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PECULIAR PAIR OF DISTANT PERIODIC COMETS C/2002 A1 AND C/2002 A2 (LINEAR)

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ABSTRACT

Distant comets C/2002 A1 and C/2002 A2 make up a peculiar pair that moves about the Sun in virtually identical, somewhat unstable orbits, extending currently between about 4.7 and 29 AU from the Sun. The two objects, observed since late 2001, are unquestionably of common origin. Analysis of their relative motion indicates that their parent body split nontidally most probably between mid-1977 and early 1979 at a heliocentric distance of 22.5 ± 0.1 AU and about 2.5 AU below the ecliptic, with a separation velocity of 2.7 ± 0.2 m s^{-1}. The motion of C/2002 A2, the secondary component that trails behind the primary, is found to be affected by a nongravitational deceleration of (13.4 ± 1.5) × 10^{-5} units of solar gravitational acceleration relative to C/2002 A1, which is in a range of decelerations that companions of split comets are usually subjected to. C/2002 A2 was somewhat less condensed and, interestingly, brighter than C/2002 A1.

Subject headings: comets: general — comets: individual (C/2002 A1, C/2002 A2) — methods: data analysis

1. INTRODUCTION

Comets C/2002 A1 and C/2002 A2 were discovered with a 1 m f/2.15 folded prime-focus Cassegrain reflector of the Lincoln Near Earth Asteroid Research (LINEAR) Project[1] on 2002 January 8 as objects of asteroidal appearance some 40′ apart, sharing the same motion and displaying nearly parallel tails (Green 2002). The comets, obviously of common parentage, were later identified in the prediscovery images taken by LINEAR on 2001 December 13 and 17 (Blythe et al. 2002a, 2002b). The second comet was also detected in the LINEAR images obtained on 2001 November 19 and in the images taken 1 month later, on December 18, with a 1.2 m Oschin Schmidt telescope of the Near-Earth Asteroid Tracking Project (Helin et al. 2002). Prior to being recognized as a comet, C/2002 A1 was given an asteroidal designation 2001 XG_{115} (Green 2002). The last astrometric observations of C/2002 A1 and C/2002 A2 in 2002 were made on February 6 and April 5, respectively (Nakamura 2002c; Manteca 2002c). In 2003, the two comets were detected only at the Kleť Observatory with a 1.06 m f/2.7 telescope of the KLENOT Project (Tichá, Tichý, & Kočer 2002a): C/2002 A1 between February 25 and April 4, C/2002 A2 between February 22 and April 4 (Tichá, Tichý, & Kočer 2003a, 2003b, 2003c).

2. BRIGHTNESS

The comets were about equally bright when detected together for the first time in the prediscovery images of 2001 December 13. Only 4 days later, however, C/2002 A2 was brighter, and it remained so until the beginning of February 2002. Afterward, C/2002 A1 was not seen for more than a year. When detected in late February 2003, it was again fainter than C/2002 A2. The reported magnitude differences ΔH in the sense C/2002 A2 minus C/2002 A1 (Blythe et al. 2002a, 2002b; Tichá, Tichý, & Kočer 2002b, 2002c; Bickel 2002; Buzzi 2002a, 2002b; Nakamura 2002a, 2002b; Seki 2002; Manteca 2002a, 2002b; Manca et al. 2002a, 2002b; Akahori 2002a, 2002b; Sugie 2002; the 2003 Kleť data being added by us), which in spite of the inherent uncertainties illustrate the systematically greater brightness of C/2002 A2, are presented in Table 1.

[1] Operated by Massachusetts Institute of Technology's Lincoln Laboratory, Lexington, Massachusetts.

3. ORBITS

Separate sets of orbital elements for C/2002 A1 and C/2002 A2 were calculated by Marsden (2003), with no nongravitational terms included. They differ very little except that C/2002 A1 reached its 2001 perihelion 7.6 days before C/2002 A2 did. Such an orbital configuration is typical for a fragmentation scenario in which the parent comet splits long before observation (e.g., Sekanina 1997) and the leading object, in this case C/2002 A1, is the principal (primary or more massive) component. This tentative conclusion is fully supported by a detailed fragmentation solution (§ 5), thus implying that the principal component was consistently fainter than its companion (secondary, less massive component). Such cases are untypical but not exceptional among split comets.

The calculations of Marsden (2003) indicate that the orbit of the two comets has a perihelion distance of 4.7 AU and a relatively low inclination of 14°, so that close encounters with Jupiter are possible. Indeed, both objects were reported to have approached the planet to within 0.4 AU only about 5 months before their 2001 perihelion (Green 2002). The aphelion, currently at a heliocentric distance near 29 AU, is just inside the orbit of Neptune. Because of effects by the planetary perturbations, the orbital period has been rather unstable, its osculating value amounting to ∼77 yr near perihelion (late November 2001) but only ∼69 yr some 12 months later.

4. ASTROMETRIC OFFSETS AND FRAGMENTATION MODEL

The motion of the companion, C/2002 A2, relative to the primary, C/2002 A1, is readily described by the offsets in right ascension and declination between the two components. However, because of their large angular distance, their astrometric positions cannot usually be determined from common exposures. Thus, the relative motion between the exposures is appropriately accounted for and the offsets are then referred to

TABLE 1
REPORTED BRIGHTNESS DIFFERENCES BETWEEN C/2002 A1 AND C/2002 A2

Date (UT)	Difference ΔH[a] (mag)	Observer(s)
2001 Dec 13.3	−0.1	M. Blythe et al. (Socorro)
2001 Dec 17.4	−0.6	M. Blythe et al. (Socorro)
2002 Jan 8.3	−0.7	M. Blythe et al. (Socorro)
2002 Jan 9.8	−0.75	M. Tichý, M. Kočer (Kleť)
2002 Jan 9.9	−0.8	W. Bickel (Bergisch Gladbach)
2002 Jan 10.8	−0.7	M. Tichý (Kleť)
2002 Jan 12.9	0.0	L. Buzzi (Varese)
2002 Jan 13.5	*−0.7*	A. Nakamura (Kuma Kogen)
2002 Jan 13.6	*−0.5*	T. Seki (Geisei)
2002 Jan 16.0	*−0.4*	M. Tichý (Kleť)
2002 Jan 16.9	*−0.3*	J. Manteca (Begues)
2002 Jan 18.9	−1.1	F. Manca et al. (Sormano)
	−0.1	J. Manteca (Begues)
2002 Jan 19.4	*−0.8*	A. Akahori (Akashina)
2002 Feb 1.5	*−0.8*	A. Sugie (Dynic)
2003 Feb 25.9	*−0.7*	J. Tichá et al. (Kleť)
2003 Mar 5.0	*−0.9*	M. Tichý, M. Kočer (Kleť)
2003 Mar 22.8	*−1.2*	J. Tichá, M. Tichý (Kleť)
2003 Mar 23.8	*−1.2*	J. Tichá, M. Tichý (Kleť)
2003 Apr 4.8	*−1.1*	J. Tichá, M. Tichý (Kleť)

[a] Roman numbers refer to "nuclear" magnitudes, whereas italic numbers refer to "total" magnitudes; minus signs mean that C/2002 A2 was brighter than C/2002 A1.

TABLE 2
RESULTING FRAGMENTATION SOLUTION FOR PAIR C/2002 A1 AND C/2002 A2

Quantity	Value
Time of fragmentation:	
Most probable year and fraction	1978.4
Years before 2001 perihelion	23.5 ± 0.9
Heliocentric distance (AU)	22.5 ± 0.1
Distance from ecliptic (AU)	−2.53 ± 0.03
Separation velocity (m s^{-1}):	
Radial component, V_R	2.66 ± 0.17
Transverse component, V_T	−0.28 ± 0.04
Normal component, V_N	−0.067 ± 0.003
Total velocity	2.68 ± 0.17
Differential deceleration[a]	13.4 ± 1.5
Astrometry:	
Period of observation	2001 Dec 13–2003 Apr 4
Time covered by observations (days)	477.5
Number of observations used	57
rms residual (arcsec)	±0.35

[a] In units of 10^{-5} the solar gravitational acceleration.

the observation times of the secondary component. Since it is customary to secure a set of astrometric positions for both the primary and secondary during each night's observing session, the described procedure allows one to average the offsets for a given observation of the secondary component compared with a number of observations of the primary at times that differ by a very small fraction of a day (usually less than 1 hr).

The objective of this investigation is to use the offsets of the secondary from the primary in order to derive the parameters of a fragmentation model, developed long ago (Sekanina 1978, 1982) and tested extensively ever since.

The technique employed to find the fragmentation solution is a modification of the previously applied approach in that the iterative least-squares differential-correction optimization procedure is accompanied by an orbit-integration code that accounts fully for the perturbations by all the planets, for the relativistic effect and, if necessary, for the nongravitational perturbations in style II of Marsden, Sekanina, & Yeomans (1973). This code starts from any particular osculation epoch at which we know the orbit of the primary component and integrates the motion numerically forward or backward to any osculation epoch between B.C.E. 3000 and A.D. 3000 with a variable step that automatically prevents the accumulation of error from exceeding a prescribed tolerance threshold.

In a right-handed RTN coordinate system centered on the primary object, referred to its orbit plane, and defined by the orthogonal directions radial away from the Sun, transverse in the orbit plane, and normal to the plane, an optimized fit to the observed offsets allows one to determine the following parameters of the model (Sekanina 1978, 1982): (1) the fragmentation time $t_{\rm frg}$; (2) the components of the separation velocity $V_{\rm sep}$ of the secondary from the primary in the three cardinal directions, V_R, V_T, and V_N; and (3) the differential deceleration γ, caused by nonuniform outgassing and assumed to act continuously in the direction away from the Sun and to vary as the inverse square of heliocentric distance. Since the mutual gravitational attraction of the fragments immediately following their separation is ignored (as observations provide no information on these effects), the derived separation velocity represents the relative velocity of the fragments immediately after the interaction has ceased.

The iterative differential-correction optimization procedure allows one to make use of software that solves the normal equations for an arbitrary number of unknowns, N. For the full-scale fragmentation model, one of course has $N = 5$. However, an important feature of the procedure is the option to solve for any combination of fewer than the five parameters ($N < 5$), so that a total of 31 different versions is available. This option is most beneficial at the beginning of a parametric search or when the convergence is slow.

Let the number of astrometric observations be n. Furthermore, let $({\rm R.A.}_1)_k^{\rm (obs)}$ and $({\rm decl.}_1)_k^{\rm (obs)}$ be, respectively, the observed right ascension and declination of C/2002 A1 at time t_k ($k = 1, \ldots, n$), and let similarly $({\rm R.A.}_2)_k^{\rm (obs)}$ and $({\rm decl.}_2)_k^{\rm (obs)}$ be these coordinates for C/2002 A2 at the same time. The observed offsets are

$$\mathcal{R}_k = [({\rm R.A.}_2)_k^{\rm (obs)} - ({\rm R.A.}_1)_k^{\rm (obs)}] \cos\,({\rm decl.}_1)_k^{\rm (obs)},$$

$$\mathcal{R}_{n+k} = ({\rm decl.}_2)_k^{\rm (obs)} - ({\rm decl.}_1)_k^{\rm (obs)}, \quad k = 1, \ \ldots, n. \quad (1)$$

Next, let the right ascension and declination of the primary derived from its perturbed orbital elements for time t_k be, respectively, $({\rm R.A.}_1)_k^{\rm (cal)}$ and $({\rm decl.}_1)_k^{\rm (cal)}$, and let the right ascension and declination of the secondary calculated for the same time from a starting set of fragmentation parameters, $(t_{\rm frg})_0, \ldots, \gamma_0$, be similarly $({\rm R.A.}_2)_k^{\rm (cal)}$ and $({\rm decl.}_2)_k^{\rm (cal)}$. The calculated offsets are

$$\Re_k = [({\rm R.A.}_2)_k^{\rm (cal)} - ({\rm R.A.}_1)_k^{\rm (cal)}] \cos\,({\rm decl.}_1)_k^{\rm (cal)},$$

$$\Re_{n+k} = ({\rm decl.}_2)_k^{\rm (cal)} - ({\rm decl.}_1)_k^{\rm (cal)}, \quad k = 1, \ \ldots, n. \quad (2)$$

The equations of condition for minimizing the differences between the observed and calculated offsets, i.e., their residuals, can formally be written as

$$\mathcal{R}_k - \Re_k = \frac{\partial \Re_k}{\partial t_{\rm frg}} \Delta t_{\rm frg} + \frac{\partial \Re_k}{\partial V_R} \Delta V_R + \frac{\partial \Re_k}{\partial V_T} \Delta V_T + \frac{\partial \Re_k}{\partial V_N} \Delta V_N + \frac{\partial \Re_k}{\partial \gamma} \Delta \gamma, \quad k = 1, \ \ldots, 2n, \quad (3)$$

TABLE 3
Observed Offsets and Final Residuals for Pair C/2002 A1 and C/2002 A2

Time (UT)	Offset[a] R.A. (arcsec)	Offset[a] Decl. (arcsec)	Residual[b] R.A. (arcsec)	Residual[b] Decl. (arcsec)	Observer(s)
2001 Dec 13.29701	−2344.6	−300.0	−0.1	−0.6	M. Blythe et al.
2001 Dec 13.32726	−2344.6	−298.8	+0.1	+0.6	M. Blythe et al.
2001 Dec 17.39324	−2361.6	−307.5	+0.1	−0.3	M. Blythe et al.
2001 Dec 17.40840	−2361.5	−307.8	+0.3	−0.6	M. Blythe et al.
2002 Jan 8.33908	−2398.4	−356.2	+0.4	+0.1	M. Blythe et al.
2002 Jan 8.38627	−2398.9	−357.1	−0.1	−0.6	M. Blythe et al.
2002 Jan 9.84291	−2397.7	−359.6	−0.1	+0.1	M. Tichý, M. Kočer
2002 Jan 9.84561	−2397.4	−359.8	+0.2	−0.1	M. Tichý, M. Kočer
2002 Jan 9.84774	−2397.6	−360.1	0.0	−0.3	M. Tichý, M. Kočer
2002 Jan 9.85141	−2397.8	−359.9	−0.2	−0.1	M. Tichý, M. Kočer
2002 Jan 9.93649	−2397.2	−359.7	+0.4	+0.2	W. Bickel
2002 Jan 9.94032	−2397.0	−359.7	+0.5	+0.3	W. Bickel
2002 Jan 9.94417	−2397.4	−359.5	+0.1	+0.5	W. Bickel
2002 Jan 9.94801	−2397.3	−359.7	+0.2	+0.2	W. Bickel
2002 Jan 10.83551	−2396.7	−362.3	−0.1	−0.4	M. Tichý
2002 Jan 10.83693	−2396.2	−362.0	+0.3	−0.1	M. Tichý
2002 Jan 10.83831	−2396.2	−362.1	+0.3	−0.2	M. Tichý
2002 Jan 10.83968	−2396.2	−362.0	+0.3	0.0	M. Tichý
2002 Jan 10.84166	−2396.6	−362.0	−0.1	0.0	M. Tichý
2002 Jan 11.34619	−2396.1	−363.6	−0.2	−0.6	T. B. Spahr
2002 Jan 11.35079	−2396.3	−363.5	−0.4	−0.4	T. B. Spahr
2002 Jan 11.63211	−2395.5	−363.9	+0.1	−0.2	R. H. McNaught
2002 Jan 11.63372	−2395.8	−363.9	−0.2	−0.2	R. H. McNaught
2002 Jan 11.66478	−2395.2	−363.9	+0.3	−0.1	R. H. McNaught
2002 Jan 11.66638	−2395.5	−363.8	0.0	−0.1	R. H. McNaught
2002 Jan 13.58549	−2392.8	−367.3	−0.4	+0.6	A. Nakamura
2002 Jan 13.60118	−2392.9	−367.4	−0.5	+0.5	T. Seki
2002 Jan 16.03514	−2387.5	−372.9	−0.1	+0.1	M. Tichý
2002 Jan 16.03681	−2387.6	−372.4	−0.1	+0.5	M. Tichý
2002 Jan 16.03817	−2387.7	−372.6	−0.2	+0.3	M. Tichý
2002 Jan 16.03950	−2387.9	−372.7	−0.4	+0.2	M. Tichý
2002 Jan 18.07280	−2382.9	−376.9	−0.5	0.0	S. P. Laurie
2002 Jan 18.08962	−2382.4	−377.3	−0.1	−0.3	S. P. Laurie
2002 Jan 18.10382	−2382.6	−376.9	−0.3	+0.1	S. P. Laurie
2002 Jan 19.43958	−2378.0	−379.5	+0.5	0.0	A. Akahori
2002 Jan 19.45000	−2378.0	−379.3	+0.4	+0.2	A. Akahori
2002 Jan 19.45694	−2378.2	−379.4	+0.2	+0.2	A. Akahori
2002 Feb 1.48148	−2324.1	−397.7	−0.1	+0.1	A. Sugie
2002 Feb 1.49091	−2324.2	−397.6	−0.3	+0.3	A. Sugie
2003 Feb 25.93816	−1000.4	+243.5	−0.5	+0.5	J. Tichá et al.
2003 Feb 25.94019	−1000.7	+242.8	−0.7	−0.2	J. Tichá et al.
2003 Mar 5.01874	−1000.5	+237.6	+0.4	−0.3	M. Tichý, M. Kočer
2003 Mar 5.02203	−1000.6	+237.7	+0.2	−0.2	M. Tichý, M. Kočer
2003 Mar 5.02377	−1000.7	+238.1	+0.2	+0.2	M. Tichý, M. Kočer
2003 Mar 5.02449	−1000.9	+237.9	0.0	0.0	M. Tichý, M. Kočer
2003 Mar 5.03840	−1001.2	+237.6	−0.3	−0.3	M. Tichý, M. Kočer
2003 Mar 5.03905	−1001.1	+237.6	−0.3	−0.4	M. Tichý, M. Kočer
2003 Mar 22.81634	−983.9	+217.0	+0.3	−0.1	J. Tichá, M. Tichý
2003 Mar 22.81751	−984.0	+217.6	+0.2	+0.5	J. Tichá, M. Tichý
2003 Mar 22.81851	−984.1	+216.5	+0.1	−0.6	J. Tichá, M. Tichý
2003 Mar 22.82250	−983.8	+216.4	+0.4	−0.7	J. Tichá, M. Tichý
2003 Mar 23.79418	−983.0	+215.4	−0.6	−0.3	J. Tichá, M. Tichý
2003 Mar 23.79877	−982.5	+215.9	0.0	+0.2	J. Tichá, M. Tichý
2003 Mar 23.79976	−982.8	+216.1	−0.3	+0.4	J. Tichá, M. Tichý
2003 Mar 23.80063	−982.9	+216.0	−0.5	+0.3	J. Tichá, M. Tichý
2003 Apr 4.82553	−954.2	+197.8	+0.6	+0.6	J. Tichá, M. Tichý
2003 Apr 4.82947	−954.0	+197.6	+0.7	+0.4	J. Tichá, M. Tichý

[a] As defined by eq. (1).
[b] As defined by eq. (3).

where $\Delta t_{\rm frg}, \ldots, \Delta\gamma$ are the differential corrections to the starting values of the parameters that yield their refined values $t_{\rm frg} = (t_{\rm frg})_0 + \Delta t_{\rm frg}, \ldots, \gamma = \gamma_0 + \Delta\gamma$ for the next iteration. The equations of condition serve to set up the normal equations from which the optimized corrections and the improved set of parameters are actually computed. Identifying the individual parameters by $P_1 \equiv t_{\rm frg}$, $P_2 \equiv V_R, \ldots, P_5 \equiv \gamma$, and writing the expressions involving the partial derivatives as

$$[Q_{ij}] = \sum_{k=1}^{2n} \frac{\partial \Re_k}{\partial P_i} \frac{\partial \Re_k}{\partial P_j}, \quad i, j = 1, \ldots, N, \tag{4}$$

$$[Q_i] = \sum_{k=1}^{2n} (\mathcal{R}_k - \Re_k) \frac{\partial \Re_k}{\partial P_i}, \quad i = 1, \ldots, N, \tag{5}$$

one finds the normal equations in the form

$$\sum_{j=1}^{N} [Q_{ij}] \Delta P_j = [Q_i], \quad i = 1, \ldots, N, \tag{6}$$

where $\Delta P_1 \equiv \Delta t_{\rm frg}, \ldots, \Delta P_5 \equiv \Delta\gamma$. The steps of variation in the expressions for the partial derivatives, the convergence thresholds for the iterated corrections of the fragmentation parameters, and the upper limit on the number of iterations can freely be selected and controlled by input. A successful iterative procedure terminates with the solution's convergence, when $\Delta P_j \rightarrow 0$ for $j = 1, \ldots, N$. The quality of the fit is characterized by the sum of squares of the residuals in right ascension and declination,

$$[Q_0] = \sum_{k=1}^{2n} (\mathcal{R}_k - \Re_k)^2 \rightarrow \min . \tag{7}$$

The residuals from the offsets included in the solution describe the quality of the fit in greater detail than $[Q_0]$, because for a satisfactory solution no systematic trends should be apparent. The differences between the residuals derived from the equations of condition and from the set of iterated fragmentation parameters measure the degree of convergence of the optimization scheme.

5. DATA SET AND RESULTS

In conformity with the interpretation proposed in § 3, the search for a fragmentation solution was based on the right ascension and declination offsets of C/2002 A2 from C/2002 A1, computed from the astrometric positions of the two objects. The complete set of observations initially employed in our model calculations (Blythe et al. 2002a, 2002b; Tichá et al. 2002b, 2002c, 2003a, 2003b, 2003c; Bickel 2002; Spahr 2002; McNaught 2002a, 2002b; Buzzi 2002a, 2002b; Nakamura 2002a, 2002b; Seki 2002; Manteca 2002a, 2002b; Laurie 2002; Manca et al. 2002a, 2002b; Akahori 2002a, 2002b; Sugie 2002) consisted of 86 offset pairs, determined as described at the beginning of § 4. Of these, 29 were found to leave positional residuals exceeding an adopted threshold of $\sim 0''.7$ and were subsequently removed from the data set.

The resulting parameters of the fragmentation model are listed in Table 2, whereas the positional residuals for the 57 used offset pairs are presented in Table 3. The quality of fit is deemed excellent, with no systematic trends apparent. The solution indicates that the parent comet broke up most probably in 1978 May with a formal uncertainty of less than a year. The comet was at that time more than 22 AU from the Sun and about 2.5 AU below the ecliptic. It is therefore clear that the fragmentation event was nontidal in nature (Sekanina 1997). The fragments separated from one another with a velocity of approximately 2.7 ± 0.2 m s^{-1}, mostly along the Sun-comet line. The deceleration is, as expected, positive, thus confirming the companion status of C/2002 A2. Its value is somewhat higher than average for the persistent companions but lower than for the short-lived companions (Sekanina 1982). Based on this information, the endurance of C/2002 A2 against disintegration can be estimated at between 70 and 280 equivalent days (i.e., days normalized to 1 AU from the Sun; Sekanina 1978, 1982). At the time of the last 2003 observation, the lifetime of C/2002 A2 was about 82 equivalent days, and by the time of opposition in 2004, it will increase to 91 equivalent days. There is therefore a good chance that both components of the pair will be observable in 2004, even though their brightness will further decrease. Tentatively, one can expect that they will then be of total apparent magnitude 22 or fainter.

A search for an alternative solution, with no differential nongravitational deceleration (i.e., forcing $\gamma = 0$), led to an unacceptable result, as there were systematic trends in the positional residuals exceeding $1''$. The presented solution is therefore unique.

For comparison, we also searched for a solution based exclusively on the 2001–2002 observations. We found that the length of the orbital arc covered by these observations was inadequate, the model yielding an indeterminate result. The incorporation of the 2003 observations was thus critical, with an overwhelming impact on the fragmentation solution.

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