Runaway Fragmentation of Sungrazing Comets Observed with the Solar and Heliospheric Observatory

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ABSTRACT

The strong propensity of the SOHO sungrazing comets for clustering is a product of their runaway fragmentation throughout the orbit about the Sun. This nonuniformity of their temporal distribution is examined quantitatively in terms of the Poisson distribution law. Since the sungrazers in tight pairs occasionally appear in the field of view of the SOHO coronagraphs simultaneously, their offsets can be used to determine their separation parameters, including the time of their parent's breakup, by applying a standard model for split comets. The fragmentation mode of seven sungrazer pairs is shown to differ from that of a SOHO non-Kreutz double comet. Further support for runaway fragmentation is provided by a statistically significant argument that employs an orbit-based search for pairs among the sungrazers.

Subject headings: comets: general — comets: individual (SOHO sungrazers) — methods: data analysis

1. Introduction

Closely spaced pairs and clusters of the Kreutz system sungrazers[1] detected in the images taken with the Large Angle and Spectrometric Coronagraph (LASCO) experiment onboard the Solar and Heliospheric Observatory (SOHO) have been shown to be products of runaway fragmentation that occurs throughout the orbit about the Sun, including the aphelion region some 100 to 200 AU from the Sun (Sekanina 2000; hereafter referred to as Paper 1). The effect on the time of perihelion passage of fragments depends on the orbital locations of the breakup events and the magnitude and direction of a relative velocity that the fragments acquire at the separation times (Sekanina 2002; hereafter referred to as Paper 2). Near aphelion, for example, a separation velocity of 5 m s^{-1} perpendicular to the Sun-comet line in the orbit plane changes the perihelion time by ~3–4 days. On the other hand, the same separation velocity along the direction of the motion near perihelion causes a change of hundreds of years in the orbital period, an effect on the order of tens of percent or more.

The occurrence of runaway fragmentation at large heliocentric distances was shown in Paper 2 to be also consistent with sizable scatter in the angular orbital elements of the SOHO sungrazers' pairs and clusters and with the observed disappearance of these objects in the coronagraph's field of view before they reach perihelion. The massive parent (or parents), which had survived the previous perihelion passage, must indeed have undergone a very large number of fragmentation events during a single revolution about the Sun.

2. Temporal Distribution of the SOHO Sungrazing Comets

The sizable number of closely spaced SOHO sungrazers that their distribution appears to display in comparison with an expected uniform distribution of a statistically random sample can be measured quantitatively by a Poisson distribution law. Let the difference between the perihelion times T_k and T_{k+1} of two successive entries in a chronologically organized list of N sungrazers be $\Delta T_k = T_{k+1} - T_k$ $(k = 1, \ldots, N-1)$ and let all the entries for which $x - \frac{1}{2}\Delta x < \Delta T_k \le x + \frac{1}{2}\Delta x$ be counted as if $\Delta T_k = x$, where the x's make a

[1] D. A. Biesecker at URL http://sungrazer.nascom.nasa.gov.

progression of standard ΔT values that are separated from one another by a constant interval Δx. Starting with $x = 0$, the Poisson distribution for a random sample normalized to an interval of Δx can then be written as

$$\mathcal{P}(x; z, \Delta x) = \frac{z^x}{x\,\Gamma(x)} \exp(-z)\,\Delta x,$$
$$\sum_{\substack{x=0\\(\Delta x)}}^{\infty} \mathcal{P}(x; z, \Delta x) = 1, \qquad (1)$$

where $\Gamma(x)$ is the Gamma function and z is the average value of ΔT_k over the entire sample. The Poisson distribution peaks at $x_{\rm peak}$, which is somewhat smaller than z and can be iteratively calculated from a formula

$$x_{\rm peak} = \frac{\ln z + C}{\displaystyle\sum_{k=1}^{\infty} \frac{1}{k(x_{\rm peak} + k)}}, \qquad (2)$$

where $C = 0.57721566\ldots$ is Euler's constant.

By the end of 2001, the chronological list of the SOHO sungrazers included 361 comets, yielding 360 entries of ΔT_k. To account approximately for the times of interrupted data acquisition (such as a 110-day long period following the loss of contact with the spacecraft on 1998 June 24, or a 43-day long period following the failure of the last gyroscope on 1998 December 21), only values $\Delta T_k \leq 30$ days have been retained, leaving a total of 349 entries that cover a period of 1596.61 days and yield $z = 4.57$ days. This Poisson distribution peaks at $x_{\rm peak} = 4.06$ days, based on a solution to Eq. (2) that uses 10^4 terms in the series and requires 32 iterations to satisfy a convergence threshold of 10^{-8}. The selected distribution step is $\Delta x = 0.2$ days and the count starts with $x = \frac{1}{2}\Delta x = 0.1$ days (rather than $x = 0$), so that the first interval includes all entries for which $0.0 < \Delta T_k \leq 0.2$ days, the second interval all entries for which $0.2 < \Delta T_k \leq 0.4$ days, etc.

The observed distribution of perihelion times of the SOHO sungrazers is compared with the Poisson distribution law in Fig. 1. The evidence for clusters of tightly related sungrazers (at small values of ΔT) is indeed overwhelming. This conclusion also applies to various subsets of the sample, when temporal and/or instrumental (coronagraphs C2 vs. C3) constraints are introduced.

3. Separation Parameters Derived from Simultaneous Coronagraphic Imaging

As shown in Paper 1, the best approach to investigating a possible common source of two closely spaced SOHO sungrazers is by analyzing their relative motion from available positional separations (i.e., offsets in right ascension and declination) in a set of C2 and/or C3 coronagraphic frames. This information can readily be extracted from the absolute astrometric observations of these objects, published first in the Minor Planet Electronic Circulars (MPECs)[2] and subsequently in the Minor Planet Circulars. Since the published positions are in the SOHO-centric coordinate system, their processing involves a transformation into the geocentric coordinate system before the standard model for the split comets (Sekanina 1978, 1982) can be applied. The model allows one to determine up to five parameters: the time of separation, the RTN components of the separation velocity (i.e., radial, transverse, and normal in a right-handed cometocentric coordinate system referred to the orbit plane of the parent object and aligned with the Sun-comet direction), and the differential nongravitational deceleration of one fragment relative to the other. The procedure involves a least-squares, differential-correction, iterative algorithm that searches for an optimized solution and offers an option to solve for any combination of fewer than the five unknowns.

Table 1 lists the SOHO sungrazer pairs for which the offsets could be derived because of the simultaneous presence of both fragments in the field of view of the LASCO coronagraphs. Interestingly, the brightness of the fragments in a pair is found to be more critical for their simultaneous detection than the difference between their perihelion times ΔT. The fragments of the most prominent pair, C/1998 K10 and C/1998 K11, could be measured for fully 1.5 days as they traveled side by side first through the field of view of the C3 coronagraph and then the C2 coronagraph. And, even though the perihelion times were as much as 0.86 days apart, fragments C/2001 U5 and C/2001 U7, which made up another fairly bright pair, could be measured in more common frames than a faint pair of C/2000 H4 and

[2] B. G. Marsden et al., IAU Minor Planet Center, at URL http://cfa-www.harvard.edu/mpec/RecentMPECs.html.

C/2000 H5, whose temporal separation at perihelion was merely 0.01 days. In the subsequent analysis, only the 14 pairs from Table 1 with more than four common frames are analyzed. Based on the previous experience, the eccentricity assumed in all these cases was 0.9999, corresponding to orbital periods near 400–600 years. However, it was shown in Paper 1 that, within reasonable limits, the results are not critically dependent on the choice of the eccentricity.

Because of the absence of activity during virtually the entire orbit, it is justified to employ a four-parameter version of the standard model that does not solve for a deceleration (see Paper 1). Limited experimentation with the five-parameter version and with other versions has shown indeed that the inclusion of the deceleration as one of the unknowns does not lead to satisfactory results. Solutions yielding the time of separation and the components of the separation velocity $V_{\rm sep}$ in the three cardinal directions, $V_{\rm R}$ (radial), $V_{\rm T}$ (transverse), and $V_{\rm N}$ (normal), have successfully been derived for seven of the 14 pairs, with the results listed in Table 2. Five of the fragmentation events are found to have taken place prior to the previous aphelion, two after aphelion.

For the remaining seven examined pairs, no fragmentation event was found, due either to low accuracy of the offsets used, or to the incorrect pairing identity. Indeed, as emphasized in Paper 2, the products of a particular recent fragmentation event do not necessarily have to be the comets with the minimum value of ΔT between them, even though some of them are.

4. Problem of Perihelion Distance

The orbit determination for the SOHO sungrazers observed over only a very short arc of its orbit involves uncertainties large enough that orbital solutions with perihelion distances smaller or larger than the Sun's radius fit the astrometric observations equally well (Marsden 2000, personal communication; cf. Paper 2). Before the concept of runaway fragmentation was introduced, perihelion distances smaller than the solar radius could not be explained, which led to a preconceived, though understandable, consensus that all Kreutz comets are sungrazers, i.e., have perihelia just outside the Sun's photosphere. Derivation of the orbital elements from a fragmentation scenario now renders this opinionated judgment clearly vulnerable.

The perihelion distances of the comets from Table 2 are listed in Table 3, which compares the values for the trailing fragments derived by Marsden in the traditional way with those computed in this study from the fragmentation solutions. The agreement is excellent for pairs 1, 2, 5, and 7, fair for pairs 4 and 6, and poor for pair 3. The total orbital arcs covered by the observations vary between 0.08 days for C/1998 V3 and 2.16 days for C/1998 K11, so that the best perihelion-distance match for the second pair and the worst match for the third pair are not surprising. The fragmentation scenario suggests that C/2001 U4, which was observed for 1.12 days, was indeed quite possibly on a collision course with the Sun.

5. Comparison with a Non-Kreutz Comet

More than two dozen comets among the nearly 400 detected by the end of 2001 in the LASCO coronagraphic images do not belong to the Kreutz sungrazer system. The most interesting of these objects are C/2000 Y6 and C/2000 Y7, which arrived at perihelion (at $\sim$5.4 $R_\odot$) in close succession (less than 0.01 days apart; separation between the components $\sim$100 arcsec; see Marsden 2001) on 2000 Dec 20 and made up a pair that rivals the tightest pairs among the Kreutz system comets.

This double comet is mentioned here, because application of the same version of the fragmentation model that has successfully been used for the Kreutz system pairs now fails miserably. On the contrary, the model's versions that solve for a differential nongravitational deceleration and have provided unsatisfactory results for the sungrazers, converge rapidly. An excellent fit is achieved with the simplest, two-parameter model; the solution, listed in Table 4, shows that the pair had broken up only about three weeks before it was discovered. In general, the episode involving C/2000 Y6 and C/2000 Y7 is strongly reminiscent of breakup events of other nontidally split comets.

The fragmentation modes of the Kreutz system objects and this non-Kreutz double comet are clearly very different. The inferred runaway fragmentation of the sungrazers is thus genuine, as one finds no evidence on any artifact of the coronagraph-based astrometric observations.

6. Separation Parameters Derived from the Orbital Elements

The constraints shown to limit the application of the standard technique for split comets to the Kreutz system sungrazers inspire one to search for an alternative approach.

In principle, the separation parameters for a pair of fragments of common parentage can be derived directly from their orbital elements based on the obvious condition that the heliocentric positional vectors of the two fragments, $\boldsymbol{r}'_{\rm sep} = \boldsymbol{r}'(t_{\rm sep})$ and $\boldsymbol{r}''_{\rm sep} = \boldsymbol{r}''(t_{\rm sep})$, coincide at the time of their separation, $t_{\rm sep}$. Let, in the ecliptical coordinate system $\{x, y, z\}$, the unit vectors from the Sun toward their perihelion points be, respectively, $\boldsymbol{P}' = \{P'_x, P'_y, P'_z\}$ and $\boldsymbol{P}'' = \{P''_x, P''_y, P''_z\}$; similarly, let the unit vectors toward the orbital points at a true anomaly of +90° be $\boldsymbol{Q}' = \{Q'_x, Q'_y, Q'_z\}$ and $\boldsymbol{Q}'' = \{Q''_x, Q''_y, Q''_z\}$; and, finally, let the unit vectors in the direction of the north poles of the respective orbital planes be $\boldsymbol{R}' = \{R'_x, R'_y, R'_z\}$ and $\boldsymbol{R}'' = \{R''_x, R''_y, R''_z\}$. These vector components are known to be readily expressible in terms of the angular elements of the orbits of the two fragments, i.e., ω', Ω', i' and ω'', Ω'', i''. Dropping the primes, one has for either orbit:

$$\begin{pmatrix} \boldsymbol{P} \\ \boldsymbol{Q} \\ \boldsymbol{R} \end{pmatrix} = \begin{pmatrix} \cos\omega & \sin\omega & 0 \\ -\sin\omega & \cos\omega & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos i & \sin i \\ 0 & -\sin i & \cos i \end{pmatrix} \times \begin{pmatrix} \cos\Omega & \sin\Omega & 0 \\ -\sin\Omega & \cos\Omega & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (3)$$

Neglecting differential planetary perturbations and requiring that the positions of the two fragments coincide at separation, one finds the following conditions to be satisfied:

$$|\boldsymbol{r}'_{\rm sep}| = |\boldsymbol{r}''_{\rm sep}| = r_{\rm sep} \quad (4)$$

and

$$P'_\gamma \cos v'_{\rm sep} + Q'_\gamma \sin v'_{\rm sep} = P''_\gamma \cos v''_{\rm sep} + Q''_\gamma \sin v''_{\rm sep}, \quad \gamma = x, y, z, \quad (5)$$

where $r_{\rm sep} = r(t_{\rm sep})$ is the heliocentric distance at separation and $v'_{\rm sep} = v'(t_{\rm sep})$ and $v''_{\rm sep} = v''(t_{\rm sep})$ are the true anomalies that determine the common position of the two fragments at that time. The two true anomalies are the only unknowns to solve for using the four equations. It is useful to introduce a true anomaly difference

$$\Delta v = v''_{\rm sep} - v'_{\rm sep}, \quad (6)$$

and solve for $v'_{\rm sep}$ and Δv, rather than $v'_{\rm sep}$ and $v''_{\rm sep}$. After some algebra, one finds from (5):

$$\begin{aligned} \tan\Delta v \;=\; & \{(\boldsymbol{P}'\!\cdot\!\boldsymbol{R}'')\,Q''_\gamma - (\boldsymbol{Q}'\!\cdot\!\boldsymbol{R}'')\,P''_\gamma \\ & + (\boldsymbol{R}'\!\cdot\!\boldsymbol{P}'')\,Q'_\gamma - (\boldsymbol{R}'\!\cdot\!\boldsymbol{Q}'')\,P'_\gamma\} \\ & \times \{(\boldsymbol{P}'\!\cdot\!\boldsymbol{R}'')\,P''_\gamma + (\boldsymbol{Q}'\!\cdot\!\boldsymbol{R}'')\,Q''_\gamma \\ & - (\boldsymbol{R}'\!\cdot\!\boldsymbol{P}'')\,P'_\gamma - (\boldsymbol{R}'\!\cdot\!\boldsymbol{Q}'')\,Q'_\gamma\}^{-1}, \\ & \gamma = x, y, z, \quad (7) \end{aligned}$$

where the parenthesized expressions are scalar products of the unit vectors. Since Δv is always a small angle, its quadrant is determined unequivocally by Eq. (7) alone; in any case, the expressions for $\sin\Delta v$ and $\cos\Delta v$ can readily be derived. For the pairs of fragments with identical inclinations, the option $\gamma = z$ should be avoided, as it leads to an expression of a type 0/0.

By eliminating Δv, Eqs. (5) can be employed to calculate true anomaly $v'_{\rm sep}$:

$$\tan v'_{\rm sep} = -\frac{\boldsymbol{P}'\!\cdot\!\boldsymbol{R}''}{\boldsymbol{Q}'\!\cdot\!\boldsymbol{R}''}. \quad (8)$$

For any fragmentation event that involves the Kreutz system comets and does not occur at the proximity of perihelion, the true anomaly is near $\mp180°$, so that its quadrant is determined unequivocally by Eq. (8). If the orbital elements were absolutely accurate, all four conditions would yield identical values for $v'_{\rm sep}$ and Δv. Because of observational errors propagating into the orbital elements, the values of $v'_{\rm sep}$ calculated from Eqs. (4) and (5) are not necessarily the same. Since Eqs. (5) do not involve the dimensions and shape of the orbit, condition (4) is distinctly preferable for determining $v'_{\rm sep}$. The result is a quadratic equation with the following solutions:

$$\begin{aligned} \tan\tfrac{1}{2}v'_{\rm sep} \;=\; & \Big\{p'e''\sin\Delta v \\ & \pm \Big[2p'p''(1-e'e''\cos\Delta v) \\ & - p'^2(1-e''^2) - p''^2(1-e'^2)\Big]^{\frac{1}{2}}\Big\} \\ & \{p'\,(1-e''\cos\Delta v) - p''(1-e')\}^{-1}, \quad (9) \end{aligned}$$

where e' and e'' are the orbit eccentricities for the two fragments and p' and p'' are their orbital parameters. For parabolic solutions, which, although dynamically inferior, are the only ones available for all the SOHO sungrazers, Eq. (9) simplifies to

$$\tan \tfrac{1}{2} v'_{\rm sep} = \cot \tfrac{1}{2} \Delta v \pm \sqrt{q''/q'} \, {\rm cosec} \tfrac{1}{2} \Delta v, \quad (10)$$

where q' and q'' are the respective perihelion distances. The two solutions are always dramatically different and at best it is just one of them that fits our overall constraints.

In a parabolic approximation, a temporal separation of the SOHO sungrazers in a pair at perihelion is expected to be less than ~2 weeks. However, the magnitude of the effect of the (unknown) orbital period is so large (Paper 2; cf. also Sec. 1) that the time of perihelion passage cannot be employed to constrain fragmentation solutions.

Once the true anomalies at separation are determined, the RTN components of the separation velocity vector $\boldsymbol{V}_{\rm sep}$ (see Sec. 3) are given by the following expressions:

$$V_j = \boldsymbol{V}_{\rm sep} \cdot \boldsymbol{U}_j, \qquad j = {\rm R, T, N}, \qquad (11)$$

which are the dot products computed from the ecliptical components of the separation velocity vector $\boldsymbol{V}_{\rm sep} = \{V_x, V_y, V_z\}$ (in km s^{-1}),

$$\boldsymbol{V}_{\rm sep} = \frac{29.78}{\sqrt{p''}} \left[-\boldsymbol{P}'' \sin v''_{\rm sep} + \boldsymbol{Q}''(e'' + \cos v''_{\rm sep}) \right] - \frac{29.78}{\sqrt{p'}} \left[-\boldsymbol{P}' \sin v'_{\rm sep} + \boldsymbol{Q}'(e' + \cos v'_{\rm sep}) \right], \qquad (12)$$

and the ecliptical components of the unit vectors $\boldsymbol{U}_{\rm R}$, $\boldsymbol{U}_{\rm T}$, and $\boldsymbol{U}_{\rm N}$:

$$\begin{pmatrix} \boldsymbol{U}_{\rm R} \\ \boldsymbol{U}_{\rm T} \\ \boldsymbol{U}_{\rm N} \end{pmatrix} = \begin{pmatrix} \cos v'_{\rm sep} & \sin v'_{\rm sep} & 0 \\ -\sin v'_{\rm sep} & \cos v'_{\rm sep} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \boldsymbol{P}' \\ \boldsymbol{Q}' \\ \boldsymbol{R}' \end{pmatrix}. \qquad (13)$$

The parabolic approximation is of course bound to have an effect on the calculated separation velocity, whose value derived in this fashion should therefore be regarded as an estimate only.

As expected, the symetrical solutions to (7) and (9) [or (10)] are independent of the choice of the reference object. This can be proven both mathematically and numerically. The SOHO pairs that satisfy the conditions $0.1 \leq r_{\rm sep} \leq 200$ AU and $V_{\rm sep} \leq 7$ m s^{-1} are listed chronologically in Table 5. Multiple entries are noticed at once: two comets pair up with five other objects; three comets with four others; six with three others; and 14 with two others. The fragmentation events are distributed almost equally before and after aphelion and the heliocentric distances at separation always exceed 10 AU. Altogether, the table includes 55 sungrazers. Because of the low accuracy of the orbital elements, the tabulated fragmentation events should be regarded as possible rather than well established, while pairs missing from the table may in fact be genuine (including the seven pairs in Table 2). If the effects of parabolic approximation and observational errors are allowed for by relaxing the limit on $V_{\rm sep}$, the number of sungrazers in pairs increases to 143 when $V_{\rm sep} \leq 20$ m s^{-1} and to 228 when $V_{\rm sep} \leq 50$ m s^{-1}. Given the uncertainties, the only objective of this exercise is to support a statistical argument: if there is a large number of pairs present in the sample, a sufficiently large number of pairs should be recognized by the search procedure on the probability grounds. The failure to do so would be detrimental to the concept of runaway fragmentation of the SOHO sungrazers. To this end, the exercise presented in this section fulfils its purpose.

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TABLE 1

PAIRS OF SOHO SUNGRAZERS IN COMMON FRAMES

NUMBER OF COMMON FRAMES	PAIR OF SOHO SUNGRAZERS: LEADING	PAIR OF SOHO SUNGRAZERS: TRAILING	TEMPORAL SEPARATION ΔT (days)
34......	C/1998 K10	C/1998 K11	0.18
25......	C/2001 U3	C/2001 U4	0.40
14......	C/1999 O1	C/1999 O3	0.24
11......	C/2000 X2	C/2000 X3	0.07
9......	C/2001 U5	C/2001 U7	0.86
8......	C/2000 H4	C/2000 H5	0.01
	C/2001 M2	C/2001 M3	0.16
7......	C/1998 K9	C/1998 K15	0.04
	C/2001 Y2[a]	C/2001 Y3[a]	0.00
6......	C/1997 J3	C/1997 J4	0.09
	C/1998 X9	C/1998 X10	0.01
5......	C/1998 V2	C/1998 V3	0.03
	C/2001 H1	C/2001 H3	0.15
	C/2001 H3	C/2001 H4	0.09
4......	C/1997 U5	C/1997 U6[b]	0.01
3......	C/1997 K4[a]	C/1997 K7[a]	0.00
	C/1998 V5	C/1998 V6	0.04
	C/2001 L4	C/2001 L5	0.18
	C/2001 L6	C/2001 L7	0.22
2......	C/2001 H2	C/2001 H3	0.07
	C/2001 K6	C/2001 K7	0.19
1......	C/1997 X3	C/1997 X4	0.07
	C/2001 H1	C/2001 H2	0.08

[a] As perihelion times of these two comets coincide, choice of leading fragment is arbitrary.
[b] Existence of this sungrazer is somewhat questionable.

TABLE 2

ORBITAL SOLUTIONS FOR SIX FRAGMENTATION EVENTS INVOLVING SOHO SUNGRAZERS (ECCENTRICITY 0.9999 ASSUMED)

PAIR No.	SOHO SUNGRAZERS		EVENT'S ORBIT LOCATION		VELOCITY OF SEPARATION ($\mathrm{m\,s^{-1}}$)					MEAN RESIDUAL
	LEADING	TRAILING	$(t_{\rm sep} - T)$[a]	$r_{\rm sep}$ (AU)[b]	$V_{\rm sep}$	$V_{\rm R}$	$V_{\rm T}$	$V_{\rm N}$	$N_{\rm off}$[c]	(arcsec)
1...	C/1998 K9	C/1998 K15	-0.62 ± 0.23	108 (pre)	5.1 ± 0.7	$-0.1 \pm 0.0_{04}$	$+5.1 \pm 0.7$	$-0.1 \pm 0.0_{3}$	6	± 1.6
2...	C/1998 K10	C/1998 K11	-0.12 ± 0.08	67 (post)	4.2 ± 1.3	$+0.2 \pm 0.1$	-3.5 ± 1.4	-2.4 ± 1.0	12	± 4.9
3...	C/1998 V2	C/1998 V3	-0.70 ± 0.24	96 (pre)	6.3 ± 0.2	$-0.1 \pm 0.0_{03}$	$+5.9 \pm 0.2$	-2.2 ± 0.1	4	± 3.3
4...	C/1999 O1	C/1999 O3	-0.80 ± 0.23	77 (pre)	4.2 ± 1.6	$-0.1 \pm 0.0_{2}$	$+3.5 \pm 1.7$	-2.3 ± 1.4	5	± 4.6
5...	C/2000 X2	C/2000 X3	-0.75 ± 0.36	92 (pre)	2.0 ± 1.1	$0.0 \pm 0.0_{04}$	$+0.1 \pm 0.1$	$+2.0 \pm 1.1$	5	± 3.7
6...	C/2001 U3	C/2001 U4	-0.94 ± 0.20	38 (pre)	6.8 ± 0.3	$+0.1 \pm 0.0_{05}$	-5.1 ± 0.4	$+4.5 \pm 0.1$	7	± 4.2
7...	C/2001 Y2[d]	C/2001 Y3[d]	-0.35 ± 0.16	102 (post)	5.5 ± 0.1	$-0.1 \pm 0.0_{01}$	$+5.2 \pm 0.1$	-1.8 ± 0.1	4	± 3.6

[a] Separation time measured from current perihelion passage in units of orbital period of leading object.
[b] Heliocentric distance at nominal separation time; location of this separation point relative to aphelion (i.e. either preaphelion or postaphelion) is parenthesized.
[c] Number of positional offsets used in solutions.
[d] Perihelion times of these two comets coincide; choice of leading fragment is arbitrary.

TABLE 3

PERIHELION DISTANCES $q_{\rm leading}$ AND $q_{\rm trailing}$ OF FRAGMENTS IN PAIRS

LEADING FRAGMENT	$q_{\rm leading}$ ($R_\odot$)[a,b]	TRAILING FRAGMENT	$q_{\rm trailing}$ ($R_\odot$)[a]	
			From Marsden	This Study
C/1998 K9	1.20	C/1998 K15	1.68	1.66
C/1998 K10....	1.25	C/1998 K11	1.08	1.08
C/1998 V2	1.14	C/1998 V3	1.18	1.61
C/1999 O1	1.09	C/1999 O3	1.13	1.31
C/2000 X2	1.19	C/2000 X3	1.19	1.20
C/2001 U3	1.07	C/2001 U4	1.04	0.94
C/2001 Y2[c]	1.15	C/2001 Y3[c]	1.59	1.58

[a] Units of the Sun's radius: $1 R_\odot = 0.0046524$ AU.

[b] From Marsden (various Minor Planet Circulars; see also Marsden & Williams 1999).

[c] Perihelion times of these two comets coincide; choice of leading fragment is arbitrary.

TABLE 4

FRAGMENTATION SOLUTION FOR NON-KREUTZ COMET PAIR C/2000 Y6 AND C/2000 Y7.

Quantity	Value
Conditions at separation:	
Time from perihelion, $t_{sep} - T^{a}$ (days)	-23.8 ± 4.1
Date 2000 (UT)	Nov 27.0
Heliocentric distance, r_{sep} (AU)	0.89
Differential nongravitational deceleration	
(units of 10^{-5} solar attraction)[b]	98 ± 17
Number of offset pairs employed	6
Mean residual (arcsec)	± 1.3

[a] Minus sign indicates time before perihelion.
[b] Referring to C/2000 Y7 relative to C/2000 Y6; 1 unit is equivalent to acceleration 0.593×10^{-5} cm s^{-1} at 1 AU from Sun.

TABLE 5

POSSIBLE FRAGMENTATION EVENTS DERIVED FOR SOHO SUNGRAZERS FROM ORBITAL ELEMENTS

PAIR No.	POSSIBLE SUNGRAZER PAIR: FRAGMENT 1	FRAGMENT 2	EVENT AT r_{sep} (AU)[a]	VELOCITY V_{sep} (m s^{-1})
1...	C/1996 B4	C/1997 Y2	66 (post)	4.6
2...	C/1996 Q2	C/2000 U2[d]	178 (post)	4.4
3...	C/1996 Q3	C/2001 R2[b]	13 (pre)	4.5
4...	C/1996 X2[b]	C/1997 K3	166 (post)	4.7
5...		C/2001 U7[b]	119 (post)	5.2
6...	C/1996 Y1	C/1998 H4[c]	86 (pre)	6.6
7...	C/1996 Y2	C/1997 K1	11 (pre)	6.1
8...	C/1997 P1	C/1998 H4[c]	27 (pre)	5.5
9...	C/1997 U3	C/1999 J9[b]	93 (post)	0.8
10...	C/1997 V2	C/1999 K1	142 (post)	5.4
11...	C/1997 W1[b]	C/2001 U7[b]	67 (pre)	5.6
12...		C/2001 R5[b]	199 (pre)	5.5
13...	C/1997 X1	C/2000 K5[b]	183 (post)	1.9
14...	C/1998 G4[c]	C/2001 Y5[e]	198 (post)	4.9
15...		C/2000 B5[c]	185 (post)	6.6
16...		C/1999 L5[d]	49 (post)	6.9
17...	C/1998 H4[c]	C/1999 L5[d]	192 (post)	5.5
18...	C/1998 H2	C/2000 J7[b]	64 (post)	5.4
19...	C/1998 K8	C/2001 K2[b]	158 (post)	5.7
20...	C/1998 K14[c]	C/1999 U6[b]	63 (pre)	3.5
21...		C/2000 K5[b]	45 (post)	3.8
22...		C/2000 N1[e]	45 (post)	6.7
23...	C/1998 K10[d]	C/1999 J9[b]	131 (pre)	2.2
24...		C/2001 B3[c]	140 (pre)	6.1
25...		C/2000 N1[e]	47 (post)	5.8
26...		C/2000 V1[b]	28 (post)	5.9
27...	C/1998 L9	C/1999 S7	52 (pre)	2.6
28...	C/1999 K11	C/2001 J4	16 (post)	4.7
29...	C/1999 L1	C/1999 Y3[b]	152 (pre)	6.2
30...	C/1999 L5[d]	C/2001 U4[b]	160 (pre)	5.6
31...		C/2000 W3	193 (post)	5.1
32...	C/1999 N3[b]	C/2001 Y5[e]	125 (pre)	6.9
33...		C/2000 U2[d]	134 (pre)	4.3
34...	C/1999 Q2	C/2001 O1	58 (post)	2.0
35...	C/1999 Q3	C/2001 R2[b]	36 (post)	5.4
36...	C/1999 U6[b]	C/2001 U4[b]	54 (pre)	4.8
37...	C/1999 V2	C/2001 C2[c]	33 (pre)	5.3
38...	C/1999 Y3[b]	C/2000 N1[e]	32 (pre)	6.5
39...	C/2000 B5[c]	C/2001 C2[c]	12 (pre)	6.1
40...		C/2000 U2[d]	97 (pre)	6.1
41...	C/2000 H2	C/2000 N1[e]	135 (pre)	1.3
42...	C/2000 J7[b]	C/2001 H1	178 (post)	4.9
43...	C/2000 J5	C/2001 K2[b]	194 (post)	5.3
44...	C/2000 N1[e]	C/2000 V1[b]	55 (post)	6.9
45...	C/2000 U2[d]	C/2001 Y5[e]	134 (pre)	6.5
46...	C/2001 B3[c]	C/2001 C2[c]	163 (post)	4.3
47...		C/2001 Y5[e]	101 (post)	6.3
48...	C/2001 M11	C/2001 V2	101 (pre)	2.2
49...	C/2001 R5[b]	C/2001 Y5[e]	86 (pre)	6.7

[a] Heliocentric distance at calculated separation time and, in parentheses, location relative to aphelion (i.e. either preaphelion or postaphelion).
[b] May have been involved in two fragmentation events.
[c] May have been involved in three fragmentation events.
[d] May have been involved in four fragmentation events.
[e] May have been involved in five fragmentation events.

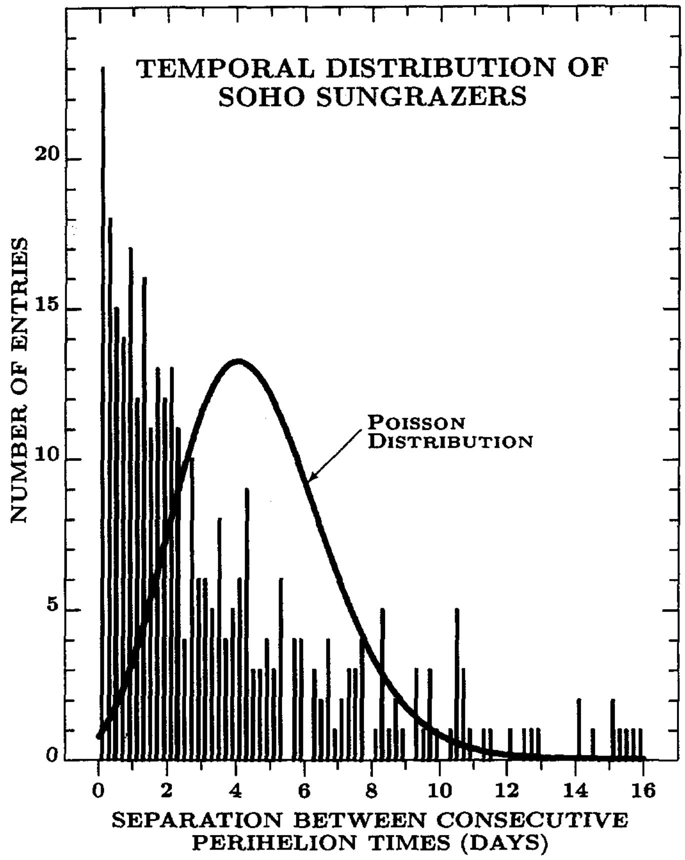

Fig. 1.— Temporal distribution of the SOHO sungrazers. The vertical bars show the observed distribution of the differences between the perihelion times of the consecutive entries in the list of the SOHO sungrazers. The adopted step is 0.2 days, with the first entry on the left displaying the number of temporal differences between 0 and 0.2 days, etc. The differences of more than 30 days have been eliminated from the statistics to account approximately for the times of major interruptions in the data acquisition by the LASCO experiment. The entire sample employed contains 349 entries. The curve is the Poisson distribution law, which describes the expected behavior of a random sample. It is normalized to a standard interval of 0.2 days and an average temporal separation of 4.57 days. The distribution peaks at 4.06 days. The plot shows the overwhelming evidence for the SOHO sungrazers' strong propensity for clustering.