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Use of long-term nongravitational force models for fitting astrometric observations of comet Encke

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Abstract

Based on the equations derived in (Usanin et al., 2016) a new solution combining the observations of 30 apparitions of the comet Encke from 1911 to 2010 is obtained. For the first time in the worldwide practice the solution is obtained by using converging differential correction of all 60 observed returns of the comet, however, the deviations are still unsatisfactory. The single solution has allowed to draw some preliminary conclusions. The contributions of planetary and nongravitational perturbations to the change of the elements of the orbit during the entire period of observation are determined. The extrapolation of the solution shows that for the past two thousand years the elements of the orbit orientation could change for a half of turnover, which should be taken into account when identifying the comet and associated meteor showers in ancient records. The predictions made by Z. Sekanina and I. Ferrín about oncoming termination of the comet activity are confirmed.

Keywords: Comets; Celestial mechanics; Nongravitational forces; Marsden's model; 2P/Encke

1. Processing of observations of the comet Encke: dynamical model and weights determination

The data on the comet Encke ground-based optical astrometric observations from 1881 was taken from the "MPCOBS" base of the Minor Planet Center (Marsden et al., 1993). The information on the observations taken from 1786 to 1961 was provided at our request by B.G. Marsden who noticed that he could guarantee neither reliability of the observations nor their conformity with what the observers had originally published (Marsden, personal communication, 2010). The observations used in the present work had been already converted to the equator and equinox of J2000.0 and were represented according to the standard format of the Minor Planet Center by Marsden himself, therefore we could use them during the calculations on a par with the other ones without introducing any additional reductions. The orbital elements obtained earlier (Marsden and Sekanina, 1974) from these observations have not been reconsidered until now and are reproduced in all comet catalogues, therefore, we may certainly be sure that this data is as reliable as possible. From each pair of identical records one was deleted. Thus, the data on 2695 observations from 60 apparitions of the comet Encke from 1786 to 2010 (except 1868) was collected.

A set of computer codes were created for observations processing according to the derived equations (Usanin et al., 2016). Theoretical positions for the comet were calculated by numerical integration of the equations of motion with relativistic term and nongravitational effects in two options: with model of significant non-volatile mass without impeding the sublimation and the low-mass crust

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that reduces effective area linearly in thickness – without simplification. To integrate the equations of motion the Everhart method with nodes of 35th order and constant step of 1 day was used, while for solving equations of non-gravitational effects the Radau quadratures were applied. Gravitational attractions of the Sun, major planets, the Moon, Ceres, Pallas, Vesta, Pluto, and Charon were taken into account. Initial positions in the J2000.0 ecliptic coordinate system and masses of the gravitating bodies were taken from the JPL NASA "HORIZONS" service (Giorgini et al., 1996), but the origin of coordinates was shifted to their barycenter according to the relativistic formula. The differences between TDB and UT time scales, diurnal parallax (position of an observer influenced by precession and nutation of the Earth's axis of rotation), planetary aberration (light-time), and differential relativistic deflection of light caused by the gravity of the Sun were taken into account when comparing theoretical and observed positions of the comet. The motion parameters of the comet and their root-mean-square deviations were determined by the weighted least squares method using differential correction with damping. At all stages of the development the software was checked by solving control examples. The error in closure after integrating the motion equations of the comet Encke from 2011 to 1785 and inversely was 6.9 km. The total integrating error could be a few tens of km, which is acceptable for the considered problem.

Since over the period of 225 years during which the comet Encke was observed the accuracy of observations dramatically increased, it is incorrect to combine significant number of the comet apparitions without determining observations' weights. Usually, the values which are inversely proportional to the squares of a priori root-mean-square deviations σ_{apr} of observations are accepted as weights. It is clear that they should be defined so that they do not depend on the model of nongravitational force, but at the same time according to the sample as representative as possible. Since the nongravitational forces are significant near the perihelion, division into groups containing halves of the number of observations from pairs of consecutive apparitions satisfies these conditions. The first and the last apparitions are included in the corresponding groups completely. Apparently erroneous observations incompatible by 3σ criterion with the other ones are revealed and removed. According to the results of differential correction in 59 groups, 145 observations are eliminated, for the rest 2550 the values of σ_{apr} are determined and presented in Table 1. The values in Table 1, although differ in figures due to distinctions in sets of observations, are consistent with the data on the corresponding time periods from the earlier works (Marsden and Sekanina, 1974; Giorgini et al., 1996). It should be noted that in the modern epoch the accuracy of astrometric observations of comets is much lower than of asteroids, for instance. These errors arising due to the diffuse appearance of comets are usually considered to be random. The question of systematical offset of photocenters relative to centers of mass of comets remains debatable (Chesley et al., 2001).

Table 1
A priori root-mean-square deviations in the groups of observations.

Interval	Observations eliminated	Observations left	σ_{apr}, ″
2007–2010	13	184	1.69
2003–2007	104	589	0.68
2000–2003	15	552	0.72
1997–2000	1	86	1.56
1994–1997	1	130	2.31
1990–1994	1	83	2.16
1987–1990	0	29	1.93
1984–1987	0	33	1.51
1980–1984	0	30	4.61
1977–1980	1	27	5.83
1974–1977	3	19	3.31
1971–1974	0	19	2.97
1967–1971	0	15	3.70
1964–1967	0	9	2.28
1961–1964	1	18	1.07
1957–1961	2	22	1.68
1954–1957	0	13	1.73
1951–1954	0	11	2.26
1947–1951	0	13	3.71
1941–1947	0	8	3.58
1937–1941	0	12	2.34
1934–1937	2	24	2.30
1931–1934	0	18	5.14
1928–1931	0	10	2.43
1924–1928	0	28	3.33
1921–1924	0	27	6.80
1918–1921	0	16	8.78
1914–1918	0	11	4.35
1911–1914	0	6	1.36
1908–1911	0	4	1.40
1905–1908	0	11	1.89
1901–1905	1	21	5.69
1898–1901	0	14	13.0
1895–1898	0	20	3.72
1891–1895	0	28	3.66
1888–1891	0	12	3.17
1885–1888	0	25	3.75
1881–1885	0	29	7.60
1878–1881	0	10	4.32
1875–1878	0	11	3.60
1871–1875	0	14	3.26
1865–1871	0	19	3.12
1862–1865	0	20	2.67
1858–1862	0	14	3.17
1855–1858	0	21	2.75
1852–1855	0	46	3.08
1848–1852	0	34	3.30
1845–1848	0	8	5.75
1842–1845	0	12	6.67
1838–1842	0	17	6.65
1835–1838	0	9	8.76
1832–1835	0	5	5.31
1829–1832	0	16	7.02
1825–1829	0	30	7.45
1822–1825	0	20	8.56
1819–1822	0	11	10.1
1805–1819	0	11	11.5
1795–1805	0	8	28.4
1786–1795	0	8	33.4