6

DIFFERENTIAL NONGRAVITATIONAL FORCES IN THE MOTIONS OF THE SPLIT COMETS

Z. SEKANINA

The new model, which has recently been proposed for the motions of fragments of the split comets, is critically examined through a comparison with the traditional approach. It is concluded that the new model, based on the premise that the rate of separation of any two fragments of a split comet is determined primarily by the differential nongravitational forces in their motions, is preferable in many a respect to the traditional hypothesis, built on the assumption that significant impulses are exerted on the fragments at the time of splitting. The new model appears to have interesting implications for the physics of cometary splitting, suggesting that the breakup mechanism may essentially be non-violent or of a low degree of violence, and for estimates of cometary masses.

Less than two dozen comets are known to have split during the past 150 years. Relative motions of the fragments of a split comet have long been believed to result from an impulse exerted on the fragments at breakup. Although the techniques applied in the studies of individual split comets have varied from an elementary fit through the measured angular separations corrected only for the earth-comet distance (*e.g.*, Pittich 1971) to very elaborate investigations of the orbital elements of the fragments (*e.g.*, Guigay 1955), the basic idea has almost always been to adjust the time of splitting and the velocity of separation (or its component normal to the line of sight) so as to obtain the best possible match to the observations. Thus, the traditional approach postulates that in the absence of the gravitational field the fragments would separate at a constant rate, as illustrated schematically by a straight line on the plot of the "normalized" separation vs. time in Fig. 1. The major drawback of this hypothesis has been the failure to make the positions of the fragments coincide with one another at the time of splitting. Miss distances, often on the order of 10^4 km, have remained unaccounted for.

Very recently I have proposed that two fragments of a split comet may be drifting apart because of a slight systematic difference between the effective solar attractions they are subjected to. The net force, which is believed to result from the difference between the momenta transferred to the fragments by outgassing, is of the same nature as the nongravitational forces, first studied by Whipple (1950) and now positively detected in the motions of most of the short-period comets and of some of the nearly-parabolic comets (for a review,

https://doi.org/10.1017/S025292110006989X Published online by Cambridge University Press

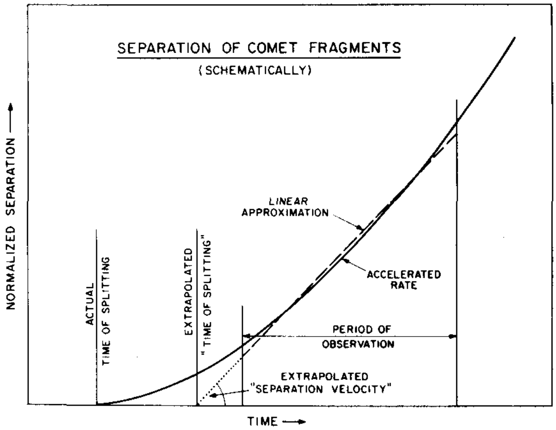

Figure 1. Schematic representation of the relative motions of fragments of a split comet as interpreted by the traditional approach (linear approximation) and by the new model (accelerated rate).

see Marsden 1974). A nongravitational term in the transverse component of motion was with some success applied by Marsden in his orbital study of the split Comet Biela (Marsden and Sekanina 1971), and a "perturbation" force had previously been considered by Kreutz (1891) in his investigation of the splitting of Comet 1882 II.

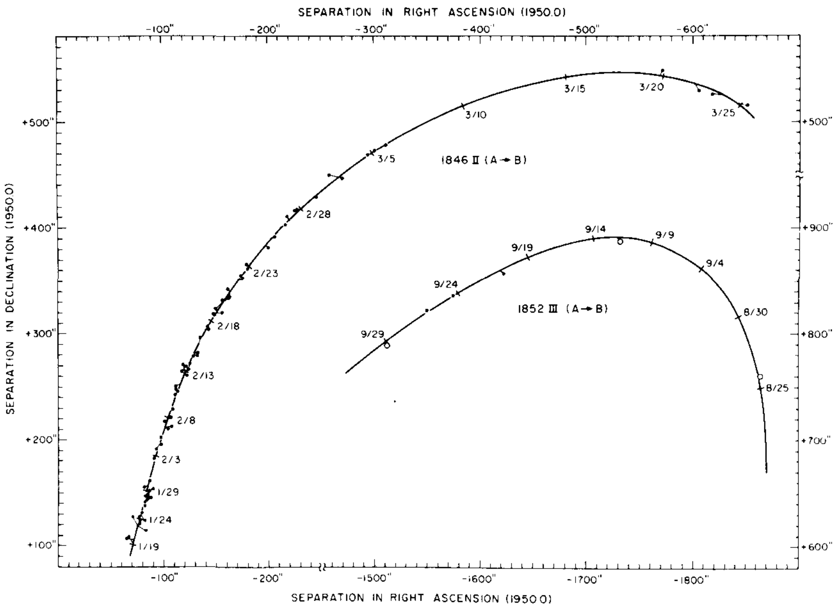

Figure 2. Apparent separation of fragment B of P/Biela from fragment A in right ascension and in declination. Dots: observed separation in 1846 and in 1852. Open circles: separations in 1852 derived from orbital calculations by Marsden. Heavy curves are least-squares solutions provided by the new model. Short lines connect the observed separations with their calculated positions. Marks give the dates in 1846 and in 1852. (From Sekanina 1976a).

https://doi.org/10.1017/S025292110006989X Published online by Cambridge University Press

The newly proposed model, discussed in detail elsewhere (Sekanina 1976a), has been shown to be compatible with the precise positional observations of fragments of all the well-documented split comets with the exception of Comet Wirtanen (1957 VI). As an example, the separations between the two nuclei of Comet Biela in 1846 and 1852 are shown in Fig. 2. Since the magnitude of the differential force (assumed to vary inversely as the square of heliocentric distance) is a measure of the post-split behavior of the fragments and since the velocity of separation is now neglected, the time of splitting serves in this model as the sole parameter of the breakup event. Note that in the absence of the gravitational field the fragments would still be subjected to the forces from outgassing and, as schematically depicted in Fig. 1, would separate from each other at an accelerated rate. Also note in Fig. 1 that because of the neglect of any impulse at breakup the separation curve of this model is tangent to the time axis at the instant of splitting.

The comparison of the new approach with the traditional one offers some interesting conclusions and inferences that can be summarized as follows:

(1) A great advantage of the new model has been its ability to fit observations with only two parameters to be adjusted. The traditional model has enjoyed a considerably greater degree of flexibility with its four adjustable parameters (the time of splitting and three components of the velocity of separation).

(2) The progressively increasing rate of separation with time, postulated by the new model, implies that fragments of a split comet cannot be discriminated optically until long after breakup. This fact has been a major obstacle in the attempts to correlate the breakup events with other indices of cometary activity.

(3) Figure 1 shows that in order to fit the same set of observations, the traditional approach should yield systematically later times of splitting than does the new model. This expectation has been checked numerically by comparing the times of splitting listed by Sekanina (1976a) for the new model, t_{split} (new), with those based on the traditional approach t_{split}(trad.), and compiled from various papers (Jeffers 1922, Guigay 1955, Roemer 1962, 1963, Stefanik 1966, Pohn 1966, Sekanina 1966, 1967, 1968, Harwit 1968, Marsden and Sekanina 1971, Pittich 1971). The results, $\Delta t_{split} = t_{split}(\text{trad.}) - t_{split}(\text{new})$, listed for 10 comets in Table I, confirm the presence of the inferred effect most convincingly.

(4) If the times of splitting from the traditional approach are systematically much too late, the velocities of separation should be much too high. A list prepared by Stefanik (1966) indicates that the required separation velocities for 13 split comets vary from a few to 40 meters per second. These are indeed in conflict with an upper limit on the velocity of separation estimated from neglect of the initial impulse by the new model. The best guess is that an initial rate of separation substantially exceeding 1 meter per second would have had a very damaging effect on the quality of the fit of observations by the new model.

(5) Low velocities of separation represent an important new result, since they suggest that the breakup mechanism can be described in relative terms as a not very violent one.

(6) Separation velocities as low as ~1 m sec^{-1} also impose a rather strict upper limit on the velocity of escape from the comet and thus provide a useful dynamical estimate for the *maximum* mass of the cometary nucleus; it comes out to be on the order of only 10^{16} grams.

(7) If interpreted as rotational velocities, low initial rates of separation would suggest that cometary nuclei spin with periods not shorter than about 2 or 3 hours.

(8) If, furthermore, the spin is assumed to be responsible for the break-

TABLE I

DIFFERENCES IN THE TIMES OF SPLITTING DERIVED FROM THE TRADITIONAL AND NEW MODELS

Comet	Δt_{split} (trad. minus new) (days)
P/Biela	+600 to +1200
1860 I	(+58)
1882 II	0 to +12
1899 I	+10 to +11
1905 IV	(+69)
1915 II	+72
P/Taylor	+85 to +90
1947 XII	+4 to +7
1957 VI	(+300 to +600)
1965 VIII	0 to +4

Uncertain data are in parentheses.

TABLE II

COMPONENTS OF SEPARATION BETWEEN THE TWO NUCLEI OF COMET WIRTANEN (1957 VI) NORMAL TO THE ORBIT PLANE

Date of the earth's crossing of the comet's orbit plane	Normal component of separation (km)
1957 May 14	17,000
1958 May 14	15,000
1958 Nov. 15	12,000
1959 May 14	3,000

up, a structural weakness that fails to sustain stresses on the order of 10^4 dynes cm^{-2} must develop in the nucleus.

(9) Since the nongravitational forces acting on the fragments are assumed to be directed away from the sun, the new model implies that the motions of the fragments should be confined to a common orbit plane [see Fig. 3 for the results on Comet West (1975n)]. While Chandler (1891) found that this was the case of the two major fragments of P/Brooks 2 in 1889, this condition is generally not satisfied except in the first approximation. Recently we have established the existence of separations of several thousand kilometers in the direction normal to the orbit plane between the fragments of Comet West (Sekanina 1976b). Such separations may come either from the normal component of the velocity of separation, or from that of the differential nongravitational force, or from both. Preliminary results for Comet Wirtanen (1957 VI) in Table II suggest that there the effect cannot be due to the initial impulse because the normal component of separation would then have to increase linearly with time.

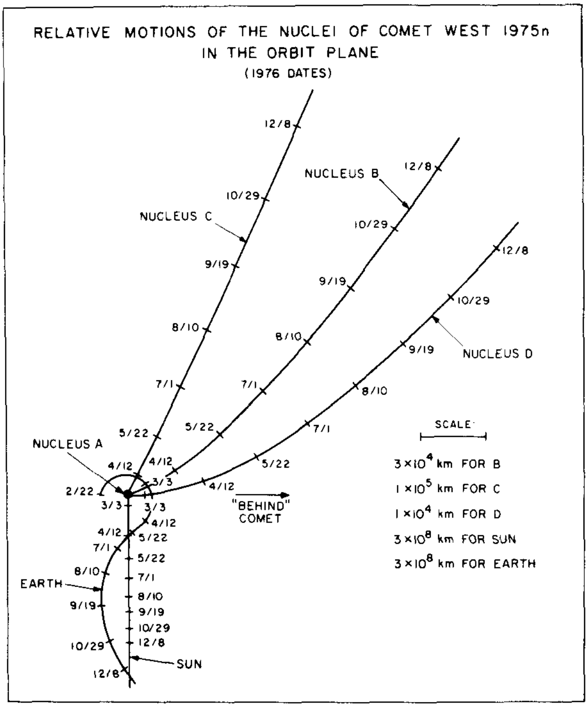

Figure 3. Relative motions of the fragments of Comet West (1975n) in the orbit plane. The configuration is referred to the fixed orientation of the radius vector of nucleus A. Note the different scales for different fragments.

We conclude that the new model, based on the premise that the relative motions of fragments of the split comets are determined primarily by the differential nongravitational forces, is clearly preferable to the traditional approach, which emphasizes the existence of significant impulses on the fragments at the time of breakup. The study of second-order effects (such as slight systematic trends in positional residuals, or motions normal to the orbit plane) in the future will, however, require that the new model allow for the small initial impulses and for the complicated character of the nongravitational forces.

This work has been supported by a grant NSG 7082 from the National Aeronautics and Space Administration.

REFERENCES

Chandler, S. C. 1891, *Astron. J., 10,* 153.
Guigay, G. 1955, *J. Obs., 38,* 189.
Harwit, M. 1968, *Astrophys. J., 151,* 789.
Jeffers, H. M. 1922, *Lick Obs. Bull., 10,* 120.
Kreutz, H. 1891, *Publ. Sternw. Kiel.,* No. 6.
Marsden, B. G. 1974, *A. Rev. Astron. Astrophys., 12,* 1.
Marsden, B. G., and Sekanina, Z. 1971, *Astron. J., 76,* 1135.

Pittich, E. M. 1971, *Bull. Astron. Inst. Czech., 22,* 143.
Pohn, H. A. 1966, *Sky and Tel., 31,* 376.
Roemer, E. 1962, *Publ. Astron. Soc. Pacific, 74,* 351.
Roemer, E. 1963, *Astron. J., 68,* 544.
Sekanina, Z. 1966, *Bull. Astron. Inst. Czech., 17,* 207.
Sekanina, Z. 1967, *Bull. Astron. Inst. Czech., 18,* 296.
Sekanina, Z. 1968, *Bull. Astron. Inst. Czech., 19,* 153.
Sekanina, Z. 1976a, *Icarus,* in press.
Sekanina, Z. 1976b, *Astrophys. Lett.,* in press.
Stefanik, R. P. 1966, *Mém. Roy. Soc. Sci. Liège (Sér. 5), 12,* 29.
Whipple, F. L. 1950, *Astrophys. J., 111,* 375.

DISCUSSION

DONN: 1. How good a fit to the observations could you get assuming splitting with some initial separation velocity?

2. In your list, several comets split beyond 2 AU when non-gravitational forces are presumably very small. How does this effect show in your analysis and results?

SEKANINA: 1. Attempts based exclusively on the separation velocity have never been completely successful because the orbits of the fragments could not be made to intersect each other.

2. This might be the reason (or one of the reasons) why the present approach failed for 1957 VI (q = 4.4 AU). On the other hand, the fit is perfect for P/Biela (which split between 3 and 4 AU). Since the splitting presumably implies exposure of previously locked highly-volatile materials from the inside of the nucleus, the applied inverse-square law might apply out to vary large heliocentric distances.

KELLER: Does your approach have implications on the maximum rotation rate of cometary nuclei?

SEKANINA: The estimated separation velocities (the measured values refer only to their normal components) of the fragments of Comet West, if interpreted as rotational velocities, would suggest the rotation period of about 2 to 3 hours for an assumed nucleus of 1 km in radius.

DELSEMME: From the maximum possible velocity of separation to get a good fit of the orbits, what is the tensile strength of the nucleus?

SEKANINA: On the order of only 10^3 *dynes/cm*^{2} *for Comet West.*