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Research Note

433 Eros – comparison of lightcurve extrema from 1901–1931 with the present rotation state

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Abstract. The NEAR/Shoemaker space probe determined accurately the rotation period and spin axis direction of asteroid Eros (Konopliv et al. 2002, Icarus, 160, 289). The synthetic lightcurves of Eros derived from its actual rotation state and known shape are compared with the times of lightcurve extrema determined visually, photographically or photometrically during the oppositions in years 1901–1931. The results show that the actual rotation period derived from the NEAR/Shoemaker observations corresponds to the old data (about 290 individual points). The search for any possible acceleration or deceleration of Eros's rotation (caused by, e.g., the YORP effect) was negative due to large errors in the epochs of lightcurve extrema. Nevertheless, the data put a limit on the change of Eros's rotation angular velocity $\mathrm{d}\omega/\mathrm{d}t$ that cannot be greater than $\sim 5 \times 10^{-20}\,\mathrm{s}^{-2}$. The formal fit to the data gives the deceleration of Eros's rotation $-1.4 \times 10^{-20}\,\mathrm{s}^{-2}$, which is in agreement with the theoretical value $-1.5 \times 10^{-20}\,\mathrm{s}^{-2}$ derived by Čapek & Vokrouhlický (2004, Icarus, 172, 526).

Key words. minor planets – asteroids – methods: data analysis

1. Introduction

Asteroid Eros is undoubtedly the most explored object of the whole asteroid population. This is mainly due to the successful NEAR/Shoemaker spacecraft that was orbiting Eros in 2000–2001. Among many other scientific results, one is important for the scope of this work – the accurate determination of Eros's rotation period and spin axis direction. The rotation period was determined with a relative error of only 6×10^{-9} (Konopliv et al. 2002), which is much better than the accuracy obtainable from lightcurve analysis. The relative error of the period determination from the lightcurve analysis from 1951–1993 is of the order of 10^{-7} (Kaasalainen et al. 2001).

The first determination of Eros's rotation period dates back to 1901, when its brightness variations were detected (von Oppolzer 1901) and recognized as due to Eros's rotation and elongated shape. The epochs of lightcurve minima and maxima can be found in the literature and compared with the present rotation state. Although the visual observations are not accurate enough to rival with the period accuracy achieved by NEAR/Shoemaker, the hundred year time base could reveal a possible deceleration or acceleration of Eros's rotation. The steady change in the rotation angular velocity is expected due to the YORP effect – the thermal re-emission of absorbed sunlight (Vokrouhlický & Čapek 2002; Čapek & Vokrouhlický 2004). If the hypothetical variation in the angular velocity was linear with time, the shift in rotation phase (and thus in observed lightcurve extrema) would be proportional to the square of the time.

A rotation period relative accuracy of 6×10^{-9} was obtained from one year observation of NEAR/Shoemaker. We can assume that the fractional period change is limited by the value $(\mathrm{d}P/\mathrm{d}t)/P \simeq 6 \times 10^{-9}\,\mathrm{yr}^{-1}$. The corresponding shift in the rotation phase cumulated over 100 years is 0.31 rad or ~15 min. The accuracy of 15 min in the determination of lightcurve extrema is realistic, especially in the case of sharp lightcurve minima, and would be in principle detectable in the old data.

2. Data compilation

All the data used in the analysis are listed in the Table 1. The first lightcurve extrema timings are from 1901. Prediscovery trails of Eros were found on photographic plates and derived lightcurve maxima from 1894 and 1896 were reported by Pickering (1901). The formal errors assigned to the individual reported epochs of lightcurve extrema were estimated as 10, 15 or 20 min depending on the observational method and reported uncertainty of observations.

The lightcurves observed after the 1931 opposition were not included in the analysis – the expected maximum phase

Table 1. List of observed lightcurve extrema. Here N denotes the number of lightcurve extrema (some of the original epochs were excluded if duplicated in two or more references), observational methods are "pt" – photographic trails, "vis" – visual, "pm" – different kinds of photometric measurements, "pg" – photographic, "dif" – more different methods, and "u" – unknown.

Year(s)	N	Type	Reference
1894, 1896	5	pt	Pickering (1901)
1901	2	u	André (1901)
	5	vis	Becker (1901)
	7	vis	Deichmüller (1901)
1916	1	pm	Pickering (1917)
1930–31	4	pg	Baade (1930)
	4	pg	Schorr (1930)
	3	pm	Müller (1930)
	11	pg	Barbier et al. (1931)
	3	pg	Delporte & Bourgeois (1931)
	11	pm	Graff (1931)
	1	pm	Guerrieri (1932)
	5	pg	Hartmann & Dartayet (1931)
	5	dif	Jacchia (1931a)
	13	pm	Jacchia (1931b)
	4	pg	Lacchini (1931)
	2	pg	Paraskevopoulos & Steyn (1931)
	19	dif	Taffara (1931)
	1	pm	Viaro (1932)
	23	u	Zessewitsch & Florja (1931)
	8	u	Zessewitsch (1930)
	10	pm	Beyer (1935)
1900–1931	98	pm	Campbell (1931)
1901–1931	44	dif	Stobbe (1940)

shift is ~7 min and quadratically decreases with time to become zero in 2000. The photometric lightcurves from 1951 up to now are compiled in the Asteroid Photometric Catalogue (Lagerkvist et al. 2001) and were used for Eros shape modelling and spin state determination by Kaasalainen et al. (2001).

3. Comparison

To compare the published lightcurve extrema with the present rotation state, I used the shape model of Eros by Thomas et al. (2002) available at `http://www.psi.edu/pds/archive/nearmod.html` and the spin state solution by Konopliv et al. (2002) – prime meridian $W = 326.08°$ for the epoch J2000, rotation rate $1639.389\,28 \pm 0.000\,01°$/day (corresponding to the rotation period $P = 5.270\,255\,27 \pm 0.000\,000\,03$ d), pole right ascension and declination $\alpha = 11.363 \pm 0.001°$, $\delta = 17.232 \pm 0.001°$. The viewing and illumination geometry for the times of observations were determined from Earth's and Eros's ephemeris computed by means of JPL's HORIZONS ephemeris generator (`http://ssd.jpl.nasa.gov/horizons.html`). The synthetic lightcurves of Eros were generated using the Hapke's scattering model with parameters derived by Domingue et al. (2002) and assuming a constant rotation period and fixed spin axis orientation. During the NEAR/Shoemaker mission no wobble greater than 0.02° was detected (Miller et al. 2002), which justifies the assumption of a fixed spin axis direction. The predicted lightcurve minima and maxima were compared with the original data.

The results are plotted as the O–C graph in Fig. 1. There are 289 points (41 maxima and 248 minima) together with the estimated error bars. The scatter of the data with respect to the zero O–C line is significantly greater than the scatter expected from random noise. Paradoxically, the data from the 1930/31 opposition are more scattered than the older measurements from 1901–05. This is caused probably by (i) underestimation of formal errors (e.g., the first five points from 1894, 1896 derived from trails on photographic plates); (ii) systematic errors – e.g., two outlying points from 1901 and 1916. Another important source of systematic errors is the fact that even when the shape and spin state of Eros are known accurately, the synthetic lightcurves do not match the observed ones exactly (and lightcurve extrema may be shifted) – the physical description of the surface scattering behaviour is not perfect and there remain unmatched observed features (Ďurech & Kaasalainen 2003).

4. Results

If Eros's rotation period is constant with time, the O–C plot of the phase shift will show observed points randomly scattered around the zero value. On the other hand, if the YORP effect is present, the O–C difference in the phase will increase from the present to the past.

We can denote the rate of change of the rotation angular velocity ω by the parameter $k_Y = d\omega/dt$. The k_Y describes the torque caused by thermal re-emission of absorbed sunlight averaged over the rotation and revolution cycles (Vokrouhlický & Čapek 2002). The corresponding shift in the rotation phase $\Delta\phi$ is then $\Delta\phi = -1/2\, k_Y\, \Delta t^2$, where Δt is a time interval between a fixed epoch (J2000 for the Eros rotation model) and the epoch of observation. The best fit of the YORP effect to the data is plotted as the dashed curve in Fig. 1 and gives the value $k_Y = -1.4 \times 10^{-20}\,\mathrm{s}^{-2}$, which is in agreement with the result of Čapek & Vokrouhlický (2004) who derived the fractional change of Eros's rotation period $(dP/dt)/P = 1.4 \times 10^{-9}\,\mathrm{yr}^{-1}$, which gives $k_Y = -1.5 \times 10^{-20}\,\mathrm{s}^{-2}$. The derived value $k_Y = -1.4 \times 10^{-20}\,\mathrm{s}^{-2}$ is dominated mainly by the data up to 1905. The data before 1905 give $k_Y = -2.1 \times 10^{-20}\,\mathrm{s}^{-2}$ and the data from 1915 to 1931 give $k_Y = -5.7 \times 10^{-21}\,\mathrm{s}^{-2}$, which is practically zero. The outlying points play only marginal role.

The detailed statistical analysis of confidence limits depends on the formal errors of individual measurements. Nevertheless, the data put reliable limits on the possible range of the k_Y parameter. The k_Y lies between the values -5×10^{-20} and $2 \times 10^{-20}\,\mathrm{s}^{-2}$ with 99% probability, implying that the constant period hypothesis with $k_Y = 0$ cannot be rejected. This interval may be affected by varying the formal errors of individual points but the change is not dramatic.

Although the data are too scattered to provide definitive confirmation of the hypothetic change in rotation period, they are in agreement with the results of Čapek & Vokrouhlický (2004) having predicted the deceleration of Eros's rotation.

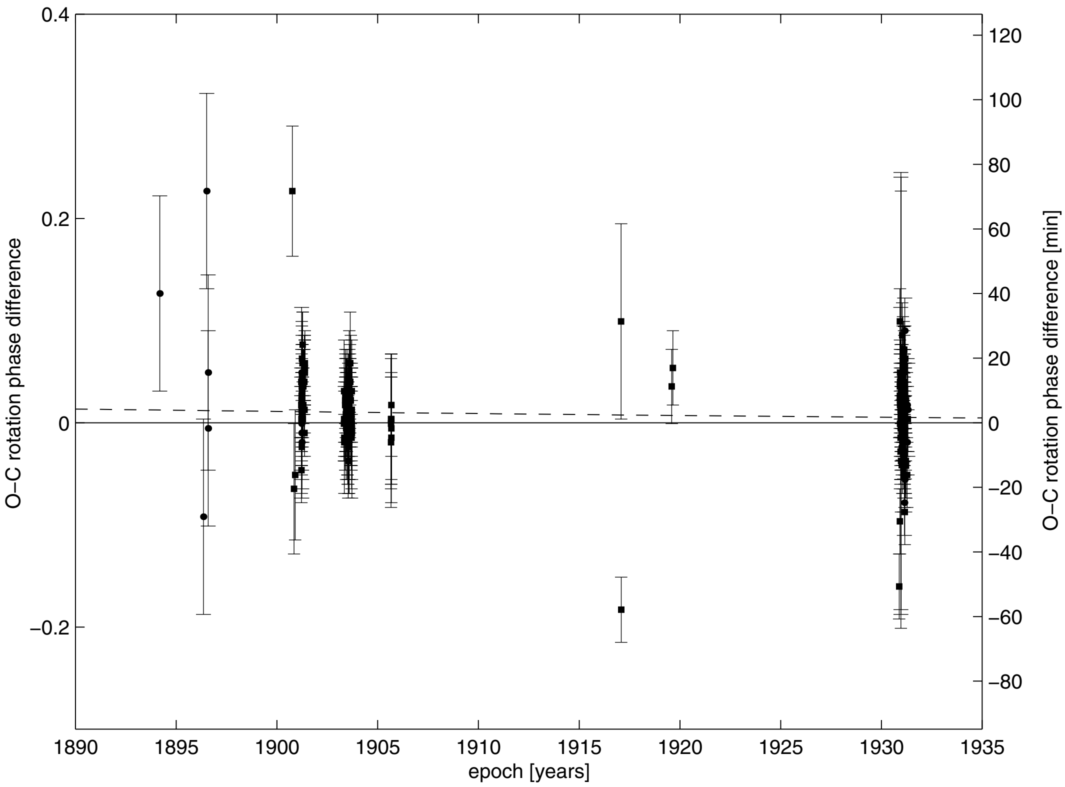

Fig. 1. The O–C plot of lightcurve maxima (circles) and minima (squares) for the data from 1893 to 1931. The dashed curve is the best fit of the YORP effect with $d\omega/dt = -1.4 \times 10^{-20}\ s^{-2}$.

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