35. AN INVESTIGATION OF THE MOTION OF PERIODIC COMET BORRELLY FROM 1904 TO 1967

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Abstract. The motion of P/Borrelly has been investigated using all precise published positions and taking into account the perturbations by Venus to Pluto. Nongravitational forces have been found to influence the motion of the comet considerably, formerly as a secular deceleration, more recently as a secular acceleration. By linking the seven apparitions 1904–1960, with allowance for the nongravitational effects, we have obtained a set of elements which represents 802 observations with a mean error of 1″89.

1. Introduction

Periodic comet Borrelly was discovered by Alphonse Borrelly at the Marseilles Observatory on 1904 December 28 as an object of magnitude 10, 1′–2′ in diameter and possessing a small nucleus (Vsekhsvyatskij, 1958). Having a period of 6.9 yr, the comet was observed at eight apparitions 1904–1967; it was missed in 1939 and 1946. The first apparition of the comet was thoroughly investigated by Fayet (1914), who calculated a final orbit from 430 observations in eight normal places, taking into account perturbations by the six planets Mercury to Saturn; his set of elements represents the normal places with a mean error of 1″397. Later (Fayet, 1925), he formed ten normal places from 259 observations at the 1911–1912 apparition and obtained a set of elements that gave a good representation of the first nine normal places; the last normal place, formed from seven observations at the end of the apparition, produced a residual that was considerably larger than the rest. Fayet then linked the apparitions of 1904–1905 and 1911–1912 and derived a predicted set of elements for 1919, taking into account perturbations by the planets Venus, Earth, Jupiter, and Saturn.

2. Investigation of the Comet's Motion under the Influence of Gravitational Forces

We have investigated the motion of the comet from 1904 to 1967, with the help of the BESM-4 computer at the Institute for Theoretical Astronomy. The following programmes have been used: integration with a variable step, in double precision and with allowance for perturbations by all the major planets (Kazimirchak-Polonskaya, 1967), integration by Cowell's method (Belyaev), comparison of observed and computed coordinates (Belyaev and Bokhan), and improvement of elliptical orbits (Bokhan and Makover). There were 105 accurate observations at the 1918–1919 apparition, 82 in 1925–1926, 33 in 1932–1933, 10 in 1954 and 7 in 1960. The 1967 apparition is represented by a single approximate observation. Using modern star catalogues, we have refined the positions of reference stars for the visual observations, proper motions being taken into account.

We first considered the set of elements (A), obtained by Schaumasse (1931) from an integration of the motion from 1911 to 1919, taking into account the perturbations by the planets Venus-Saturn:

$$
\begin{aligned}
\text{Epoch} &= \text{1919 March 23.0 ET} \\
M_0 &= 17°96984 \\
\omega &= 352.39656 \\
\Omega &= 77.36882 \quad \Big\} \quad 1950.0 \\
i &= 30.49100 \\
\varphi &= 37.96048 \\
\mu &= 0.1427191.
\end{aligned}
\tag{A}
$$

We have compared the 1918–1919 observations with the set (A) and concluded that these elements do not represent these observations adequately. We therefore made a preliminary orbit correction using 92 observations at the 1918–1919 apparition; normal places were not formed. The improved set of elements (I) represents the observations with a mean error of $2''56$:

$$
\begin{aligned}
\text{Epoch} &= \text{1919 March 23.0 ET} \\
M_0 &= 17°9742090 \\
\omega &= 352.392113 \\
\Omega &= 77.3686643 \quad \Big\} \quad 1950.0 \\
i &= 30.4899165 \\
\varphi &= 37.9565861 \\
\mu &= 0.142752508.
\end{aligned}
\tag{I}
$$

The set (I) was adopted as a basis for further investigations. We integrated the motion up to 1925 and then up to 1932, taking into account perturbations by all the major planets. We then succeeded in linking 87 observations at the returns of 1925 and 1932, obtaining the set of elements (II):

$$
\begin{aligned}
\text{Epoch} &= \text{1919 March 23.0 ET} \\
M_0 &= 17°9665203 \\
\omega &= 352.391078 \\
\Omega &= 77.3684744 \quad \Big\} \quad 1950.0 \\
i &= 30.4901315 \\
\varphi &= 37.9569632 \\
\mu &= 0.14274929.
\end{aligned}
\tag{II}
$$

The mean error was $2''44$. Using 38 observations at the same two returns Marsden (1968) obtained an orbit with mean error $2''5$.

Our attempt to link the three apparitions 1918–1919, 1925-1926 and 1932–1933 gave a mean error of $15''4$. On attempting to fit the observations at the 1932, 1953 and 1960 returns Marsden found $(O-C)$ residuals as high as $30''$. He pointed out that P/Borrelly evidently has a nongravitational secular acceleration, amounting to something like 0^d05 per $(\text{period})^2$.

3. Influence of Nongravitational Forces on the Motion of the Comet

On comparing the observations with the calculated orbit, and taking into account gravitational forces very completely, we confirm that P/Borrelly is affected by nongravitational forces, these appearing as systematic secular accelerations and decelerations, their values changing from apparition to apparition.

It is probable that this is not the only comet with this kind of motion. Instances where investigators have found only accelerations or only decelerations, or no nongravitational effects at all, can be explained by the small number of apparitions considered. It is possible that such variations in the action of the nongravitational forces could result in the failure to link particular apparitions of a comet, even when a large number of precise observations is available.

We have investigated the nongravitational variation of the mean anomaly M_0 of P/Borrelly during the whole period covered by observations. This investigation shows that from discovery to its approach to Jupiter (1936 March 26.04717, minimum separation 0.53935 AU) the comet had a secular deceleration; subsequently, the comet had a secular acceleration. The variations of M_0 and the corresponding variations in perihelion time T are given in Table I.

TABLE I

Nongravitational variations in mean anomaly
(ΔM_0) and perihelion time (ΔT)

Apparition	ΔM_0	ΔT
1911	$-0°0310$	$+0^d2180$
1918	-0.0237	$+0.1660$
1925	-0.0154	$+0.1076$
1932	-0.0072	$+0.0503$
1953	$+0.0192$	-0.1366
1960	$+0.0204$	-0.1453

4. Improvement of the Elements

The set of elements (III) was obtained by linking 120 observations of the comet at the five returns 1918–1960 and taking into account the variation of the mean anomaly due to the influence of nongravitational forces; the mean error was $1''61$:

$$
\begin{aligned}
\text{Epoch} &= \text{1919 March 23.0 ET} \\
M_0 &= 17°9743901 \quad \pm\ 0°0000294 \\
\omega &= 352.3914940 \quad \pm\ 0.0001514 \\
\Omega &= 77.3684353 \quad \pm\ 0.0000719 \\
i &= 30.4900482 \quad \pm\ 0.0000519 \\
\varphi &= 37.9565787 \quad \pm\ 0.0000256 \\
\mu &= 0.142752542 \pm 0.000000005.
\end{aligned}
\qquad 1950.0 \qquad \text{(III)}
$$

Finally, we have incorporated the observations at the 1904–1905 and 1911–1912 apparitions, using for this purpose the normal places given by Fayet (1914, 1925), but omitting the tenth normal place at the second apparition. The set of elements (IV) satisfies the observations with a mean error of $1''.89$:

$$
\begin{aligned}
\text{Epoch} &= 1919 \text{ March } 23.0 \text{ ET} \\
M_0 &= 17°.9743786 \pm 0°.0000300 \\
\omega &= 352.3915210 \pm 0.0001439 \\
\Omega &= 77.3684353 \pm 0.0000752 \\
i &= 30.4901341 \pm 0.0000552 \\
\varphi &= 37.9565464 \pm 0.0000234 \\
\mu &= 0.142752536 \pm 0.000000004.
\end{aligned}
\qquad \text{1950.0} \qquad \text{(IV)}
$$

The final elements for the seven apparitions considered are given in Table II. The set of elements for 1967 was obtained by using an approximate value for the nongravitational effects.

TABLE II

Improved elements (equinox 1950.0, times in ET)

Epoch	1905 May 15.0	1911 Oct. 31.0	1919 Mar. 23.0	1925 Aug. 3.0
M_0	16°.8055948	353°.101935	17°.9743901	350°.618223
ω	352.350961	352.373229	352.391494	352.424228
Ω	77.3815379	77.3758291	77.3684353	77.3785897
i	30.4852542	30.4414967	30.4900482	30.5108143
φ	37.9604383	37.8823025	37.9565787	38.0532219
μ	0.142776147	0.142261202	0.142752542	0.143173005
T	1905 Jan. 17.2945	1911 Dec. 18.4893	1918 Nov. 17.0979	1925 Oct. 7.5250

Epoch	1932 July 17.0	1953 Dec. 9.0	1960 Aug. 29.0	1967 Sept. 17.0
M_0	354°.078527	25°.6743858	10°.7737019	12°.8830691
ω	352.551043	350.948992	350.974719	351.035042
Ω	77.3083608	76.1780288	76.1942250	76.1406239
i	30.5294665	31.0896158	31.0661465	31.1140951
φ	38.0765135	37.1548362	37.1150968	37.1975837
μ	0.143401646	0.140679086	0.140381401	0.140862085
T	1932 Aug. 27.2931	1953 June 9.5153	1960 June 13.2578	1967 June 17.5385

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