NEW MODEL FOR THE KREUTZ SUNGRAZER SYSTEM: CONTACT-BINARY PARENT AND UPGRADED CLASSIFICATION OF DISCRETE FRAGMENT POPULATIONS

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ABSTRACT

The structure of the Kreutz system of sungrazing comets is shown to be much more complex than formerly believed. Marsden’s (1989) division into three subgroups (I, II, Ia) is now greatly expanded, as new evidence is being offered on five main populations of fragments — I, Ia, II, Iia, and III — and four peripheral ones — Pre-I, Pe (side branch of I), IIIa, and IV. Five populations are related to naked-eye sungrazers and all nine incorporate carefully screened data sets from a collection of 1500 SOHO/STEREO dwarf Kreutz comets whose gravitational orbits were computed by Marsden. Tight correlations between the nominal perihelion latitude and the nominal longitude of the ascending node are the result of ignored effects of an outgassing-driven acceleration on the orbital motion. The average width of a gap between adjacent populations in the nodal longitude corrected for the nongravitational effect is near 9°; the overall range equals 66°. The other angular elements of the populations are determined by the condition of shared apsidal line. A self-consistent model postulates (i) an initial breakup, in general proximity of aphelion, of a contact-binary parent (progenitor) into its two lobes and the neck (originally linking the lobes), giving birth to, respectively, Population I (Lobe I; the main residual mass C/1843 D1), Population II (Lobe II; C/1882 R1), and Population Ia (the neck); followed by (ii) progressive fragmentation of the lobes (primarily Lobe II), mostly (but not exclusively) far from perihelion, giving successively rise to the other populations and clusters of naked-eye Kreutz sungrazers and their debris. The separation velocities were a few meters per second. Massive fragments of Populations Pre-I, IIIa, and IV are yet to be discovered. Relations among the products of cascading fragmentation are depicted in a pedigree chart. The age of the Kreutz system is estimated at two millennia and a mean orbital period of Lobe I and its main residual mass at ∼740 yr. The status is reviewed of the possible historical Kreutz comets seen in AD 1106, AD 363, and 372 BC.

1. INTRODUCTION

This paper is the preliminary report of a comprehensive investigation, to follow shortly, aimed at introducing a new fragmentation model for the Kreutz sungrazer system — a major revision of the diverse orbital work conducted over the past 60 years by, among others, Opik (1966), Marsden (1967, 1989, 2005), Sekanina (2002), and, in particular, Sekanina & Chodas (2004, 2007) — the two studies that employed competing rationales. Necessitated by a number of key developments during the past decade, the new model accounts for and/or is consistent with: (i) the appearance of the sungrazer C/2011 W3 (Lovejoy), an event of singular importance for revising the orbital classification of the Kreutz system; (ii) a nearly steady stepwise distribution of the longitudes of the ascending node among the naked-eye sungrazers and a correlation with the perihelion distance; (iii) growing evidence that the contact binary, ostensibly susceptible to breakup, is a fairly common figure among cometary nuclei and Kuiper Belt objects; (iv) a proposition that C/1843 D1 and C/1882 R1 are the two dominant surviving residual masses of the progenitor, the nearly 40 year wide gap between their perihelion times being the outcome of the initial rate of separation of their precursors, magnified by the orbital evolution over the lifetime of the Kreutz system; (v) a novel look at some candidates for the Kreutz-system membership among historical comets; and (vi) results from my examination of Marsden’s collection of gravitational orbits for a large number of dwarf Kreutz sungrazers detected by the coronagraphs on board the Solar and Heliospheric Observatory (SOHO) and the Solar Terrestrial Relations Observatory (STEREO).

With regard to point (vi), one should remark that the gravitational orbit approximates the motion of a Kreutz sungrazer the better the more massive the object is. While the deviation from the gravitational law is trivial and essentially undetectable in the motion of a brilliant, naked-eye member of the Kreutz system, the motion of a faint dwarf sungrazer could defy the law to a considerable degree, as argued in Section 3. Accordingly, the computation of a gravitational orbit makes sense for bright sungrazers, for which it offers an excellent fit to astrometric observations, but it is dynamically meaningless for many dwarf comets. Because the observed orbital arc of a dwarf sungrazer is short and, as pointed out below, its astrometry is inferior, the gravitational fit may look acceptable. Yet, the derived orbit is spurious, the angular elements often grossly failing to satisfy the well-
known condition of shared apsidal line.\footnote{As far as I am aware, the coincidence of the apsidal lines of C/1843 D1 and C/1882 R1 was discovered by Kreutz (1895). He was greatly impressed by the match, which contrasted with the large differences in the nodal longitudes and other angular elements of the two comets. The general validity of the condition of shared apsidal line among the Kreutz sungrazers with well-determined orbits was underscored by Marsden (1967).} Nonetheless, I demonstrate in Section 3 that when properly examined, Marsden’s gravitational orbits provide important information on major features of the orbital distribution of the Kreutz system’s dwarf comets.

2. UPGRAADING MARSDEN’S CLASSIFICATION: FROM SUBGROUPS TO POPULATIONS

When Marsden (1967) was writing his first paper on the subject, fewer than ten Kreutz sungrazers were known with moderately to highly accurate orbits. He referred to their total as the Kreutz group and, based on their orbital diversity, he divided them into two subgroups, I and II. Given the thousands of members known nowadays, I deem it more appropriate to call their total the Kreutz system and to divide the ensemble into fragment populations. Accordingly, in the following I consistently replace the term used by Marsden with the new one, even when I refer to his own work: his Subgroups I and II are now Populations I and II, respectively.

Of the sungrazers known in the 1960s, Marsden (1967) rated C/1843 D1 (then designated 1843 I), C/1880 C1 (1880 I), and C/1963 R1 (1963 V) as definite members of Population I; whereas C/1882 R1 (1882 II), C/1945 X1 (1945 VII), and C/1965 S1 (1965 VIII) as definite members of Population II.\footnote{Marsden’s assigning C/1945 X1, the only telescopic comet on his list, to Population II was rather problematic (Marsden 2005). Even nowadays the orbit is deemed too uncertain to fit unequivocally any particular population.} Of the other comets, including several historical ones, Marsden regarded C/1668 E1 (Southern of 1668), C/1695 U1 (Southern of 1695), X/1882 K1 (Tewfik; eclipse comet of 1882), and C/1887 B1 (1887 I) as potential members of Population I,\footnote{The orbit computed for C/1887 B1 by Sekanina (Marsden & Roemer 1978), nowadays accepted as the most representative and making the comet’s suspected membership in Population I more secure, was unavailable at the time of Marsden’s (1967) paper.} while he believed that C/1689 X1 (Southern of 1689) and X/1702 D1 (1702a) were likely to belong to Population II.

The orbital differences between Populations I and II are by no means minor; they amount to up to about 20° in the angular elements and approximately 0.6 $R_\odot$ (or up to some 50 percent) in the perihelion distance. Specifically, the definite members of Population I have the longitudes of the ascending node, $\Omega$, between 3° and 8° and the perihelion distances, $q$, not exceeding 1.2 $R_\odot$, while the definite members of Population II have $\Omega$ near 347° and $q$ near 1.7 $R_\odot$. The members of both populations satisfy the condition of shared apsidal line, defined by the standard perihelion longitude $L_\pi = 282°.8 \pm 0°.2$ and the standard perihelion latitude $B_\pi = +35°.2 \pm 0°.1$.\footnote{All angular elements in this paper refer to equinox J2000.} The longitude of the ascending node is shown to be the orbital element that most faithfully describes the population to which a given sungrazer belongs. The remaining angular elements — the argument of perihelion, $\omega$, and the inclination, $i$ — are fully determined by $\Omega$, $L_\pi$, and $B_\pi$.

The perihelion distance does not appear to be population diagnostic to the degree the nodal longitude is.

The sungrazer C/1970 K1, arriving nearly three years after Marsden’s pioneering paper had been published, failed to fit either of the two populations in terms of both the angular elements and the perihelion distance. To account for the anomaly, Marsden (1989) expanded his classification system by introducing Population Ia. With this comet’s value of $\Omega$ at 337°, the range of nodal longitudes was extended from 20° to 30°; and with its $q$ near 1.9 $R_\odot$, the range of perihelion distances increased to more than 0.8 $R_\odot$. Good news was that C/1970 K1 did satisfy the condition of shared apsidal line.

Only one year after Marsden’s untimely death, T. Lovejoy discovered comet C/2011 W3, which failed to fit the three-population system. With the longitude of the ascending node near 327°, this comet extended the range of $\Omega$ among the naked-eye Kreutz sungrazers by yet another ~10° to ~40°. Although this comet did fit, perhaps fortuitously, Population I in terms of the perihelion distance, further expansion of the classification system was unavoidable; comet C/2011 W3 became a representative of a new Population III.\footnote{This very suggestion was made in another context by Sekanina & Chodas (2012).}

At this point in time there were four populations, I, II, Ia, and III, with a peculiar nodal-longitude distribution: the gap between Populations I and II was ~20° wide, but the gaps between Populations II and Ia and between Populations Ia and III were each ~10° wide. For the sake of uniformity, one is tempted to speculate that yet another, hidden population — I call it Population Ia, $\Omega$ resides near $\Omega \approx 356^\circ$, approximately halfway between Populations I and II. If so, the gap widths between adjacent populations become equalized at about 9° to 10° over the entire range of nodal longitudes between Populations I and III.

Circumstantial evidence of Population Ia is offered by the orbital distribution for a group of eight SOHO Kreutz sungrazers, corrected by Sekanina & Kracht (2015) for major nongravitational effects (Section 3). The corrected longitudes of the ascending node for three of the eight comets range from 358° to 1°, outside the interval occupied by the naked-eye sungrazers of Population I, but near the above proposed nodal longitude of Population Ia (Table 1).

Another set of Kreutz sungrazers worth examining for evidence of Population Ia is 19 of the 20 comets imaged by the coronagraphs on board the Solwind (P78-1) and Solar Maximum Mission (SMM) satellites between 1979 and 1989.\footnote{One of the 20 comets had a perihelion distance much too large to qualify as a Kreutz sungrazer} Even though the orbits for these objects (see Marsden 2005 for a review) are very uncertain, more so than the orbits of the SOHO sungrazers of comparable brightness, and were, with a few exceptions, derived by forcing the condition of shared apsidal line, at least three and possibly five among the nineteen appear to have moved in orbits consistent with Population Ia.\footnote{The likely Population Ia members were C/1981 V1 (Solwind 4), C/1983 S2 (Solwind 6), and C/1984 Q1 (Solwind 9); a possible member was C/1981 W1 (Solwind 7) and perhaps even C/1987 T2 (SMM 1).} In the following I show that they represent the proverbial “tip of
the iceberg” and that Population Ia is far from being the only contender in the search for additional populations among the dwarf Kreutz sungrazers.

3. MARSDEN’S GRAVITATIONAL ORBITS FOR THE SOHO KREUTZ SUNGRAZERS

Marsden computed sets of gravitational orbital elements (i.e., with no nongravitational terms in the equations of motion; the elements are referred to below as nominal) for more than 1500 Kreutz sungrazers detected in the SOHO and STEREO coronagraphic images. A plot of the nominal inclination $i$ against the nominal longitude of the ascending node $\Omega$ for these dwarf Kreutz comets was used by Sekanina & Kracht (2015) to illustrate that the orbits failed to obey the condition of shared apsidal line. Another plot showed that the nominal latitude of perihelion $B_\pi$ (but not the longitude $L_\pi$) varied systematically with the nominal nodal longitude $\Omega$. The correlation disappeared and compliance with the condition of shared apsidal line was restored when the orbital solution included the out-of-plane component of the nongravitational acceleration. The magnitude of the needed acceleration — assumed to be driven by the sublimation of water ice — was enormous, ranging in absolute value from $0.5$ to $25 \times 10^{-5}$ AU day$^{-2}$ at 1 AU from the Sun, or from 1.7 percent to 85 percent (sic) of the Sun’s gravitational acceleration! The range of nodal longitudes for the eight dwarf sungrazers dropped from the nominal $-90^\circ$ to $11^\circ$ after the nongravitational effect was accounted for.

Sekanina & Kracht (2015) noted that in the plot of the nominal perihelion latitude against the nominal longitude of the ascending node, most of the 1500 SOHO/STEREO Kreutz sungrazers were located in a crowded branch along an approximately straight line with a slope of $d B_\pi / d\Omega = +0.28$. In addition, two parallel but sparsely populated branches were apparent, passing through the positions that closely matched those of the naked-eye sungrazers C/1970 K1 and C/2011 W3, respectively. Because of large scatter, this crude evidence on three populations of dwarf sungrazers was all that could be extracted from the plot.

The low accuracy of Marsden’s nominal orbits for the 1500 dwarf Kreutz sungrazers was a result of the poor-quality astrometry of the coronagraphic images taken from aboard SOHO. However, given that astrometric positions derived from images taken with the C2 coronagraph are a factor of about five more accurate than positions from images taken with the C3 coronagraph, elimination from the set of all sungrazers whose orbits relied in full or in part on the C3 positional data should markedly improve the quality of the select subset of C2 based orbits, the curtailed length of the orbital arc notwithstanding. Removing, in addition, orbits based on too few C2 positions, I ended up with 193 dwarf Kreutz sungrazers from the years 1997–2010, imaged exclusively with the C2 coronagraph.

The plot of a nominal $B_\pi$ against a nominal $\Omega$ for this carefully screened set of sungrazers in Figure 1 confirms the universal validity of the constant slope $d B_\pi / d\Omega$ of $+0.28$, derived now with an estimated error of less than $\pm 2$ percent. Astonishingly, the plot shows that the number of dwarf-sungrazer populations revealed by this set of select data is substantially higher than the number seen in a plot of the unrestricted set of 1500 SOHO/STEREO objects, thanks unquestionably to the much better data quality.

The comets in the crowded branch, previously assigned to Population I, turn out instead to be distributed among four populations. Next to Population I itself, which extends over a 90$^\circ$ wide range of nominal nodal longitudes, contains nearly 50 percent of the data, and appears to be closely linked to comet C/1843 D1, this branch also contains newly recognized sets of dwarf comets: (i) Population Pre-I, spanning a range of only 16$^\circ$ in the nominal nodal longitude, is centered on $\Omega \approx 15^\circ$ (and may have been detected among the SMM and Solwind sungrazers); (ii) Population Pe, clearly related to comet C/1963 R1 (Pereyra) and designated by the initial letters of the discoverer’s name, extends over a range of nominal nodal longitudes from 345$^\circ$ to 22$^\circ$; and (iii) the already suspected Population Ia, extending in the nodal longitude as widely as Population I, discriminates from the latter quite well over some intervals of $\Omega$, but less well over others. Because C/1963 R1 is a member of Population I, the associated Population Pe is merely a side branch of Population I. Population Pre-I, which was never before suspected to exist and whose naked-eye sungrazer is still awaiting discovery, is likely to have separated from Population I or Pe at some point in the past.

Dwarf sungrazers of Populations II (the main comet C/1882 R1), IIa (C/1970 K1), and III (C/2011 W3) are clearly seen in Figure 1, the widest range of nominal nodal longitudes being exhibited by IIa. Major surprise is the detection, beyond Population III, of two additional, though apparently minor, Populations IIIa and IV. No naked-eye sungrazers are known as yet, similarly to Population Pre-I. From the available data set there is no credible evidence of the existence of additional fringe populations beyond the range from Pre-I to IV, at either end of the range of corrected nodal longitudes ($\Omega \gg 11^\circ$ or $\Omega \ll 305^\circ$).

The averaged orbits of the populations identified among the 193 select data are presented in Table 1. The first two rows offer the computed or adopted (when bracketed) standard ecliptic coordinates of the direction to perihelion, the longitude $L_\pi$ and latitude $B_\pi$, which are essentially constant. Row 4 of the dwarfs columns lists for each population the true longitude of the ascending node $\Omega$ (i.e., corrected for effects of the out-of-plane component of the nongravitational acceleration), which is given by the abscissa of the point on the line fitting the data in Figure 1, whose ordinate equals the standard value of $B_\pi$ and which is marked by an oversized circled star. This true nodal longitude is then used, together with the standard values of $L_\pi$ and $B_\pi$, to compute the true values of the other two angular elements, the argument of perihelion, $\omega$, and the inclination, $i$, which are tabulated, respectively, in rows 3 and 5 of the dwarfs

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8 Most of these orbits are listed in the Catalogue of Cometary Orbits (Marsden & Williams 2008), the rest is available in a number of the 2008–2010 Minor Planet Circular issues.

9 I disregard below a small number of sungrazers whose orbits were based in part on images taken with the coronagraphs on board the two STEREO spacecraft.

10 The adopted rejection limit varied from population to population, being stricter for populations with a greater number of members, and vice versa; see the row $n_{\text{min}}$ in Table 1 below.
Figure 1. Plot of the nominal latitude of perihelion, $B_\pi$, as a function of the nominal longitude of the ascending node, $\Omega$ (equinox J2000), for 193 dwarf Kreutz sungrazers imaged in 1997–2010 exclusively with the C2 coronagraph on board the SOHO Space Observatory; their gravitational orbits were computed by Marsden. The data points cluster fairly tightly along a set of straight lines of a constant slope of $dB_\pi/d\Omega = +0.28$ and refer to one of nine sungrazer populations. Each line crosses the standard perihelion latitude of the population (Table 1) at a point whose abscissa determines the respective population’s true nodal longitude (i.e., corrected for effects of the normal component of the nongravitational acceleration). In the order of decreasing true nodal longitude, the populations are $Pre-I, Pe, I, Ia, II, III, IIIa, and IV$, as depicted in the plot; Population $Pe$ is a side branch of Population $I$. All members of a population are plotted with the same symbol; the exception is Population $IIa$, whose members with anomalously small perihelion distances, $IIa^*$ (Section 5.2), are identified by symbols that differ from the symbols for the remaining members. The position of the true longitude of the ascending node is for each population highlighted by an oversized circled star. Some data points, which were overlapping any of these major symbols or were contributing to one of awkward-looking local clumps, were either removed or slightly shifted along the slope of the fitting lines.

columns of Table 1. The average perihelion distance, $q$, is derived as a mean of the perihelion distances of individual members of each population, which could not be corrected for unknown effects of the transverse component of the nongravitational acceleration. Presented in row 6 of the $dwarfs$ columns, these values of $q$ are not population diagnostic, unlike the true nodal-longitude values. With a single exception (see below), this issue is not examined, but it may warrant a separate investigation in the future. The number of dwarf sungrazers, $N$, the average number of astrometric observations used per sungrazer, $\langle n \rangle$, and the minimum number of observations required, $n_{\text{min}}$, are shown for each population in the last three rows of Table 1.

The magnitude of the nongravitational-acceleration’s out-of-orbit component affecting the motion of a dwarf sungrazer is approximately proportional to the distance of the nominal nodal longitude from the true nodal longitude: the larger the distance, the greater the effect. Figure 1 shows that the members of Populations $Pre-I$
and Pe were subjected to relatively low accelerations, implying that the fragments were near an upper end of the size distribution (perhaps many dozens of meters across); the members of Populations I, Ia, and Ila were subjected to a wide range of accelerations, implying a broad distribution of sizes; and the members of Populations IIIa and IV were exposed to very high accelerations, implying that these fragments were near a lower end of the size distribution (possibly just meters across).

When one or more naked-eye sungrazers are known to be associated with a given population, the orbit of the most prominent one is presented in column main of Table 1. For Population Ia the main object is represented by the model, as described in Section 5. Because of perturbations as well as uncertainties resulting from astrodynamic errors, the dwarfs orbit differs from the main orbit of the same population, although much less than are the differences in both the dwarfs and main orbits between populations. Table 1 shows that the largest dwarfs-to-main differences in the nodal longitude, the element of premier interest, occur for Populations III and Ia (in excess of 2°); whereas the smallest ones, less than 1°, are for Populations Pe, I, and Ila. The difference for Population Ia might in part be due to the fact that the assumptions affecting the model orbit, such as the lobe and neck symmetries (Section 5), were unlikely to be satisfied.

4. ORBITAL EFFECTS OF FRAGMENTATION EVENTS: POPULATIONS AND CLUSTERS

When a cometary nucleus splits into, say, two parts, either fragment leaves the point of breakup with an orbital momentum that differs from the parent’s orbital momentum. This difference is manifested by a separation velocity, whose vector sum with the parent’s orbital velocity at the point of breakup determines the fragment’s heliocentric orbit that deviates from the parent’s. In other words, the fragment has been perturbed, each of its orbital elements by an amount that depends both on the magnitude and direction of the separation velocity vector and, substantially, on the fragmentation event’s orbital location, which is entirely unrestricted.

It turns out that perturbations of the inclination and the nodal longitude vary as the distance from the Sun at fragmentation, whereas perturbations of the orbital period induced by the transverse component of the separation velocity vary as the inverse distance at fragmentation.11 Given the extreme shape of a Kreutz sungrazer’s orbit, its distance from the Sun at aphelion is more than $10^4$ times (1) greater than at perihelion, so that perturbations of the angular elements are by far the largest when the fragmentation event takes place in the general proximity of aphelion, whereas perturbations of the orbital period skyrocket when splitting occurs at, or close to, perihelion. Conversely, it is impossible to appreciably perturb the angular elements of a fragment when the comet breaks up near perihelion, while the orbital period cannot change much on account of a near-aphelion breakup. Another peculiar property of Kreutz sungrazers is their anomalously low orbital velocity at aphelion, of about 20 m s$^{-1}$, very unusual at less than 200 AU from the Sun. As a result, a separation velocity of a few meters per second could cause a fragment’s orbital velocity to differ by more than 10 percent from the parent’s, a sizable relative change that implies a major orbit transformation. And if fragmentation events should be distributed randomly in time, their occurrence at large heliocentric distance is strongly preferred: with a 90 percent probability beyond 60 AU from the Sun and with a 99 percent probability beyond 13 AU.

Marsden (1967) called attention to a tendency of the naked-eye Kreutz sungrazers to arrive at perihelion in clusters, the two most recent ones about 80 years apart.

11 The orbital period is also perturbed by the radial component of the separation velocity; this perturbation depends on the true anomaly, rather than the distance, at the time of fragmentation.
Even though he eventually dismissed this peculiarity as “largely fortuitous,” the above lines suggest that clustering is linked to near-aphelion fragmentation. On the other hand, the existence of major temporal gaps between clusters is linked to near-perihelion fragmentation. By the same token, it is ruled out in principle that two Kreutz sungrazers could simultaneously be members of the same population and the same cluster, even though the strict validity of this rule is mitigated by fragmentation events that occur far from both perihelion and aphelion, as well as by ongoing effects of the outgassing-driven non-gravitational acceleration and possibly by the indirect planetary perturbations. Yet, compliance with the rule was clearly demonstrated by C/1882 R1 and C/1970 K1, the members of the same population belonging to different clusters; and by C/1963 R1, C/1965 S1, and C/1970 K1, the members of the same cluster belonging to different populations.

5. CONTACT-BINARY MODEL FOR THE PROGENITOR, AND ITS CASCADED FRAGMENTATION

As pointed out in Section 1, the rationale for the new conceptual model is predicated in part upon the proposed status of C/1843 D1 and C/1882 R1 as the largest surviving masses of the progenitor. The ∼40 year wide gap between their perihelion times is believed to be the outcome of the conditions at birth and of the orbital evolution. As Population I is associated with C/1843 D1 and Population II with C/1882 R1, one would expect a sizable residual mass associated with Population Ia to have arrived most probably in the 1860s, about halfway between 1843 and 1882. With no sungrazer seen in that window of time, the scenario that one confronts appears to be that of a progenitor comet made up of two mass peaks with a distinct mass deficit in between — clearly inviting comparison with the contact binary that consists of two sizable lobes connected by a narrower neck.

The idea of a contact-binary progenitor is broadly corroborated by gradually accumulating evidence based on spaceborne close-up imaging of cometary nuclei and Kuiper Belt objects. This evidence suggests that the contact binary is a fairly common figure among these objects. It suffices to mention two prominent examples: comet 67P/Churyumov-Gerasimenko (e.g., Sierks et al. 2015) and (486958) Arrokoth (e.g., Stern et al. 2019).

To account for all populations of the Kreutz system with naked-eye, massive fragments of the progenitor, I identify Lobe I with Primary I, a precursor of C/1843 D1, and assume that Lobe II included Primaries II (a precursor of C/1882 R1 and C/1965 S1), IIa (a precursor of C/1970 K1), and III (a precursor of C/2011 W3), as shown in Figure 2. The neck is identified with Primary Ia — the precursor of Population Ia. The unknown precursors of Populations Pre-I (part of Lobe I), IIa, and IV (parts of Lobe II) are omitted; Population Pe, as a side branch of Population I, derives from Lobe I. The model postulates that in the course of the Kreutz system’s initial fragmentation event the lobes separated from the neck with opposite velocities of equal magnitude.

5.1. Initial Breakup of the Progenitor

In the following I assume that the two lobes of the rotating progenitor of uniform density were spheres of equal size and that the progenitor’s center of mass coincided with the center of mass of the neck, whose figure was symmetric relative to the two lobes (Figure 2). The progenitor is proposed to have broken up near aphelion, assumed nominally at ∼170 AU from the Sun, into the three fragments, as either lobe separated from the neck at the same rate in exactly opposite directions, while the neck itself continued to move in the orbit of the pre-breakup progenitor. In practice it is of course possible (if not likely) that the contact binary split into only two fragments, with the neck remaining attached to one of the lobes (to break off later) or the plane of fissure running through the neck. It is obviously easier to accept splitting of a contact binary rather than a quasi-spherical nucleus (as was the case with the two-superfragment model; Sekanina & Chodas 2004).
Although nominally unknown, the orbit of the pre-breakup progenitor — maintained in the proposed scenario as the orbit of Primary Ia — can be constructed from the orbits of Lobe I and Lobe II approximated by the orbits of C/1843 D1 and C/1882 R1, respectively. In an effort to find a set of orbital elements for the progenitor $\mathfrak{R}$, I have searched for (i) a particular value of the out-of-orbit (normal) component of the separation velocity such that it fits the differences in $\omega$, $\Omega$, and $i$ between Primaries Ia and I, and that, at the same time, this velocity component of equal magnitude but opposite sign fits the differences in the three elements between Primaries Ia and II; and (ii) a particular value of the transverse component of the separation velocity such that it fits the difference in $q$ between Primaries Ia and I, and that, at the same time, this velocity component of equal magnitude but opposite sign fits the difference in $q$ between Primaries Ia and II.\(^{14}\) The radial component of the separation velocity vector could not be determined because it primarily contributed to the perihelion arrival time, which, as a matter of course, is also subject to the indirect planetary perturbations and nongravitational forces.

The first four rows of Table 2 refer to the initial breakup of the progenitor $\mathfrak{R}$. The large perturbations of Lobes I and II in the angular elements, of up to nearly 10°, are fitted with an out-of-plane component of the separation velocity of less than 2 m s\(^{-1}\) and, similarly, the fairly sizable perturbations of the lobes in the perihelion time examined Type of data

| Fragmentation event examined parent→fragment\(^{a}\) | Type of data | Orbit: fragment minus parent | Fragmentation time\(^{b}\) | Component of $V_{\text{sep}}$ (m s\(^{-1}\)) | Nongrav. accel, $\gamma_0$ (units)\(^{d}\) |
|---|---|---|---|---|---|
| $P_{\text{Ia}} \rightarrow P_{\text{I}}$ | observed | $+7^\circ$ | $+8^\circ$ | $+10^\circ$ | $-0.23$ | $-\Delta_0$ | $\cdots$ | $t_{\text{eph}}$ | $(0.00)$ | $-1.80$ | $-1.73$ | $\cdots$ |
| $\mathfrak{R} \rightarrow \text{Li}$ | modeled | $+7.3$ | $+9.0$ | $+1.0$ | $-0.23$ | $\cdots$ | $t_{\text{eph}}$ | $(0.00)$ | $+1.80$ | $+1.73$ | $\cdots$ |
| $P_{\text{Ia}} \rightarrow P_{\text{II}}$ | observed | $-5.8$ | $-7.1$ | $-1.4$ | $+0.27$ | $+39.5 - \Delta_0$ | $\cdots$ | $t_{\text{eph}}$ | $(0.00)$ | $-1.80$ | $-1.73$ | $\cdots$ |
| $\mathfrak{R} \rightarrow \text{Li}$ | modeled | $-5.7$ | $-7.1$ | $-1.4$ | $+0.27$ | $\cdots$ | $t_{\text{eph}}$ | $(0.00)$ | $+1.80$ | $+1.73$ | $\cdots$ |
| $P_{\text{Ia}} \rightarrow P_{\text{III}}$ | observed | $-8.3$ | $-10.7$ | $-2.9$ | $+0.24$ | $(+87.7)$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ |
| $\mathfrak{L} \rightarrow \text{IIa}$ | modeled | $-8.3$ | $-10.7$ | $-3.1$ | $+0.24$ | $\cdots$ | $t_{\text{eph}} + \Delta_1$ | $(0.00)$ | $+1.35$ | $+4.30$ | $\cdots$ |
| $P_{\text{Ia}} \rightarrow P_{\text{IIIa}}$ | observed | $-7.8$ | $-10.6$ | $-4.7$ | $-0.72$ | $(+41.6)$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ |
| $\mathfrak{L} \rightarrow \text{IIa}$ | modeled | $-7.8$ | $-10.6$ | $-4.7$ | $-0.72$ | $\cdots$ | $t_{\text{eph}} + \Delta_2$ | $(0.00)$ | $-5.30$ | $-3.60$ | $\cdots$ |
| $P_{\text{Ia}} \rightarrow P_{\text{IIIb}}$ | observed | $-8.3$ | $-10.7$ | $-2.9$ | $-0.24$ | $\cdots$ | $t_{\text{eph}} + \Delta_1$ | $(0.00)$ | $-1.80$ | $+2.66$ | $\cdots$ |
| $\mathfrak{L} \rightarrow \text{IIb}$ | modeled | $-8.3$ | $-10.7$ | $-3.1$ | $-0.24$ | $\cdots$ | $t_{\text{eph}} + \Delta_2$ | $(0.00)$ | $-2.02$ | $+2.79$ | $\cdots$ |
| $P_{\text{IIIa}} \rightarrow P_{\text{IIIb}}$ | observed | $-7.8$ | $-10.6$ | $-4.7$ | $-0.24$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ |
| $\mathfrak{L} \rightarrow \text{IIb}$ | modeled | $-7.8$ | $-10.6$ | $-4.7$ | $-0.24$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ | $\cdots$ |

Notes.

\(^{a}\) Primary sungrazer of Population X, $P_{\text{X}}$, is presumed to have moved in the orbit of the population's most prominent residual mass, listed in Table 1: $P_{\text{I}} = C/1843 \text{D1}$, $P_{\text{II}} = C/1882 \text{R1}$, $P_{\text{III}} = C/1970 \text{K1}$, and $P_{\text{IIIa}} = C/2011 \text{W3}$. The adopted elements for the other comets are taken from Sekanina & Chodas (2004); for equinox J2000 they are: $\omega = 86^\circ.2$, $\Omega = 7^\circ.9$, $i = 144^\circ.6$, and $q = 1.09 \text{R}_\odot$ for C/1863 R1; $\omega = 85^\circ.1$, $\Omega = 0^\circ.5$, $i = 144^\circ.5$, and $q = 1.19 \text{R}_\odot$ for C/1868 C1; and $\omega = 83^\circ.5$, $\Omega = 4^\circ.6$, $i = 144^\circ.4$, and $q = 1.04 \text{R}_\odot$ for C/1887 B1. Comets' designations are abbreviated by ignoring C/ and first three digits of year, e.g., 301 = C/1843 D1.

\(^{b}\) It is assumed that sizable residual mass of progenitor's neck reached perihelion at some time between perihelion times of C/1843 D1 and C/1882 R1; this time is expressed by a quantity $\Delta_t$, constrained formally by a condition $0 < \Delta_t < +39.5$ yr.

\(^{c}\) Time $t_{\text{eph}}$ refers to aphelion of progenitor's neck breakup, presuming that Lobe II continued to fragment soon after initial breakup of progenitor (0 < $\Delta_t < \Delta_\text{eph} < +39.5$). Aphelion distance of about 170 AU is assumed. Precursor's perihelion time $t_p$ is in AD 363 for separation of P(301) from P, but in 11th–12th centuries for separations of P(0c1) from P(301) and C/1887 B1 from P(0c1).

\(^{d}\) Assumed to vary inversely as square of heliocentric distance; 1 unit = $10^{-5}$ solar gravitational acceleration = $0.593 \times 10^{-5}$ cm s\(^{-1}\) at 1 AU from the Sun = 0.296 $\times 10^{-5}$ AU day\(^{-2}\) at 1 AU from the Sun.

\(^{e}\) At heliocentric distance of about 70 AU.

\(^{f}\) At heliocentric distance of about 40 AU.

\(^{g}\) At heliocentric distance of about 50 AU.

\(^{14}\) The separation velocity is customarily expressed in an RTN coordinate system referred to the parent’s center and its orbital plane; the N axis points to the north orbital pole, the R axis away from the Sun; and the T axis in a direction such that RTN is a right-handed orthogonal system. The differences in the orbital elements
helion distance, of nearly 0.3 $R_\odot$, are fitted with a transverse component of the separation velocity of less than 2 m s$^{-1}$. Thus, very modest rates of separation readily explain nominally large orbital differences between Populations I and II, in line with the general arguments in Section 4. The solution for the angular elements is particularly impressive, because a single parameter closely approximates the effects in three elements of either lobe, i.e., six variables! The tabulated data also show that the symmetry of the lobes’ separation velocity does not imply a symmetry of the resulting perturbations of the elements.

I now illustrate this exercise on the longitude of the ascending node. Table 1 shows that $\Omega = 3\degree7$ for Primary I in the column main of Population I and $\Omega = 347\degree7$ for Primary II in the column main for Population II, so that the difference Primary II minus Primary I equals $-16\degree0$. For the progenitor’s breakup at aphelion, the best orbital model for Primary Ia, found by trial and error, included Lobe I’s out-of-plane separation velocity of $-1.73$ m s$^{-1}$ (and Lobe II’s out-of-plane separation velocity of $+1.73$ m s$^{-1}$). This model’s longitude of the ascending node for Primary Ia was $354\degree8$, so that Primary I’s value of $\Omega$ differed from it by $+8\degree9$, while Primary II’s value of $\Omega$ by $-7\degree1$, as shown, respectively, in the first and third rows of Table 2. The model predicted that, relative to the progenitor $R$, the longitude of the ascending node of Lobe I should have been perturbed by $+9\degree0$ and of Lobe II by $-7\degree1$, as shown, respectively, in the second and fourth rows of Table 2. The model’s fit to $\Omega$ is thus perfect for Lobe II and good to $0\degree1$ for Lobe I.

5.2. Subsequent Fragmentation Events

Not counting minor pieces, the initial breakup is expected to have nominally resulted in two or three fragments: the two lobes and, possibly, the separate neck, with all or nearly all mass concentrated in the lobes in either case. The event is likely to have been chaotic and its products certainly not perfectly symmetric, which could in part explain the average orbit of the dwarf sungrazers in Population Ia deviating slightly from the orbit of the progenitor’s symmetric model (Table 1).

In line with the proposed classification of the Kreutz system (Section 2), it is contemplated that it was Lobe II that, following the initial breakup, continued to fragment far from the Sun probably during the same orbit. In the earliest secondary fragmentation event, most of the mass of Lobe II became Primary II (a precursor of C/1882 R1 and C/1965 S1), a smaller part in a detached fragment consisted of the futures Primaries IIa (a precursor of C/1970 K1), III (a precursor of C/2011 W3), and hypothesized primaries of Populations IIIa and IV. The transverse component of the separation velocity of Primary IIa from Primary II was again less than 2 m s$^{-1}$, the out-of-orbit component almost exactly 3 m s$^{-1}$, both deemed plausible. Lobe II appears to have been more susceptible to fragmentation at smaller heliocentric distances.

Given the large difference between the perihelion distances of C/1970 K1 and C/2011 W3, there are two possibilities for explaining the parent to C/2011 W3. If a separation velocity exceeding 5 m s$^{-1}$ is not considered unacceptably high, Primary III may have separated from Primary IIa, perhaps soon after the breakup of Lobe II. If this velocity is deemed unacceptably high, one can contemplate that, in addition to Primary IIa, another fragment that I refer to as Primary IIa$^*$ was released from Lobe II into an orbit with a perihelion distance smaller than that of Lobe II, and that Primary III was subsequently released from Primary IIa$^*$. In this scenario the separation velocity would remain within about 3 m s$^{-1}$, comparable to those from the progenitor and Lobe II. Possible fragmentation scenarios involving Lobe II and Primaries IIa, IIa$^*$, and III are listed in rows 5–12 of Table 2.

Primary IIa$^*$ may not be a purely theoretical construct. To examine its potential footprint in the data, I plot, in the upper part of Figure 3, the perihelion distance against the nominal longitude of the ascending node for

![Figure 3](image-url)

**Figure 3.** Upper panel: Relation between the nominal longitude of the ascending node, $\Omega$ (equinox J2000), and the perihelion distance, $q$, for 24 dwarf Kreutz sungrazers of Population Ia imaged exclusively by the C2 coronagraph of the SOHO Observatory. The data are sharply split into two subsets: (i) a major one with $q > 1.4 R_\odot$, which includes objects in orbits ranging from those similar to C/1970 K1 to those similar to Primary IIa$^*$ (see the text); and (ii) a minor one with $q < 1.2 R_\odot$, which contains objects in orbits of a type referred to in the text as Primary IIa$^*$; they may be part of transition to Population III (C/2011 W3). Lower panel: Histogram of perihelion distances of the 24 dwarf sungrazers, showing a sharp peak of Primary IIa$^*$ and a broad bulge of the major subset, whose boundaries are approximately delineated by the perihelion distances of C/1970 K1 and Primary IIa$^*$.
the 24 dwarf Kreutz sungrazers of Population IIa. The distribution of objects in the plot is startling: 18 points cluster in an area between 320° and 20° in the nodal longitude and between 1.4 \( R_\odot \) and 2.0 \( R_\odot \) in the perihelion distance, while the six remaining points are located completely outside the area of the cluster, confined to a narrow interval of perihelion distances between 1.0 and 1.2 \( R_\odot \), thus closely matching the perihelion distance of \( C/2011 \) W3. Since the nominal nodal longitudes are merely a measure of the nongravitational effect and all refer to nearly the same true nodal longitude of about 336° (Table 1), the plot at the top of Figure 3 effectively collapses into a histogram displayed in the lower panel. The cluster now becomes a very broad bulge on the right, while the six isolated points make up a sharp peak on the left; the two features are separated by a wide gap with no sungrazers between 1.2 and 1.4 \( R_\odot \). Comets C/1970 K1 and Primary IIa*, introduced above, pinpoint approximately the boundaries of the bulge, while the sharp peak can be equated with debris of what I refer to as Primary IIa*. Figure 1 shows that these six objects with anomalously small perihelion distance fit the same relationship between \( \Omega \) and \( B_\nu \) as the other members of Population IIa, but their nominal nodal longitudes are more distant from the true value of \( \sim 336^\circ \). It is not clear whether comet C/2011 W3 and Primary III are more closely linked to Primary IIa*, as proposed in Table 2, or to the hypothetical Primary IIa*. This case serves to illustrate the enormous complexity of the Kreutz system's structure.

On the other hand, Table 2 offers a fairly straightforward model for the history of comet C/1963 R1, which was a major hurdle to Marsden's (1989) fragmentation scenario. Rows 13–14 suggest that the comet's precursor, P(3R1), separated, after the progenitor's breakup, from Lobe I on its path to perihelion, which it should reach almost simultaneously with the other fragments of the progenitor (Section 5.3). Since the whereabouts of P(3R1) depend on the history of the Kreutz system as a whole, a description of its further evolution is postponed to Section 5.3.

Although not tabulated, Primary III is the likely parent to Primary IIIa and Primary IIIa the likely parent to Primary IV. Preliminary computations suggest that the out-of-orbit separation velocities would amount to 3.7 m s\(^{-1}\) and 3.4 m s\(^{-1}\), respectively. The remaining two rows of Table 2 show that the applied technique fits equally well more recent fragmentation events nearer perihelion, in which the parent to C/1880 C1, P(0C1), split off from the parent to C/1843 D1, P(3D1), and, later still, C/1887 B1 split off from the parent it had in common with C/1880 C1. It is noted that the timing of the tabulated fragmentation event P(3D1)→P(0C1) implies that X/1106 C1 should have arrived at perihelion double. However, as long as the radial component of the separation velocity was much smaller than 1 m s\(^{-1}\), the main comet and the companion passed perihelion only a fraction of an hour apart.

5.3. Pedigree Chart, Key Historical Sungrazers, and Estimate of the Kreutz System's Age

The products of a sequence of fragmentation events are displayed in a pedigree chart, which describes possible relationships among fragments of successive generations. Because the perceived relationships are not necessarily unambiguous, neither is the pedigree chart. The chart in Figure 4 excludes Populations Pre-I, IIIa, and IV because no naked-eye sungrazer is known to be associated with them. For the same reason the chart does not single out historical precursors of the 19th–21st century naked-eye members of the Kreutz system that the classification scheme is predicated upon.

Of historical objects, the widely recognized candidate for the Kreutz system membership is the extensively observed comet X/1106 C1. Even though no orbital elements could be derived, its reported motion across the sky was deemed consistent with the expected path of a Kreutz sungrazer by Hasegawa & Nakano (2001). However, whether X/1106 C1 was a parent to C/1882 R1 and C/1965 S1 (i.e., Population II) or to C/1943 D1 and other members of Population I remains controversial. The former possibility was contemplated by Kreutz (1888, 1901), advocated by Marsden (1967), and independently considered by Sekanina & Chodas (2004); in Figure 4 the comet would be identical with Precursor C. Marsden predicated this preference on his result of integration back in time of the accurately-determined orbit of C/1965 S1. He derived September 1116 as the time of the comet’s previous perihelion\(^{10}\) and noted that this was “remarkably close to February 1106,” the arrival time of X/1106 C1. At first sight, the argument looks reasonable. But what if Marsden’s orbital computations were more accurate than he himself believed? This is a distinct possibility given the very small error of the comet’s orbital period, amounting to just \( \pm 0.1 \) years and placing X/1106 C1 at 5\( \sigma \).

Comet C/1982 R1 was less helpful because at perihelion it split into six major fragments (Kreutz 1888) and its pre-split orbit was quite uncertain. Marsden’s (1967) integration of Kreutz’s (1891) nonrelativistic orbit for nucleus B gave the previous perihelion time in April 1138, and the eccentricity had to be adjusted to determine the differences between the orbital elements of the two comets in the early 12th century. It turned out that the differences closely mimicked those between the two nuclei of C/1965 S1, a coincidence that Marsden regarded as virtual proof that C/1965 S1 split off from a common parent at some time in the early 12th century. It did split off from their shared parent in the early 1100s, regardless of whether or not it was X/1106 C1. Unfortunately, this argument is not valid because the orbital differences between the two fragments of C/1965 S1 were products of uncertainties in the positional data used to compute the fragments’ orbits, not of the conditions at the time of fragmentation. As the differences amounted to about 0°01 in the angular elements and about 0.001 \( R_\odot \) in the perihelion distance, the separation velocity required to fit them if the breakup occurred within hours of perihelion equals 50–100 m s\(^{-1}\) or more and is thus hopelessly much too high. The bottom line is that the two comets did split off from a common parent at some time in the early 12th century, but not because of the correlation between the differences in the orbital elements.

\(^{15}\) Population Ia is included because of its special status.

\(^{16}\) This time was obtained by integrating the nonrelativistic orbit of nucleus A of comet C/1965 S1; a slightly different time resulted by integrating the relativistic orbit.
Figure 4. Example of a pedigree chart for the contact-binary progenitor assumed to have broken up into three pieces: two lobes and the neck. Based on evidence from the naked-eye Kreutz system members in the 19th–21st centuries, the scenario shows that Lobe I split into C/1843 D1 and a fragment (referred to as Precursor A) that subsequently split again into C/1963 R1 and another fragment, Precursor B or the parent to C/1880 C1 and C/1887 B1. The debris of comet C/1843 D1 is detected as SOHO dwarf comets of Population I, whereas the debris of C/1963 R1 ended up in Population Pe, a side branch to Population I. The scenario for Lobe II includes three major fragments: one was a parent to C/1882 R1 and C/1965 S1, referred to as Precursor C; the others were Primaries IIA, surviving as C/1970 K1, and a hypothetical Primary IIA* that is presumed to have later broken up into Primary III, surviving as C/2011 W3, and an unknown sungazer. The debris of Precursor C includes SOHO dwarf sungazers in Population II, while the debris of Primaries IIA and III contains dwarf sungazers in Populations IIA and III, respectively.

On the other hand, Marsden made a point by arguing that because equating the post-split position of the center of mass of C/1965 S1 with the primary nucleus was an approximation, the orbit integration back over more than eight centuries could involve additional hidden uncertainties, not reflected in the formal mean error of the orbital period. This line of reasoning was further pursued by Sekanina & Chodas (2002) in their effort to more closely examine whether X/1106 C1 was indeed the shared parent of C/1882 R1 and C/1965 S1. They adjusted the orbital position of the center of mass of either comet relative to the positions of the observed fragments to match the presumed perihelion time of X/1106 C1, 1106 January 25 according to Hasegawa & Nakano (2001), and interpolated the orbital elements proportionately. If X/1106 C1 was the parent, the positions of C/1882 R1 and C/1965 S1 should have essentially merged at the point of fragmentation. One of course expects that the merging should have occurred at, or very close to, perihelion. Instead, Sekanina & Chodas found that the positions of the two comets were nearest each other 18 days after perihelion, at 0.75 AU from the Sun, when the orbital velocities of the nascent fragments differed by 7 m s\(^{-1}\). Since these results are incompatible with the events of fragmentation observed in both 1882 and 1965, one could interpret the anomalous solution for the 1106 breakup as a product of incorrect starting assumptions, i.e., by admitting that X/1106 C1 was not the parent to C/1882 R1 and C/1965 S1.

The alternative scenario, in which X/1106 C1 was assumed to be the parent to, or the preceding appearance of, C/1843 D1, was adopted in Sekanina & Chodas (2007). In this case, the parent to C/1882 R1 and C/1965 S1 should have reached perihelion years after X/1106 C1. Either way, two bright Kreutz sungazers should have arrived within two decades or so of each other in the late 11th to early 12th century, but only one was recorded. Whether the other arrived before or after X/1106 C1, the chance is that it passed perihelion in broad daylight between late May and mid-August and was missed.\(^{17}\) Another dilemma, the whereabouts of the surviving mass of the progenitor’s neck, is of lesser con-
cern because of the possibility of its prior disintegration or sticking, at least temporarily, with one of the progenitor’s two lobes, as already pointed out.

To pinpoint the parents to X/1106 C1 and its missing sibling, which should have arrived at perihelion in the 4th or 5th century, is extremely difficult. Sekanina & Chodas (2007) suggested that the comets of AD 423 or AD 467 might have been good candidates, as both objects were ranked fairly high as potential Kreutz sungrazers by England (2002) and the first was also on Hasegawa & Nakano’s (2001) list of Kreutz suspects. However, a linkage of either of the two comets with X/1106 C1 showed that the subsequent return to perihelion occurred much too early and that a high nongravitational acceleration would be required to significantly stretch the orbital period in order to fit the perihelion time of C/1843 D1. Another problem with the two 5th century candidates is of the same nature as with the 11th/12th century sungrazers: for neither of the comet of 423 nor 467 is there any record of a second sungrazer (or two more sungrazers to account for the neck), passing perihelion at most a year or so — but possibly as little as days — apart. Interestingly, in the Sekanina & Chodas (2004) model the two superfragments passed perihelion one week apart in AD 356 and six years apart in the beginning of the 12th century. However, the two-superfragment model allowed separation velocities of up to ~10 m s$^{-1}$, much higher than contemplated in this paper.

Given the disappointing experience with the 5th century contenders, I now inspected the general catalogue of ancient and medieval comets by Kronk (1999), which is Kreutz system indifferent. I focused my attention on the critical period of time centered crudely on the middle of the 4th century, between AD 340 and 370, and found two possible candidates, presented below. One is much more promising than the other, but very little information is available on either.

One candidate is the comet of AD 349, extending into 350. Listed, next to Kronk, by both Ho (1962) and England (2002), this could be a case of three independent objects separated by two-month wide gaps. If so, only the comets at either end might be Kreutz members, but not the middle one. Of interest is Kronk’s comment that the preceding comet in his catalogue, in the year 343, was almost exactly six years earlier observed at the same location as the first of the three sightings in 349/350. On the other hand, England assigned the 349 entry low Kreutz-system membership ranking and did not list the 343 comet at all. Hasegawa & Nakano (2001) did not include either one in their table of Kreutz suspects, probably because of the lack of adequate data that they needed to test compatibility with the sungrazing orbit. Yet, the pair of potential sungrazers in 349/350 offers a possible scenario for the first appearance of the progenitor’s separated lobes, with the whereabouts of the neck still uncertain. The four-month wide gap would imply a radial component of the separation velocity of about 1 m s$^{-1}$ in the opposite directions for the two lobes, if the progenitor fragmented close to its previous passage through aphelion.

It is possible that the comet of 343 was an early fragment of the progenitor. For example, a fragment separating from the comet of 372 BC at about 3 AU from the Sun after perihelion (within ~5 months or so) with a radial component of the separation velocity of ~1 m s$^{-1}$ should indeed have arrived at perihelion about 6 years prior to the two lobes. In the following returns to perihelion the fragment would continue to masquerade as a piece of the neck, because for a breakup at 3 AU the transverse and normal components of the separation velocity of a few meters per second would cause only very minor changes in the perihelion distance and the angular elements relative to the progenitor’s.

The other candidate that could deliver X/1106 C1 and its missing sibling from the early 12th century arrived in AD 363. It was not the eastward traveling comet seen in China between late August and late September (Ho 1962), at the time of the year when a Kreutz sungrazer at its brightest would be moving in the southwesterly direction. Rather, what caught my attention was the plural in an intriguing (though brief and vague) remark by Ammianus Marcellinus, a Roman historian, who put on record that “in broad daylight comets were seen” — not a comet. All four secondary sources that I have consulted — Barrett (1978), Kronk (1999), Ramsey (2007), and Seargent (2009) — offer the quote, but only Ramsey and Seargent comment on the time of sighting. Unfortunately, they differ: Ramsey says August to September 363, whereas Seargent claims late that year, observing that Kreutz sungrazers “very late in the year would have had a strong southerly declination and might have been seen from Italy only in the daytime close to perihelion.” As Ramsey mentions “possible corroborating evidence from Asia,” it is obvious that the time slot he provides comes from the Chinese comet dismissed above. Inspection of Ammianus’ Book XXV, translated by Rolfe (1940), indicates that the narrative about the daylight comets follows his description of the arrival of Roman Emperor Jovian and his army at Antioch on the Orontes in the aftermath of the Battle of Samarra in the Sassanian Empire and the sudden death of Emperor Julian. It is known that Jovian, accompanied by Ammianus, entered Edessa in September (Elton 2018) and Antioch in October 363 (Lensi 2002). Ammianus stayed at Antioch, while Jovian left the town (“in the dead of winter” according to the historian) to continue his ill-fated journey to Constantinople. Thus, August or September could not be the time of sighting of the daytime comets. Rather, the celestial splendor was witnessed by Ammianus at Antioch either toward the end of October or later still in 363. The location was in fact unimportant, as Seargent’s argument applies to much of the northern hemisphere, not just Italy. One can guess that the event was a grand daytime spectacle, whose path across the sky could have resembled that of Lovejoy’s sungrazer in 2011.

19 Hasegawa (1979) suggested that this was the previous appearance of C/1969 Y1 (Bennett), but Seargent (2009) argued that the comet would have been too faint to detect with the naked eye.

20 Barrett (1978) erroneously dated another brief note by Ammianus on “comets blazing” to AD 364. Coming from the historian’s Book XXX (Rolfe 1939), which begins with the year 374, the reference may pertain to (in part?) the comet of 375, as pointed out by Ramsey (2007).

21 While accepting the comets’ steep southerly plunge after peri-
Remarkably, Ammianus’ daylight comets satisfy three exacting conditions at once: (i) the multitude of fragments, whether or not appearing essentially simultaneously, readily avoids the disconcerting dilemma of missing sibling(s); (ii) the daytime sighting is consistent with the comets’ expected exceptionally great brightness (X/1106 C1, C/1843 D1, and C/1882 R1 were all seen in broad daylight near perihelion); and (iii) the year of arrival offers a point in time that fits just about perfectly the sequence of perihelion returns of the main surviving mass of Lobe I: from the progenitor in the year 372 BC;\(^{22}\) to an essentially concurrent appearance with Lobe II in AD 363;\(^{23}\) to the first separate show as X/1106 C1;\(^{24}\) and, finally, to the most recent, equally impressive display as C/1843 D1 (for which \(t_\pi = 1843.2\)); it is predicted to return late in the 26th Century. As seen from Table 3, the orbital periods between the consecutive generations are nearly constant and the variations so small that they probably could be accounted for by the indirect planetary perturbations. The comets of 363 appear to be a distinctly better choice for the Kreutz sungrazers than the comets of 349, anchoring X/1106 C1 firmly in Lobe I (i.e., Population I). I might venture to suggest that *if it were not for Ammianus’ utter failure to attend to any detail whatsoever in recording this celestial episode, his daylight comets could have become the smoking gun that I have long been looking for*.  

The motion of the main residual mass of Lobe II — a precursor of C/1882 R1, C/1965 S1, C/1970 K1, and C/2011 W3 — is in this scenario related to the motion of Lobe I by assuming a differential radial nongravitational acceleration driven by the sublimation of water ice, whose magnitude is given by Marsden et al.’s (1973) parameter of \(A_1 = +0.93 \times 10^{-10} \text{AU day}^{-2}\). It implies that Lobe II was about 50 km across. The missing sibling of X/1106 C1 would have passed perihelion most probably in mid-1119, implying for the two most recent orbital periods of the residual mass of Lobe II about 756 yr and 763 yr, respectively. It would be predicted to return in the second half of the 27th century, about 80 years after the main residual mass of Lobe I, but because C/1882 R1 was subjected to extensive fragmentation, the debris will be returning over several centuries late in the third millennium.

The proposed model is apt to fit a wide range of possible fragmentation scenarios for the contact-binary progenitor. While Ammianus noted neither the number of comets seen in broad daylight nor the extent of their appearance in time, the model is consistent with up to at least seven major fragments (Populations I, Ia, IIa, III, IIIa, and IV), not counting additional, smaller ones with shorter lifetimes. In AD 363 the lobes should have arrived only days apart, if the radial component of their separation velocity was very low (much lower than 1 m s\(^{-1}\)); but months apart for a separation velocity of about 1 m s\(^{-1}\) for a breakup at aphelion. The time gap between the arrivals of the lobes should be greater, if the progenitor broke up before aphelion, but smaller if after aphelion. The differences in the angular orbital elements constrain the time of fragmentation event to within about 300 years of aphelion, at more than \(\sim 100 \text{AU}\) from the Sun, if the separation velocity was to be kept well below 5 m s\(^{-1}\). A nearly simultaneous arrival at the subsequent perihelion should imply the separation velocity vector essentially in the plane normal to the radius vector and the spin axis pointing approximately at the Sun.  

In terms of the propensity to *bulk* fragmentation, Lobe I and Lobe II were not alike. The disparity is apparent in Figure 1, in which the longitudes of the ascending node for Populations I, Pe, Pre-I, and (with the usual caveat) Ia, related to Lobe I, cluster closer to one another; whereas for Populations II, Ia, III, IIIa, and IV, linked to Lobe II, the nodal longitudes are stretched wider apart. Quantitatively this unevenness is reflected in the range of nodal longitudes: 14° for Lobe I and 44°

### Table 3

| Generation or year | Comet ID | Comet name or description | Status | Perihelion time (yr) | Orbital period (yr) |
|--------------------|----------|---------------------------|--------|---------------------|---------------------|
| 1                  | 372 BC   | Aristotle’s Comet         | Contact-Binary Progenitor | -371.0             | 734.9              |
| 2                  | AD 363   | Daylight Comets of Ammianus | Separated Lobes I, II\(^a\) | 363.9              | 742.2              |
| 3                  | X/1106 C1 | Great Comet of 1106       | Primary of Population I   | 1106.1             | 737.1              |
| 4                  | C/1843 D1 | Great March Comet of 1843 | Most Massive Fragment of X/1106 C1 | 1843.2             | (∼738)             |
| 5                  | ........... | (Predicted)               | Return of Residual Mass of C/1843 D1 | (∼2581)            |                    |

Note.

\(^{a}\) Plus potentially additional fragments, such as Primaries Ia, Iia, III, Pe, etc.
for Lobe II (Table 1). Because of the dependence of the nodal-longitude perturbations on heliocentric distance (Section 4), the discrepancy is easy to interpret: the material making up Lobe I fragments closer to the Sun than the material making up Lobe II. Yet, Table 2 shows that closer does not mean close: the Population I comets separating from their common parent with C/1843 D1 appear to have done so at estimated heliocentric distances of 40–70 AU, less than one half the distance to aphelion. On the other hand, C/1882 R1, the presumed main residual mass of Lobe II, and C/1965 S1 separated from their common parent right at perihelion (Marsden 1967), as did the six secondary nuclei of C/1882 R1 and the nuclear pair of C/1965 S1. This behavior contrasts with C/1843 D1, which was never observed double or multiple, even though the dominant contribution of Population I (associated with C/1843 D1) to the SOHO dwarf sungrazers could mean that the tendency of the Lobe I material was to fragment directly into smaller-size debris.

A major fragment whose birth is in the proposed fragmentation scenario linked to Lobe I is C/1963 R1. Its early history, outlined briefly in Section 5.2, ended with a precursor P(3+1) arriving at perihelion essentially simultaneously with Lobe I. To match the scenario predicating on Ambrian’s brief account, the precursor should have reached perihelion in late AD 363, contributing to the show of daylight comets and being a subject to more fragmentation at that time. One of the precursor’s fragments is predicted to have been thrust into an orbit with a period of 678 yr, having acquired a minor change in the momentum equivalent to \( \Delta P = -57 \) yr. This object is then envisioned to have returned to perihelion as one of the two comets of AD 1041 (England 2002), probably the Korean-Byzantine one, observed first on September 1 and listed as a Kreutz comet suspect by Hasegawa & Nakano (2001). New fragments were given birth by the comet at this return to perihelion. A significant change in the momentum of one fragment, equivalent to \( \Delta P = +244 \) yr, would have moved it into an orbit with a period of 922 yr, making it to return to perihelion as C/1963 R1. Marsden (1989) determined that the “original” barycentric orbital period of C/1963 R1 was 910 ± 13 yr. The bulk debris produced in the course of, and following, the event of 1041 became Population IC of dwarf Kreutz sungrazers.

Although C/1843 D1 and C/1882 R1 have been debated in the literature from just about every possible angle, one issue has surprisingly been seldom addressed: Which of the two comets was more spectacular? Given that they arrived nearly 40-years apart and at different times of the year (and therefore under different viewing conditions), their comparison is precarious. Besides, there is the question of how exactly is the perceived level of performance measured among comets? By the overall impression of the object on the observer? By its apparent or intrinsic brightness? By the dimensions, such as the tail length, or by the tail prominence? All criteria are questionable as they depend on the circumstances under which the comets are judged, including the time of sighting, the observer’s location, etc. One would expect that comet observers and aficionados who had the opportunity to see both sungrazers might have commented on their impressions (or be quoted by others to have done so), but in one case that I followed the result was very disappointing. Walsoun’s (1996) comprehensive monograph on the life of Lewis Swift (1820–1913) describes that the Great March Comet of 1843 “dazzled” him at the age of 23, but does not say a word about his viewing the Great September Comet of 1882 at the age of 62! A systematic search for more positive evidence is beyond the scope if this investigation, but to illustrate the diversity of opinion on the grandeur of the two sungrazers, I offer two examples. On the one hand, Lefroy (1882), regarding C/1882 R1 erroneously as the return of C/1843 D1, reported that his friend, a witness to both celestial spectacles, had conveyed in a letter that “he does not consider the comet more conspicuous on this occasion than it was in 1843.” On the other hand, Eddie (1883), a South African amateur astronomer, remarked on C/1882 R1 that it was “the most brilliant comet of the … century, not excepting the great comet of 1843, which was … not … visible during the whole day.” More than a century later, two examples illustrate that experts still have a problem to agree: while Moore (2000) maintains that “[t]he brightest comet of modern times was probably that of 1843,” it is C/1882 R1 that in the verdict of Bortle (1998) was the “[b]rightest, most extraordinary comet in over 1000 years.” The results of my photometric study (Sekanina 2002) suggest that C/1843 D1 may have been intrinsically fainter than C/1882 R1, but because of the large, poorly understood systematic errors (integrated brightness vs brightness of nuclear condensation) of the sporadic magnitude estimates available for either object, the former in particular, and the uneven role of forward scattering effects, the issue should not be regarded as conclusively resolved. Comet C/1882 R1 was under observation much longer than C/1843 D1, but this disparity was a consequence of the former comet’s fragmentation at perihelion, which greatly augmented the surface area available for activity.

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25 This is contrary to the two-superfragment model of Sekanina & Chodas (2004), in which C/1963 R1 derived from Superfragment II, equivalent here to Lobe II.
26 The reader who deems this change in the orbital period excessively large is reminded that the results of Kreutz’s (1891) orbital computations implied \( \Delta P = 204 ± 5 \) yr for the fragment pair of A and C of C/1882 R1 and \( \Delta P = 284 ± 7 \) yr for the pair of A and D. Marsden’s (1967) results showed a slightly smaller differential momentum, equivalent to \( \Delta P = 177 ± 5 \) yr, to apply to the orbital motions of the two fragments of C/1965 S1. In order that perihelion splitting of the parent sungrazer in an orbit with \( q = 1.09 \) AU and \( P = 678 \) yr should release a fragment into an orbit with \( P = 922 \) yr, the required separation velocity was 1.8 m s\(^{-1}\) in the direction of the orbital motion, comparable to the separation velocities in Table 1 and by no means extreme.

27 Lefroy, a pioneer in the study of terrestrial magnetism, published an extract of the letter he received from G. B. Bennett, his friend from Cape Town. In the document dated nine days after the perihelion passage of C/1882 R1, Mr. Bennett complained that, in reference to this comet, “…Dr. Gill is reported to have said, ‘the largest [comet] for 200 years.’ I don’t believe he said so; if so, he could not have seen the one of March, 1843.” Mr. Bennett could not have been more correct, as Sir David Gill, Her Majesty’s Astronomer at the Cape Observatory from 1879 to 1906, had been born on 12 June 1843! Gill’s assistants at the observatory, Finlay & Elkin (1882), were more diplomatic than their boss, writing that “…[as far as can be gathered from the account] [the comet of 1882] only resembles the one of 1843 in the point of extreme brilliancy at perihelion.”
28 Eddie was born two years after the appearance of C/1843 D1.
The age of the Kreutz system, reckoned from the destruction of the contact-binary bond, is estimated in this investigation at almost exactly two millennia, or $2 \times 10^2$ revolutions about the Sun. Although the scenario proposed here is clearly different from the two-superfragment model contemplated by Sekanina & Chodas (2004), the two age estimates agree to within three centuries, or better than 15 percent. They are much shorter than the age estimates based on scenarios confining fragmentation events to perihelion. Indeed, Marsden (1967) estimated the age of the Kreutz system at 10–20 revolutions about the Sun, or on the order of 10 millennia. In the second paper he revised the estimate downward (Marsden 1989) to a point that he, too, considered the comet of 372 BC as a possible progenitor. However, the time scale was compressed largely because most Kreutz sungrazers were assigned unrealistically short orbital periods, as short as 360 years. The many extra sungrazers introduced make one “painfully aware that the sequence . . . requires that six of the eight intermediaries that apparently passed perihelion unrecorded during the first 15 centuries of our era ought to have been truly spectacular objects” (Marsden 1989).

Öpik (1966), using similar but less elaborate arguments, estimated the Kreutz system’s age at 130 millennia, or more than 150 returns to perihelion. The implications of such an enormous age are daunting: even if each sungrazer should split at each perihelion into only two (approximately equal) fragments, their total number after 150 returns would reach $10^{36}$. The progenitor’s mass, even if as large as $10^{20}$ grams, would end up as a population of micron-sized dust grains after some 100 returns, if the grains did not sublimate away near perihelion in the meantime. The net result is that after 150 returns there would be no Kreutz system left. A very short age is in fact inevitable, given the recently observed massive sungrazers.

Should Aristotle’s comet of 372 BC be the progenitor of the Kreutz system along the lines proposed, it is likely that its appearance was more spectacular than that of either C/1843 D1 or C/1882 R1, even though the level of increase in the extent of active surface after the lobes decoupled is impossible to estimate. It is also hard to judge whether the chroniclers exaggerated the spectacle of the Aristotle comet and to what extent were its purported credentials affected by the fact that it appeared during the exceptional period of Ancient Greece. One may even question the accuracy of Aristotle’s account, given that at the time the comet appeared he was a boy at the age of 11 or 12, but wrote the essay on it in his book Meteorologica some 40 years later.

The comet of 372 BC was a priori equally likely to be or not be part of the Kreutz system. However, in the context of the proposed evolutionary path of the progenitor’s Lobe I, this ambivalence about the comet’s status appears to be strongly affected by the daylight comets of AD 363 entering the timeline of the Kreutz system: in their roles of putative members, the two episodes — 372 BC and AD 363 — do fit together as nicely as the final pair of pieces in a puzzle.

Lastly, given the apparent propensity of Aristotle’s comet to fragmentation that the proposed scenario implies, there is no reason why the near-aphelion separation of the lobes should have been the first fragmentation event the object underwent. There is a good chance that breakup episodes occurred near perihelion in 372 BC, and the experience with C/1882 R1 suggests that fragments could have been scattered into orbits whose periods were separated by a century-or-so wide gaps. In the adopted scenario the main fragment of such a putative 372 BC event — the contact-binary bond still intact at the time — ended up in an orbit with a period of about 735 yr to return, following the near-aphelion breakup(s), in two or more pieces in late AD 363. Another fragment might have separated at that perihelion into an orbit with a period of 838 yr to return as the comet of AD 467, yet another one into an orbit with a period of 623 yr to return as the comet of AD 252, etc. Additional breakups of both the parent and the fragments themselves might have further augmented the number of such objects. Strictly, the fragments of this kind are not legitimate members of the Kreutz system, if its inception is defined by the breakup of the contact-binary bond, yet they are of course related by virtue of sharing the common parent.

6. CONCLUSIONS

As knowledge of the Kreutz system has been advancing, the breadth of its recognized orbital diversity has expanded from Marsden’s (1967, 1989) original two-population (I, II) and subsequent three-population (I, II, Ia) classification schemes to the currently proposed eight independent populations (Pre-I, I, Ia, II, IIa, III, IIIa, IV) and a side branch Pe of Population I. The major revision of the previous models of the Kreutz sungrazer system was necessitated in order to accommodate new conceptual ideas, events, and a spate of important data that only became available over the past decade or so. The introduction of Population III was dictated by the appearance of C/2011 W3, while the rationale for adding Population Ia was more subtle: maintaining approximate uniformity in the stepwise distribution of the populations’ nodal longitudes over the interval of Populations I–III. Footprints of the new populations were retrieved by examining a carefully screened set of Marsden’s gravitational orbits for 193 dwarf Kreutz sungrazers imaged exclusively with the C2 coronagraph on board the SOHO spacecraft. Because of the ignored major effects of an outgassing-driven acceleration in the motions of most dwarf Kreutz sungrazers, the computed orbits defied the condition of shared apsidal line, valid for all naked-eye Kreutz comets. In a plot of the nominal latitude of perihelion against the nominal longitude of the ascending node for the set of select SOHO comets, the populations are discriminated from one another by their nodal longitudes corrected for the out-of-orbit nongravitational effects. In terms of the true nodal longitude,
adjacent populations are separated by gaps 9° to 10° wide on the average, while a total range of the nodal
longitudes is 66°. Dwarf comets of Populations I, II, IIa, III, and Pe are associated with naked-eye sungrazers; for
Populations Pre-I, IIIa, and IV, they are yet to be discovered. Their predicted longitudes of the ascending node
(for equinox J2000) are, respectively, near 11°, 313°, and 305°, all outside the range of the five main populations.

With the image of the Kreutz system now fundamentally overhauled, the examination and modeling of its
populations are carried out primarily in terms of a sequence of early, near-aphelion fragmentation events. The
initial episode is proposed to have involved a breakup of the contact-binary progenitor into its two massive lobes,
Lobe I and Lobe II, and the low-mass connecting neck. It is possible, if not likely, that the neck — the predecessor
of Population Ia — remained attached to one of the lobes (more probably Lobe I) over a period of time following
the initial event. In either case, the separation velocities of the fragments, necessary to explain the large pertur-
bations of the populations’ mean orbital elements, the longitude of the ascending node in particular, did not exceed a few meters per second. The most sizable surviving masses of Lobe I and Lobe II are believed to be
C/1843 D1 and C/1882 R1, respectively. Lobe II apparently was more than Lobe I susceptible to continuing
fragmentation at very large heliocentric distance, near aphelion. Lobe II was not only the parent to Population
II objects, but also the precursor of the parent to Population IIa objects; this parent (or its sibling with a lesser
perihelion distance) was the precursor of the parent to Population III; which in turn was the precursor of the
parent to Population IIIa; which was the precursor of the parent to Population IV. Lobe I, the parent to Popula-
tion I objects, appears to have been fragmenting less profusely on the kilometer-size scale, but probably more sign-
ificantly on the dekameter-size scale, judging from the dominance of Population I among the SOHO sungra-
izers. However, Lobe I or another precursor of C/1843 D1 or C/1963 R1 should have produced the primary frag-
ment linked to Population Pre-I. Comet C/1963 R1, a second-generation fragment of the precursor that sepa-
rated from Lobe I in a fragmentation event following the progenitor’s breakup, is associated with Population Pe,
a side branch to Population I.

The perceived relations among the products of cascading fragmentation, described by the population class-
ification scheme, are summarized in the pedigree chart. Uncertainties grow as one proceeds back in time, from
the current generation of fragments (in the 19th–21st centuries) to previous generations. In the immediately
preceding generation, the most likely Kreutz system candidate was X/1106 C1, the parent to either C/1843 D1 or
C/1882 R1. Although I distinctly prefer the former, either case can be argued. The 12th century parent to
one of the two 19th century giant sungrazers was plainly missed, possibly because of extremely unfavorable view-
ning geometry. Fragments of the generation preceding the 12th century generation are believed to have arrived at
perihelion nearly simultaneously in the 4th century AD; identities of possible candidates are offered, but only very
incomplete data are available. An intriguing scenario involves comets seen in broad daylight in late 363, as
recorded by the Roman historian Ammianus Marcelli-

nus. Although neither the number of the comets nor
their spread over time are known, inserting the year of this event as a third link in the chain of returns in 1843
and 1106 is conducive to incorporating Aristotle’s comet of 372 BC — the last perihelion passage of the contact-
binary progenitor — as a fourth, and the earliest traceable, link. Together they allude to a nearly constant orbital period of 738 yr for the main residual mass of Lobe I over an estimated age of the Kreutz system of
about two millennia, or 2’revolutions about the Sun. Earlier perihelion fragmentation of the comet of 372 BC,
not involving the destruction of the contact-binary bond, is by no means ruled out.

The proposed model differs dramatically from both the
two-supefragment model (Sekanina & Chodas 2004) and
the alternative model (Sekanina & Chodas 2007), yet ret-
aining some of the features of either. The new traits of the present model stem from the many significant de-
velopments that have taken place since 2007. As pointed out
in Section 1, the arrival of Comet Lovejoy (C/2011 W3)
was perhaps the most important, but still only one, of
these events. Irrevocably valid, and common to all three
models, are the conclusions that by no means have we
seen the last spectacular Kreutz sungrazer and that an-
other cluster of these objects is on the way to perihelion,
expected to arrive in the coming years and decades. If
anything, this case can now be argued more vigorously
than ever before.

In the interest of further progress in the understanding of
the fragmentation history of the Kreutz system, it is
desirable that — as the next milestone — orbit integra-
tion experiments be conducted, with full account of the
planetary perturbations and simulated nongravitational
effects, in order to test and thereby confirm, refute, or
impose limits on, the proposed conceptual model. Com-
pared to the previous hypotheses, the current scenario is
straightforward and strongly rationale oriented; its ulti-
mate success depends on whether, or to what extent, it
can be supported by rigorous computations.

Addendum. After completing this paper, I came across a brief remark by Frisy (1883) that the orbital elements of the Great September Comet of 1882 “bear a considerable resemblance to Comet I, B.C. 371; and it may possibly be its third return, a very brilliant comet having been seen in full daylight A.D. 363.” Apart from
the fact that the orbit of the comet of 372 BC (or −371,
not 371 BC) is not known, this statement is — to my
knowledge — one of only two instances that suggest a
possible link of the spectacle of AD 363 to the Kreutz
system, the other being the noted narrative by Seargent
(2009), commented on in Section 5.3. The reference to
“full daylight” makes it clear that Frisy meant the Roman, not the Chinese, event. It is remarkable that, relying on his own orbit computations, Frisy had apparently no qualms whatsoever about the orbital period of the Great September Comet of 1882 in a range of 750–800 yr at the time when Kreutz’s (1883)
value was 843 yr, Elkin’s (1883) best guess hovered near

30 The set of elements published by Pingré (1783; see also Kronk
1999), which does not at all bear a resemblance to that of the Great
September Comet of 1882 (or any other Kreutz sungrazer for that
matter) in terms of spatial orientation, is merely a wild guess; it
implies a perihelion longitude of about 180° (equinox J2000),
compared to the Kreutz system’s 282°.
1500 yr, and not long after Chandler (1882a, 1882b) had derived a period of 4000 yr. It was not until five years later that Kreutz (1888) considered the potential identity of the 1882 comet with that of 1106 and it took him another three years to arrive at his final verdict on the pre-fragmentation orbital period of the 1882 comet by estimating its lower limit at 770 yr and upper limit at 1000 yr (Kreutz 1891).

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