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The problem of split comets revisited

Z. Sekanina

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, U.S.A

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Abstract. The results from studies of D/Shoemaker–Levy 9 and other recent split comets and comet pairs lead to the recognition of fundamental differences between breakup products of the tidally and the nontidally split comets and to the conclusive identification of the so-called dissipating comets, i.e., secondary nuclei of previously split comets, whose separately arriving principal nuclei had in most cases been missed. The primary attribute of the nontidally split comets is the leading position of the principal nucleus, with all the companion nuclei trailing behind. No such configuration has been observed for the tidally split comets of more than two components. Dominant effects in the relative motions of fragments derived from the tidal disruptions are due to separation velocities, while *differential decelerations* (due, presumably, to outgassing-driven nongravitational perturbations) prevail for fragments derived *from the nontidal* breakups. This diversity is interpreted in terms of major differences between the breakup *mechanisms for the two categories* of objects and between the resulting mass distributions of fragments.

Key words: tidally and nontidally split comets – comet pairs – principal *and secondary nuclei – configurations of* fragments – separation velocity – differential deceleration

1. Introduction

This *research note has been* stimulated by several significant developments that occurred during the 15 years since *the publication of the most recent major* review on the split comets (Sekanina 1982, referred to heretofore as Paper I). *Of particular interest are the disruption* of D/Shoemaker–Levy 9 and its collision with Jupiter, the prevalence of old and short-period *comets among the split* comets that have been observed since 1982, and the appearance of comet pairs.

It is shown below that application of the model for the split comets, developed in the 1970s (Sekanina 1977, 1978, 1979) and reviewed in Paper I, to an expanded sample of objects *leads to fundamentally new information* and to a classification of the split comets into two distinct groups, with major implications *for the fragments*.

Send offprint requests to: Z. Sekanina

2. Fitting the model for the split comets

The developed model for the split comets was shown in Paper I to have up to five parameters: the time of splitting, the differential nongravitational deceleration, and the three Cartesian components of the separation velocity. The deceleration is attributed to uneven effects that the sun-directed outgassing from the individual components is believed to exert on their orbital momenta, whereas the separation velocity is the result of an impulse acquired by the components in the course of their splitting.

For a split comet with two components, the model is fitted to a set of observed positional offsets between the companion, or the secondary nucleus, and the parent, or the principal (primary) nucleus. Mathematically it is *unimportant* which of the two components is the principal nucleus. However, in practice only one component *usually survives*, it is *appropriate* to identify it with the principal nucleus, because it almost certainly must be by far the more massive one.

It was shown in Paper I that when the deceleration effects dominate, the principal nucleus is always the leading component, the secondary nucleus trailing behind, eventually along the orbit. On the other hand, when the separation velocity effects prevail, there is no constraint on the relative positions of the components.

If a comet breaks up into more than two components, it is necessary to identify the principal nucleus and the companion of each split pair. This is accomplished by comparing the optimized solutions calculated from the sets of offsets that involve various fragment pairs. A secondary of one pair may become the principal nucleus in another pair, with a sequence of such breakups building up a complex hierarchy of fracture products.

In practice, the fitting of the multiparameter model is accomplished by applying an iterative least-squares differential correction procedure, with an option to solve for any combination of fewer than the five unknowns in order to facilitate a reasonably rapid convergence. Consequently, 31 different variants of possible solutions are available, which is especially useful in early stages of the search for the best solution. This option also allows one to force the deceleration to be zero and thus to appraise its role in the motions of the fragments.

3. Nontidally and tidally split comets

The relative contributions from the differential deceleration and the separation velocity to the rate at which two components of a split comet drift apart appear to be an important criterion for discriminating between the tidally and the nontidally split comets, as shown below.

An updated list of the *nontidally split comets* is presented in Table 1. With no exception, the observed fragment configurations show that *the principal nucleus is always the leading component, with all the companions trailing behind*. These configurations imply that deceleration effects clearly prevail over separation velocity effects. The differential decelerations attain values typically between a few and ~500 units of 10^{-5} the solar attraction. All companions vanish before does (if ever) the principal nucleus. The duration of a companion's visibility was found in Paper I to be generally correlated with its deceleration: the lesser the deceleration, the longer the lifetime.

Table 1. List of known nontidally split comets.

1846 II 1852 III	3D/Biela
1860 D1	Liais
1888 D1	Sawerthal
1889 O1	Davidson
1896 R2	D/Giacobini
1899 E1	Swift
1906 E1	Kopff
1914 S1	Campbell
1915 C1	Mellish
1915 W1	69P/Taylor
1942 X1	Whipple-Fedtke
1947 X1	Southern Comet
1955 O1	Honda
1956 F1	Wirtanen
1968 U1	Wild
1969 O1	Kohoutek
1969 T1	Tago-Sato-Kosaka
1975 V1	West
1982 C1	79P/du Toit-Hartley
1985 V1	108P/Ciffréo
1986 P1	Wilson
1991 L1	101P/Chernykh
1994 G1	Takamizawa-Levy
1994 P1	P/Machholz 2
1994g	51P/Harrington
1994w	73P/Schwassmann-Wachmann 3

Table 2. List of known tidally split comets.

1882 R1	Great September Comet	at Sun
1889 N1	16P/Brooks 2	at Jupiter
1963 R1	Pereyra (possibly split)	at Sun
1965 S1	Ikeya-Seki	at Sun
1993 F2	D/Shoemaker-Levy 9	at Jupiter

The *tidally split comets* are listed in Table 2. Three were observed to have broken up into more than two components: two at Jupiter (D/Shoemaker-Levy 9 and 16P/Brooks 2) and one at the Sun (1882 R1 = the Great September Comet). Comparison with the nontidally split comets indicates that an average tidal disruption event generates a significantly larger number of fragments.

Numerous investigations of D/Shoemaker-Levy 9, the most extensively studied tidally split comet, firmly established that the most massive components — G, K, and L — were all near the middle of the nuclear train, while the leading nucleus A was much less conspicuous and obviously less massive (e.g., Hammel et al. 1995). This evidence is supported by the results from the orbital determinations (Chodas and Yeomans 1996) for the comet's 21 components, which yielded excellent solutions without the need to incorporate nongravitational terms in the equations of motion. A more recent, extensive study of discrete secondary-fragmentation episodes (Sekanina et al. 1996), which were found to have occurred over a period of many months following the comet's encounter with Jupiter in July 1992, implies the absence of any detectable differential decelerations except for the motion of the component P_1 that disintegrated entirely before reaching Jupiter in July 1994.

The only other comet known to have split tidally near Jupiter is 16P/Brooks 2. The closest approach, to 2.0 Jovian radii from the planet's center, took place in July 1886. Unlike Shoemaker-Levy 9, Brooks 2 was perturbed by Jupiter into a slightly hyperbolic post-encounter jovicentric orbit, which brought the object to 1.95 AU from the Sun in 1889. Barnard's (1889) drawing (also cf. Fig. 1 of Sekanina 1996) made eight weeks before perihelion shows the principal nucleus A (the component that is still surviving today) to be trailing the companion nuclei. Only the companion C was positively identified to have separated from A at Jupiter. Solving for both the deceleration and the separation velocity as unknowns, I ascertained that the deceleration was indeterminate. Solving for the separation velocity only offered a better fit than all the other models that incorporated the deceleration (Sekanina 1978). The third component, B, was found to have separated from C nearer the Sun, about 19 months after the comet's encounter with Jupiter (Sekanina 1977, 1982). This episode may have been either a secondary-fragmentation event (similar to those observed for Shoemaker-Levy 9) or, less probably, an independent nontidal splitting.

The nucleus of the brightest member of the sungrazing comet group, 1882 R1, was observed after perihelion to consist of up to six separate components, arranged — like the fragments of Shoemaker–Levy 9 — in a rectilinear train immersed in a sheath of nebulous material (Kreutz 1888). However, useful orbital information is available for only the four components nearest the Sun. The two brightest and longest surviving components were the second and the third from the sunward end of the train, so that once again the leading component was not the principal nucleus. The solutions that included the differential deceleration γ and those in which γ was replaced with a transverse component V_{sep} of the separation velocity fitted the data equally well (Sekanina 1977). This equivalence was explained as due to an extremely steep decrease in the deceleration (assumed to vary inversely as the square of heliocentric distance) near the perihelion point of any sungrazing orbit (Sekanina 1978, 1982). From the virial theorem, the relationship between the two quantities for the orbit of 1882 R1 is $V_{sep} = 2.39\gamma$, where V_{sep} is in m/s and γ in units of 10^{-5} the solar attraction. Identifying the separation velocity with the equatorial rotational velocity, one can calculate the minimum effective diameter of the parent nucleus from $D_{min} = P_{crit}\Delta V_{sep}/2\pi$, where P_{crit} is a critical rotation period and ΔV_{sep} is the range of V_{sep} for the components located at the train's ends. Only a lower limit to this quantity can be calculated from the available results for the first and the fourth components (Sekanina 1977): $\Delta V_{sep} > 4.6$ m/s. For an assumed nucleus bulk density of $\sim$0.3 g/cm^3, for example, $P_{crit} \simeq 6$ hr and $D_{min} > 16$ km, a plausible value.

Another tidally split sungrazer, 1965 S1 (Ikeya–Seki), displayed only two nuclear components. Even though the principal (and systematically the brighter) nucleus was the leading component, the derived differential deceleration for the companion is very small and outside the range of values indicated by the nontidally split comets (Sekanina 1978, 1982). This circumstance suggests that, once again, one deals here with a disguised separation-velocity effect, in which case one now obtains $\Delta V_{sep} > 1.6$ m/s and, with the same critical rotation period as above, $D_{min} > 5.5$ km. Thus, the leading position of the principal nucleus presented a signature of the direction of nuclear rotation rather than of the companion's differential deceleration.

I thus find that among the three *tidally split comets* that displayed more than two nuclear fragments, *the principal nucleus was never the leading component* and that the leading position of the principal nucleus of the two component tidally split comet Ikeya–Seki should not be interpreted as an effect of a deceleration. It can safely be concluded that the motions of the tidally split comets are essentially determined by effects of the separation velocity acquired by the components at the time of their splitting. The physical significance of this fundamental difference between the two categories of the split comets is briefly discussed in Sec. 5.

4. Dissipating comets and comet pairs

I introduced the term *dissipating comets* (Sekanina 1984, referred to heretofore as Paper 2) to describe a group of comets observed to undergo rapid physical changes. A fading sets in suddenly, without warning, and the central condensation disappears usually in a matter of days, terminating astrometry. The coma expands gradually and becomes progressively elongated. The surface brightness decreases at an alarmingly fast rate until the head essentially vanishes before the eyes of the surprised observers. Interestingly, the comet is sometimes survived by a dust tail, the signature of an outburst that had preceded the fading but for whatever reasons remained unobserved.

The terminal changes experienced by the dissipating comets were shown in Paper 2 to bear a strong resemblance to the physical behavior of secondary nuclei of the split comets. This similarity is illustrated by 1996 Q1, the most recent dissipating comet (Green 1996), which confirms that the dissipating comets *are* secondary nuclei of split comets: the orbits of 1996 Q1 and 1988 A1 (Liller) indeed are practically identical (Jahn 1996). The two objects make a comet pair (Table 3) and were unquestionably a single object in the past, probably as recently as one revolution, or some 2900 yr, ago. An estimate for the deceleration γ in the relative motion of two comets of the common parentage is obtained from the assumption that their breakup occurred exactly at previous perihelion, in which case $\gamma = 2\times10^5 \Delta P_{orb}/P_{orb}$, where P_{orb} is the revolution period of the original orbit of the principal comet (in this case 1988 A1) and ΔP_{orb} is the time difference between the perihelion passages of the secondary (in this case 1996 Q1) and the principal comets; γ is again in units of 10^{-5} the solar attraction. If the breakup occurred n revolutions in the past, the value of γ from the formula must be divided by a factor of $\frac{1}{2}n(n+1)$. For the 1988 A1/1996 Q1 pair, $\Delta P_{orb} = 8.60$ yr and $\gamma = 586$ units (for $n = 1$).

Two other comet pairs are also listed in Table 3. The orbits of Neujmin 3 and Van Biesbroeck were found to have virtually coincided before a close approach to Jupiter in 1850. Although the numbers are somewhat uncertain, this pair is likely to be of tidal origin. The remaining pair (Bardwell 1988) includes comets 1988 F1 (Levy) and 1988 J1 (Shoemaker–Holt), whose $P_{orb} \simeq 14{,}000$ yr, $\Delta P_{orb} = 0.209$ yr, and for which therefore $\gamma = 3$ units ($n = 1$), or a factor of $\sim$200 smaller than the γ value for the Liller/Tabur pair. The low γ may explain why 1988 J1 was not observed to disintegrate. The splittings of 1988 F1/1988 J1 and 1988 A1/1996 Q1 are nontidal and in both cases the comet that appeared first was intrinsically the brighter one. Finally, of course, there is the sungrazer comet group, which has 24+ known members (cf. Sec. 3). For more on this group's history and orbital evolution, the reader is referred to Marsden (1967, 1989). Other proposed comet groups (e.g., Porter 1963) can be dismissed as products of chance orbital coincidences.

Table 3. Known comet airs.

1951 J1	42P/Neujmin 3	tidally split (?)
1954 R1	53P/Van Biesbroeck	
1988 F1	Levy	nontidally split
1988 J1	Shoemaker Holt	
1988 A1	Liller	nontidally split
1996 Q1	Tabu	

Table 4. Statistics of nontidally split comets and comet pairs.

Comets	1982 Sample	996 Sample
New (Oort cloud)	5	6
Fairly new	2	2
Old (long period)	6	9
Short period	3	9
Parabolic (approx.)	2	2
Total number	18	28

An outstanding issue is why most dissipating comets do not pair with other objects. The answer may be ob servational selection: the missing principal comets should have appeared at *earlier* times, when the discovery prob ability was lower. For comets of longer orbital periods ($> 10^4$ yr), the time between the perihelion passages of the components could reach decades or even centuries. Perhaps the most difficult case to explain is 20D/Westphal. Will another comet be eventually discovered in its orbit?

5. S atistics of non idal split ing and conclusions

The recent additions to the split comets have dramatically affected the orbital-period distribution of these objects. Defining as the new (or the Oort cloud) comets those having original orbits with $P_{\rm orb} > 1$ million yr, as the fairly new comets those with $50,000 < P_{\rm orb} < 1$ million yr, as the old comets those with $200 < P_{\rm orb} < 50,000$ yr, and as the short period comets those with $P_{\rm orb} < 200$ yr, the 1982 (from Paper 1) and 1996 samples are compared in Table 4. The numbers now favor heavily the old and the short period comets as the objects that experience nontidal splitting most often.

This fact appears to strengthen even further the conceptual model proposed in Paper 1, which can now be slightly refined by identifying most companions of the *nontidally split comets* as randomly jettisoned pancake shaped fragments of the surface mantle of refractory material, with limited supplies of subsurface volatiles attached to it to account for activity. The nuclear surface of old and short-period comets is indeed believed to be heavily mantled, with only a minor fraction still active. And since a differential deceleration varies inversely as the secondary-to principal nucleus mass ratio (Paper 1), the detected major deceleration effects imply that the companions are *considerably less massive* than the principal nuclei.

On the other hand, separation-velocity effects are independent of the secondary-to principal nucleus mass ratio. Their prevalence in the motions of components of a *tidally split comet* indicates that the fragments are of *comparable masses*, none of them dominant. One can say that nuclei of the tidally split comets *truly break up*, while nuclei of the nontidally split comets *tend to peel off* instead (Paper 1).

The breakup mechanism for the nontidally split comets is unknown, but stresses built up due to rapid rotation and/or tumbling of an irregular object as well as due to high temperature gradients in the nuclear surface layer are the primary candidates. It is possible that the tidal force is not the only and perhaps not even the decisive cause for tidal splitting. Whereas it apparently is instrumental in cracking the nucleus, a tidal breakup may in fact likewise be completed by rotational and/or thermal forces.

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