t. \tag{7}$$

The number of events along the selected branch of secondary fragmentation (or, equivalently, the number of generations of secondary fragments) is given by the largest integer n that now satisfies the following condition:

$$n < \frac{\ln\left[1 + (k-1)\dfrac{P - t_0}{\Delta t}\right]}{\ln k}. \tag{8}$$

The number of secondary fragmentation events that occur before aphelion is similarly given by

$$n' < \frac{\ln\left[1 + (k-1)\dfrac{\frac{1}{2}P - t_0}{\Delta t}\right]}{\ln k}, \tag{9}$$

so that the number of postaphelion events is

$$n'' = n - n'. \tag{10}$$

The validity of this law remains to be tested, and the ever growing sample of the *SOHO* sungrazers should be the obvious database for this exercise. If the proposed law is compatible with information provided by the data, the plausible values of the two parameters can be estimated. In the meantime, Table 7

TABLE 7
NUMBER OF SECONDARY FRAGMENTATION EVENTS AS A FUNCTION OF INITIAL FRAGMENTATION INTERVAL AND SLOWDOWN RATE
($t_0 = 0$, $P = 800$ YEARS)

Initial fragmentation interval, Δt (years)	Number of secondary fragmentation events (pre-/at aphelion, post-aphelion, total)								
	Rate $k = 1.5$			Rate $k = 2.0$			Rate $k = 3.0$		
	n'	n''	n	n'	n''	n	n'	n''	n
0.1	18	2	20	11	1	12	8	0	8
1	13	2	15	8	1	9	6	0	6
10	7	2	9	5	1	6	4[a]	0	4
100	2	1	3	2	1	3	2[a]	0	2

[a] Last event at aphelion.

presents the predicted number of secondary fragmentation events for the primary breakup at perihelion, an orbital period of 800 years, and several arbitrarily selected values of the initial fragmentation interval and the slowdown rate. A strong aphelion asymmetry in the number of events is prominently exhibited.

5 Conclusion

By advocating the described fragmentation scenario, one implies that comets can break up into fragments of all possible sizes anywhere in space and at any time, but that this disintegration process proceeds in a steplike, discontinuous manner, in discrete events. The tidally-triggered splitting entails a sequence of nontidal episodes, which speeds up the evolution and leads to a complex hierarchy of fragment generations. Nontidal splitting is spontaneous or nearly spontaneous, and it requires a nonuniform makeup of cometary nuclei, with planes of structural weakness (cracks, crevices, etc.) crisscrossing their interior. There may be a close relationship between fragmentation and deactivation of comets, if volatile solids (including water ice) play a role of cosmic "glue" that holds refractory material together.

It is conceivable that the history and dynamical evolution of the entire observed population of the Kreutz group could be modeled as a process that can reach the current stage of disintegration in not much more than two revolutions about the Sun. The complete results of this effort should contribute significantly to our understanding of the formation, structure, mechanical strength, activity, and disintegration of cometary nuclei as well as the role of comets in the solar system evolution.

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