Letter to the Editor

A double nucleus of comet Evans-Drinkwater (C/1996 J1)

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Abstract. The nucleus of comet C/1996 J1, whose duplicity was first detected in early May 1997, ~ 4 months after perihelion, is found to have split nontidally ~ 70 days before perihelion at 1.65 AU from the Sun. The secondary nucleus, discovered when in outburst and subsequently observed for $8\frac{1}{2}$ months, had separated from the primary nucleus at a rate of 1.7 m/s and drifted away from it with a radial nongravitational deceleration of $\sim 31 \times 10^{-5}$ the Sun's attraction, typical for the short-lived companions. At the time of splitting, this dynamically new comet was near conjunction with the Sun and therefore unobservable from Earth. In late 1997 and early 1998, when last seen, the companion was $\gtrsim 100$ times fainter relative to the primary component than it had been when first reported.

Key words: comet Evans-Drinkwater – double nucleus – nontidal splitting – brightness variations – new comets

1. Introduction

Although comet Evans-Drinkwater had been discovered on May 10, 1996 (McNaught 1996), the duplicity of its nucleus was first detected only one year later, on May 5, 1997. At that time, J. Kobayashi noticed that component A, a bright condensation of total magnitude 9.8, was accompanied by component B, whose total magnitude was 12.9 (Nakano 1997). From the better fit to the available orbit, the fainter component B was immediately identified by Nakano as the principal mass.

A few days later, this identity was independently confirmed by Sekanina's (1997a) finding that, with respect to nucleus B, nucleus A was subjected to a radial nongravitational deceleration of an estimated 0.0003 the Sun's attraction. Nucleus B was therefore the leading component. It was shown long ago (Sekanina 1982a) that, invariably, a deceleration is the signature of a less enduring (and, presumably, less massive) nuclear fragment. An interesting – although possibly fortuitous – circumstance is a nearly perfect correspondence between the reported magnitude of component B and the magnitude predicted for the time (Marsden et al. 1997) from preperihelion observations made almost one year earlier. The obvious inference is that the

companion – component A – was caught by Kobayashi in the middle of a major outburst (Sect. 3).

2. Relative motion of the nuclei

A total of 124 positions of nucleus A with respect to B has been collected from the available astrometric data, covering a period of time from May 5, 1997 to Jan. 23, 1998, or $\sim 8\frac{1}{2}$ months. The major contributors were Gajdoš et al. (1997, 1998), Sugie (1997), Yamanishi et al. (1997, 1998), and Nakamura (1997, 1998). Positional data were likewise reported by Kojima (1997), by Kobayashi (1997), by Manca and Cavagna (1997), by Holvorcem (1997), by Hergenrother and Spahr (1997), and by Pravec and Šarounová (1997). The maximum angular separation between the two components, about 3 arcmin, occurred in October 1997.

Analysis of the positional offsets has followed the standard technique for split comets. As described by Sekanina (1982a), this iterative least-squares differential-correction orbital procedure solves for up to five separation parameters: the time of splitting, t_{split}; three components of the separation velocity, V_{total}, in the cardinal directions; and the companion's relative radial nongravitational deceleration, γ. The separation-velocity components in the directions referred to the plane of the parent comet's heliocentric orbit are, respectively, the radial (away from the Sun), transverse, and normal velocities, V_{radial}, V_{transv}, and V_{normal}, in the right-handed RTN coordinate system. The deceleration is assumed to vary inversely as a square of heliocentric distance and is usually expressed in units of 10^{-5} the solar gravitational acceleration. The mutual gravitational attraction of the fragment nuclei is ignored.

Unless the comet experiences a grazing approach to a planet, the planetary perturbations can safely be neglected. The orbital elements by Nakano (1998), calculated for an osculating epoch of Dec. 23, 1996, have been used below, after they were precessed to equinox B1950.0. Because of the diffuse nature of the nuclear condensations, their astrometric positions are measured with a nontrivial uncertainty, usually a fraction of 1 arcsec. It is therefore necessary to prescribe a rejection cutoff for the residuals of the offsets in right ascension and declination. In this investigation, the separation parameters were computed for six assumed rejection cutoffs that vary from 1.2 arcsec down to 0.2 arcsec in steps of 0.2 arcsec.

Table 1. Separation parameters from solutions for varying rejection cutoffs (equinox B1950.0).

Parameter	Rejection cutoff (arcsec)					
	1.2	1.0	0.8	0.6	0.4	0.2
Time of splitting						
$t_{\rm split}$ (days from						
perihelion)	-65.6 ± 3.2	-66.4 ± 3.0	-68.6 ± 2.5	-69.1 ± 2.2	-69.3 ± 2.0	-66.2 ± 1.9
(date 1996 UT)	Oct. 25.8	Oct. 25.0	Oct. 22.8	Oct. 22.3	Oct. 22.1	Oct. 25.2
Separation velocity						
$V_{\rm total}$ (m/s)	1.76 ± 0.24	1.76 ± 0.21	1.67 ± 0.15	1.73 ± 0.13	1.67 ± 0.11	1.86 ± 0.13
$V_{\rm radial}$ (m/s)	$+1.41 \pm 0.29$	$+1.35 \pm 0.27$	$+1.13 \pm 0.22$	$+1.09 \pm 0.19$	$+1.04 \pm 0.18$	$+1.30 \pm 0.17$
$V_{\rm transv}$ (m/s)	$+0.62 \pm 0.12$	$+0.75 \pm 0.10$	$+0.87 \pm 0.09$	$+1.02 \pm 0.08$	$+1.04 \pm 0.06$	$+1.10 \pm 0.05$
$V_{\rm normal}$ (m/s)	-0.85 ± 0.04	-0.84 ± 0.04	-0.87 ± 0.04	-0.88 ± 0.03	-0.80 ± 0.03	-0.76 ± 0.02
Deceleration γ						
(units of 10^{-5}						
solar attraction)	33.8 ± 0.7	33.0 ± 0.7	32.3 ± 0.6	31.3 ± 0.5	31.2 ± 0.4	30.8 ± 0.3
Mean residual						
(arcsec)	± 0.51	± 0.45	± 0.38	± 0.33	± 0.21	± 0.11
Number of measured						
pairs of offsets used	98	87	74	63	33	13
Dates covered, 1997	5/5–12/31	5/9–12/31	5/9–12/31	5/9–12/31	5/17–12/31	6/7–12/6

The sets of separation parameters from the orbital solutions constrained by each of the six rejection cutoffs are listed in Table 1. The apparent, expected decrease in the nominal mean residual with decreasing rejection cutoff is diagnostically meaningless. In fact, an excessively tight rejection cutoff requires that most observations be discarded (e.g., 90% for a cutoff of 0.2 arcsec), including many at either end of the time span covered, thus shortening the orbital arc to be used in the computations and leading necessarily to relatively inferior solutions. In truth, the most constraining rejection cutoff is yielded by its minimum value that is expressed in terms of the standard deviation σ of a fitted Gaussian distribution law.

A discriminating search criterion can appropriately be formulated on the basis of a simple consideration that follows. Let $z \equiv {\rm o} - {\rm c}$ be the residual between the observed value of a offset of nucleus A from nucleus B and its value calculated from the chosen solution. Let $z_{\rm c}$ be the absolute value of an intrinsic rejection cutoff. Since the offset residuals for each solution's output are given to 0.01 arcsec, the intrinsic rejection cutoff equals its nominal value (as listed in Table 1) + 0.005 arcsec. Similarly, the intrinsic number ν of the offset residuals equals to $2N+1$, where N is the number of pairs of offsets. The unity is the most likely correction that, for a continuous distribution, expresses the fact that N pairs of offsets do satisfy the rejection cutoff, but $N+1$ do not. Since, for a Gaussian distribution, $d\nu \sim \exp(-\frac{1}{2}z^2/\sigma^2)\,dz$ and since $-z_{\rm c} \leq z \leq +z_{\rm c}$, then

$$\nu = C \int_{-z_{\rm c}}^{+z_{\rm c}} \exp\left(-\frac{z^2}{2\sigma^2}\right) dz = \sqrt{2\pi} C \sigma\, {\rm erf}(\zeta_{\rm c}), \qquad (1)$$

where C is a constant of proportionality and $\zeta_{\rm c}$ is given by

$$\zeta_{\rm c} = \frac{z_{\rm c}}{\sigma\sqrt{2}}. \qquad (2)$$

Table 2. Comparison of the solutions

Rejection cutoff (arcsec)		No. of offsets,	Sum $\Sigma({\rm o}-{\rm c})^2$	Ratio	Ratio
nominal	intrinsic, $z_{\rm c}$	ν	(arcsec^2)	F	$z_{\rm c}/\sigma$
1.2	1.205	197	50.5715	0.1768	2.166
1.0	1.005	175	34.6230	0.1959	1.976
0.8	0.805	149	20.9932	0.2174	1.769
0.6	0.605	127	13.2861	0.2858	1.065
0.4	0.405	67	2.6748	0.2434	1.517
0.2	0.205	27	0.2662	0.2346	1.603

Since, furthermore, the squares of residuals summed up over the N pairs of offsets can be expressed as

$$\sum ({\rm o}-{\rm c})^2 = C \int_{-z_{\rm c}}^{+z_{\rm c}} z^2 \exp\left(-\frac{z^2}{2\sigma^2}\right) dz$$
$$= 2\sqrt{2} C \sigma^3 \left[\tfrac{1}{2}\sqrt{\pi}\, {\rm erf}(\zeta_{\rm c}) - \zeta_{\rm c}\, e^{-\zeta_{\rm c}^2}\right], \qquad (3)$$

a ratio $\dfrac{1}{\nu z_{\rm c}^2} \sum ({\rm o}-{\rm c})^2 \equiv F$ can be written in the form

$$F = \frac{1}{2\zeta_{\rm c}^2} \left[1 - \frac{2}{\sqrt{\pi}} \frac{\zeta_{\rm c}}{{\rm erf}(\zeta_{\rm c})} e^{-\zeta_{\rm c}^2}\right]. \qquad (4)$$

It can be shown that F is a monotonically nonincreasing function of $\zeta_{\rm c}$, with $\lim_{\zeta_{\rm c} \to 0} F = \frac{1}{3}$ and $\lim_{\zeta_{\rm c} \to \infty} F = 0$. Since, for any solution, F is expressible in terms of the quality-of-fit data, Eqs. (2) and (5) can be used to find $z_{\rm c}/\sigma$, the quantity of interest here, from this information.

Table 2 compares the six solutions in terms of $z_{\rm c}/\sigma$. It is apparent that the condition $0 \leq F \leq \frac{1}{3}$ is satisfied by each of the tabulated values of F and that the most constraining rejection cutoffs are near 0.6 arcsec. The standard deviation of the
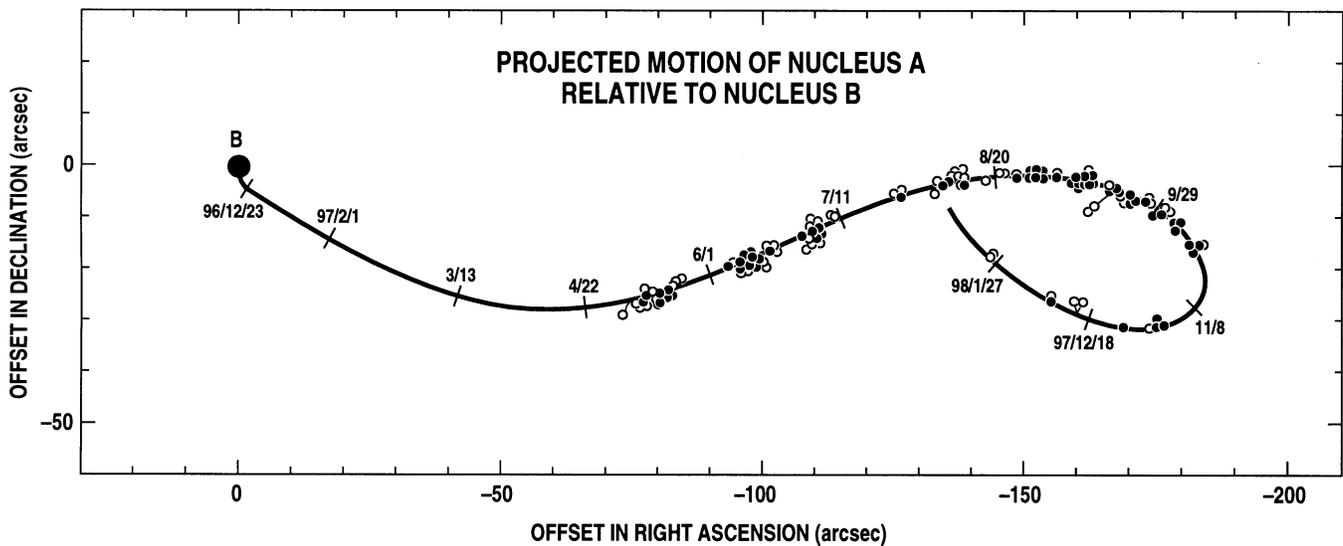
Fig. 1. Motion of nucleus A relative to nucleus B of comet Evans-Drinkwater in projection onto the plane of the sky (equinox B1950.0). The large circle is the fixed location of nucleus B, the smaller solid circles are the 63 measured positions of nucleus A that have been used in the solution with the assumed rejection cutoff of 0.6 arcsec. The curve represents this solution. The open circles are the 61 positions of nucleus A that yield residuals larger than 0.6 arcsec. On the scale of this plot, those of these positions with residuals essentially along the trajectory may fortuitously appear to fit the solution. The tick marks indicate the calculated positions of nucleus A at the standard 40-day epochs between December 1996 and January 1998.

Gaussian function amounts then to ±0.57 arcsec, or about 1.7 times the mean residual listed in Table 1. Inspection of the actual distribution of the relevant offset residuals has confirmed that within ±0.6 arcsec they have indeed been fitted most satisfactorily by the Gaussian law; for larger residuals, the distribution rapidly becomes distinctly non-Gaussian. The author is satisfied that the solution with the rejection cutoff of 0.6 arcsec offers a high-quality set of parametric values, probably the best achievable one under the circumstances.

The magnitude of the nongravitational deceleration classifies nucleus A as a typical *short-lived* companion, even though its calculated *endurance* (cf. Sekanina 1982a for the definition) of 109 equivalent days is more than twice the expected value for its minimum lifetime.

The excellent match to the measured offsets of nucleus A is apparent from Fig. 1, which also shows the computed motion of the companion prior to its discovery. Unfortunately, the comet's appearance at the time of splitting will never be known, as the object was then only ∼ 20° from the Sun, heading for conjunction with it on Feb. 10, 1997, 6 weeks after perihelion. In fact, the comet was not at all observed between July 18, 1996 and May 5, 1997. Even though its perihelion distance was 1.3 AU, it was never seen at heliocentric distances under 2.2 AU!

3. Remarks on physical behavior, and conclusions

Following the major outburst of the companion, its rapid fading relative to the primary was the most prominent systematic change in the comet's physical behavior. One month after the outburst, the two components were of nearly equal brightness, and several months after another, minor flare-up, component
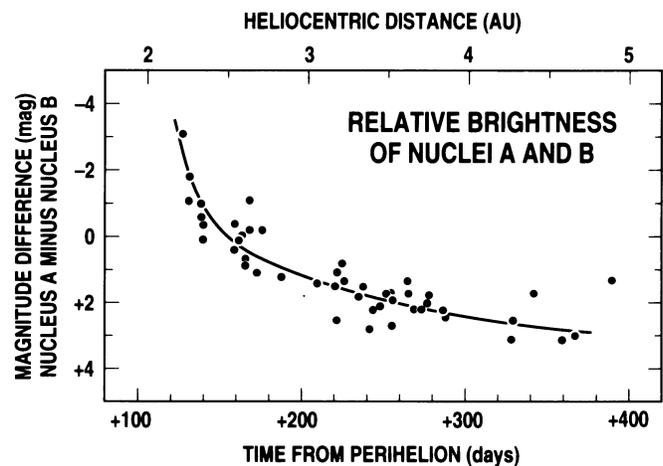

Fig. 2. Magnitude difference between components A and B vs. time and heliocentric distance. The negative values mean that the companion nucleus A was then the brighter of the two.

A became some 2 magnitudes fainter than B. The magnitude differences, obtained mostly from the same sources as the positional offsets, are presented in Fig. 2. On the whole, a fading of component A by a factor of ∼ 100 or more relative to component B is apparent on a timescale of seven or so months.

The comet's light curve, based on a set of selected observations, is shown in Fig. 3. Judging from the preperihelion magnitudes, reported by Hale and Nakamura (1996) and Luethen (1997) and reduced to a consistent system of visual magnitudes, the comet was brightening steadily, its intrinsic brightness varying inversely as about a cube of heliocentric distance. Only very few magnitude estimates of the comet as a whole are available
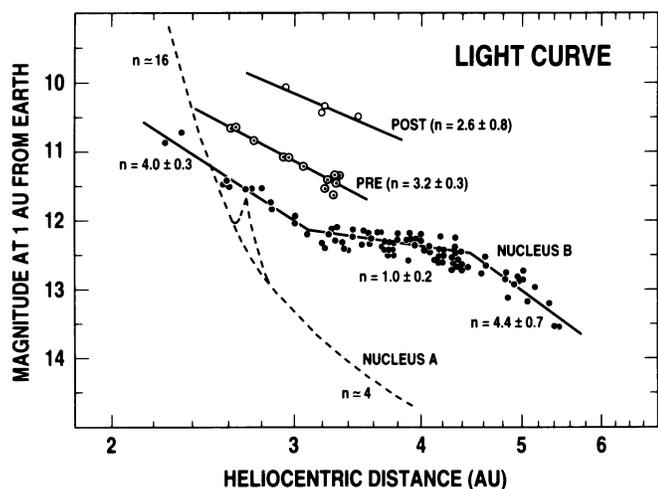
Fig. 3. The normalized light curve of comet Evans-Drinkwater. Circled dots and open circles are, respectively, the visual estimates of the comet's integrated brightness before perihelion (the "pre" curve) and afterwards (the "post" curve). The dots are magnitude estimates for the nuclear condensation of component B. The light curve of component A is schematically depicted by dashes. The brightness is shown to vary inversely as an nth power of heliocentric distance, with n being specified.

from the post-breakup period of time. Although somewhat uncertain, these data suffice to show that the comet was much brighter than implied by the numerous reported CCD "total" brightness estimates of component B, suggesting that the latter refer only to the primary's nuclear condensation (though not to the true nucleus). The light curve for component B shows interesting temporal variations: its fading proceeded at a moderate rate up to a heliocentric distance of 3.1 AU, at which time it slowed down dramatically, only to resume at a steeper rate again at 4.5 AU from the Sun. These moderate variations contrast with the precipitous drop in the brightness of component A.

In the context of split comets as a category of objects, Evans-Drinkwater is the 30th *nontidally* split comet on the list (cf. Sekanina 1997b), the seventh *new* comet (in the Oort sense) known to have split (for the original orbit, see Marsden and Williams 1997), and one of four split comets with the extremely well determined separation parameters. This is the first time that a companion to the nucleus of a new comet was discovered while in outburst and much brighter than the primary.

The previously known instances included only two short-period comets: 69P/Taylor, which confused Barnard (1916) into believing that the companion was all that was left from the comet; and 79P/du Toit-Hartley, for which the companion's rapid fading was in fact successfully predicted (Sekanina 1982b).

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