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Letter to the Editor

Detection of the YORP effect in asteroid (1620) Geographos

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ABSTRACT

Aims. The rotation state of small asteroids is affected by the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) torque. The directly observable consequence of the YORP effect is the secular change of the asteroid's rotation period. We carried out new photometric observations of asteroid (1620) Geographos in 2008 to extend the time line that, if long enough, would enable us to see possible deviations from a constant period rotation.

Methods. We used the lightcurve inversion method to model the shape and spin state of Geographos. We assumed that the rotation rate evolves in time as $\omega(t) = \omega_0 + \upsilon t$, where both the constant term of the rotation rate ω_0 and the linear term υ are parameters to be optimized. In total, we used 94 lightcurves observed in 1969–2008.

Results. We show that for $\upsilon = 0$, a constant-period model, the whole dataset of lightcurves cannot be satisfactorily fitted. However, when relaxing υ in the optimization process we obtain an excellent agreement between the model and observations. The best-fit value $\upsilon = (1.15 \pm 0.15) \times 10^{-8}$ rad d^{-2} implies that Geographos' rotation rate accelerates by ≃2.7 ms yr^{-1}. This is in agreement with the theoretically predicted value 1.4×10^{-8} rad d^{-2} obtained from numerical integration of YORP torques acting on our convex shape model. Geographos is only the third asteroid (after (1862) Apollo and (54509) YORP) for which the YORP effect has been detected. It is also the largest object for which effects of thermal torques were revealed.

Key words. minor planets, asteroids – methods: data analysis – techniques: photometric

1. Introduction

The Yarkovsky-O'Keefe-Radzievskii-Paddack effect (YORP), which is caused by the anisotropic reflection and thermal emission of sunlight, can modify rotation state of small asteroids. Rubincam (2000) was first to suggest that this effect could be important for the spin state evolution of asteroids. Since then, YORP has been recognized as an important dynamical mechanism that causes substantial changes in asteroid pole orientation (revealed by the alignment of spin axes of Koronis family members; Slivan 2002; Vokrouhlický et al. 2003), distribution of asteroid rotation rate (making it uniform; Pravec et al. 2008) and is likely to be a primary formation mechanism for small binary asteroids (Walsh et al. 2008). In spite of its theoretical importance, there are only two asteroids for which YORP has been directly measured – (1862) Apollo (Kaasalainen et al. 2007) and (54509) YORP (Lowry et al. 2007; Taylor et al. 2007). Kitazato et al. (2007) reported a direct detection of YORP for asteroid (25143) Itokawa but Ďurech et al. (2008) showed that there is no evidence for YORP in the currently available photometric data.

We present new photometric observations of asteroid (1620) Geographos that enabled us, when combined with older data, to detect an acceleration of its rotation. In particular, we show that the dataset cannot be satisfactorily fitted with a constant rotation period model, whereas the model for which the rotation rate ω accelerates as $\mathrm{d}\omega/\mathrm{d}t = (1.15 \pm 0.15) \times 10^{-8}$ rad d^{-2} fits the data well. This observed secular change in ω is in a very good agreement with the theoretically predicted YORP value based on the derived shape model.

2. Observations and model

We carried out photometric observations of Geographos and obtained new lightcurve measurements in 2001 (Krugly et al. 2002a) and early 2008 (Table 1). Observations obtained at Kharkiv and Simeiz (Crimea) Observatories are described in detail by Krugly et al. (2002b, 2008). We also used data archived in the Uppsala Asteroid Photometric Catalogue (Lagerkvist et al. 2001). Note that our new observations from 2001 complement all previous data with new viewing geometry (see, e.g., Table 1 in Magnusson et al. 1996), while those from 2008 repeat data from the close encounter in 1994. Their main importance, though, is that they allow us to reveal the phase shift due to the YORP effect.

We analyzed the whole dataset, consisting of 94 lightcurves, using the inversion method by Kaasalainen and collaborators (Kaasalainen et al. 2001, 2003; Kaasalainen & Ďurech 2007).

Table 1. Aspect data for new observations of Geographos. The table lists the asteroid's distance from the Sun r and from the Earth Δ, the solar phase angle α, the geocentric ecliptic coordinates of the asteroid (λ,β), and the observatory (HH – Hunters Hill Observatory, 35 cm; Kh – Kharkiv Observatory, 70 cm; Si – Simeiz, Crimean Astronomical Observatory, 1 m; Ha – Hamanowa Astronomical Observatory, 40 cm; Bl – Badlands Observatory, 70 cm).

Date	r [AU]	Δ [AU]	α [deg]	λ [deg]	β [deg]	Obs.
2001 08 17.0	1.082	0.304	68.7	49.1	2.6	Kh
2001 08 18.0	1.088	0.304	67.7	49.0	3.3	Kh
2001 09 18.1	1.255	0.329	35.4	36.1	24.1	Kh
2001 09 19.0	1.259	0.331	34.5	35.4	24.5	Kh
2008 01 15.0	1.376	0.509	32.3	159.9	17.6	Si
2008 01 19.0	1.358	0.471	30.8	160.2	17.5	Si
2008 01 31.6	1.298	0.355	24.3	159.8	16.3	Ha
2008 02 01.9	1.292	0.344	23.4	159.6	16.1	Si
2008 02 04.0	1.282	0.327	22.0	159.2	15.7	Si
2008 02 05.5	1.274	0.315	20.8	158.9	15.3	Ha
2008 02 06.6	1.268	0.306	20.0	158.6	15.0	Ha
2008 02 08.5	1.258	0.291	18.3	158.0	14.4	Ha
2008 02 11.9	1.241	0.266	15.2	156.7	13.2	Si
2008 02 14.5	1.227	0.247	12.6	155.5	12.0	Ha
2008 02 16.5	1.217	0.234	10.6	154.4	10.9	Ha
2008 02 17.5	1.212	0.228	9.6	153.8	10.3	Ha
2008 02 17.6	1.211	0.227	9.5	153.7	10.2	HH
2008 02 18.5	1.206	0.221	8.5	153.1	9.6	HH
2008 02 18.5	1.207	0.221	8.6	153.2	9.7	Ha
2008 02 19.5	1.201	0.215	7.6	152.5	8.9	HH
2008 02 19.5	1.201	0.215	7.7	152.5	9.0	Ha
2008 02 23.5	1.179	0.191	6.2	149.4	5.7	HH
2008 02 23.7	1.179	0.191	6.3	149.3	5.6	HH
2008 02 24.5	1.174	0.186	6.9	148.5	4.7	HH
2008 02 24.6	1.174	0.186	7.0	148.4	4.6	HH
2008 02 26.1	1.166	0.178	8.6	147.1	3.1	Kh
2008 03 03.8	1.129	0.149	21.5	139.5	−5.7	Si
2008 03 09.2	1.099	0.134	35.2	131.7	−14.8	Bl
2008 03 10.2	1.094	0.132	37.9	130.1	−16.6	Bl
2008 03 11.2	1.089	0.130	40.7	128.4	−18.5	Bl

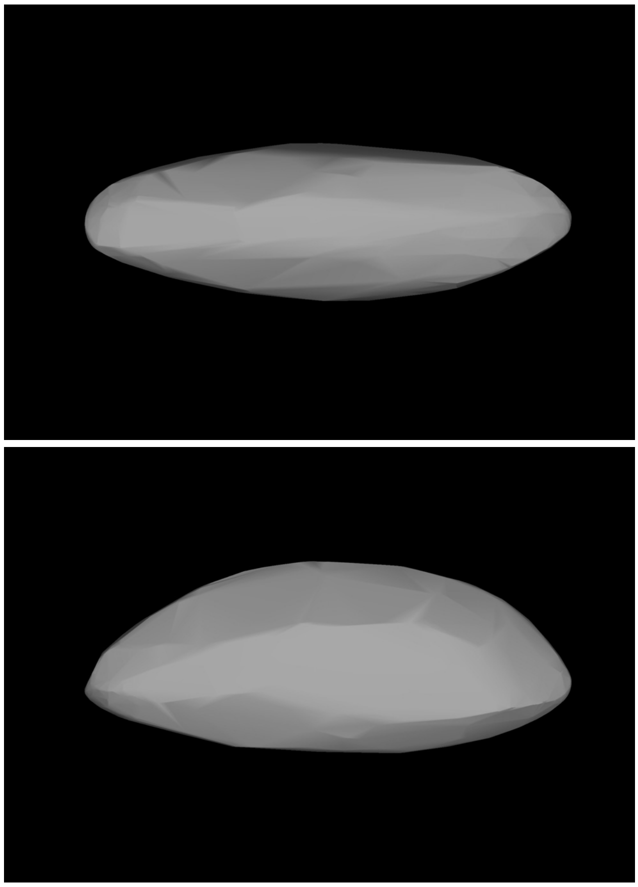

Fig. 1. The convex shape model of Geographos shown from equatorial level (*top*) and pole-on (*bottom*).

For the light scattering, we used a combination of Lambert and Lommel-Seeliger scattering models. The total time of observations was 39 years (from 1969 to 2008), a prerequisite for detection of even a small acceleration or deceleration of Geographos' rotation rate.

We first noted that the data could not be fitted with a constant-period model: the formal χ^2 remained large as an expression of the persistent phase shifts between modelled and observed lightcurves. To achieve a match between the observed data and the model, we were forced to introduce a new parameter into the optimization procedure – a linear change of the rotation rate in time $\upsilon \equiv \mathrm{d}\omega/\mathrm{d}t$. The rotation rate then evolves as $\omega(t) = \omega_0 + \upsilon t$; the constant-period model corresponds to $\upsilon = 0$. With that extension, our model fitted the whole dataset very well. The derived rotation parameters and their estimated maximum uncertainties were as follows: ecliptic coordinates of the pole direction $\lambda = 58 \pm 6°$, $\beta = -49 \pm 7°$, the sidereal rotation period $P = 5.223336 \pm 0.000002$ h for JD 2 440 229.0 (7.5 January, 1969), and $\upsilon = (1.15 \pm 0.15) \times 10^{-8}$ rad d^{-2}. The optimization procedure also provided us with a convex shape model of Geographos that is shown in Fig. 1. Four representative lightcurves and corresponding fits are shown in Fig. 2. Our results, namely the derived shape model, together with the complete lightcurve data set are available on the DAMIT[1] web page.

We used the derived shape model and spin solution and computed the theoretical YORP strength (Vokrouhlický & Čapek 2002; Čapek & Vokrouhlický 2004, 2005). We assumed a uniform bulk density $\rho = 2.5$ g cm^{-3}, an effective (volumic) diameter $D = 2.56$ km (Hudson & Ostro 1999), Bond albedo 0.1, and thermal conductivity $K = 0.02$ W m^{-1} K^{-1}. The predicted value of the YORP acceleration was $\mathrm{d}\omega/\mathrm{d}t = 1.4 \times 10^{-8}$ rad d^{-2}, which was in a good agreement with the observed value. The predicted YORP change in ω is proportional to $(\rho D^2)^{-1}$, so small adjustments in these parameters may bring the YORP-derived value of $\mathrm{d}\omega/\mathrm{d}t$ closer to the observed one. In agreement with conclusions of Čapek & Vokrouhlický (2004), the predicted YORP strength was not sensitive to the value of the surface thermal conductivity in the range 0.001–0.1 W m^{-1} K^{-1}, but it further depended on the pole orientation and the shape model resolution. Varying the pole direction within 3° around the best-fit value changed the $\mathrm{d}\omega/\mathrm{d}t$ by about ±4%. Different convex shapes models (derived using different resolution of the polyhedral model and different spherical harmonics representation) gave $\mathrm{d}\omega/\mathrm{d}t$ in a wide range from 0.3 to 1.5×10^{-8} rad d^{-2}. To pursue this issue, we also tested whether the numerically computed YORP strength is sensitive to small-scale surface features (like in case of (25 143) Itokawa; Ďurech et al. 2008; Scheeres et al. 2007) or whether it is dominated for Geographos

[1] Database of Asteroid Models from Inversion Techniques, http://astro.troja.mff.cuni.cz/projects/asteroids3D

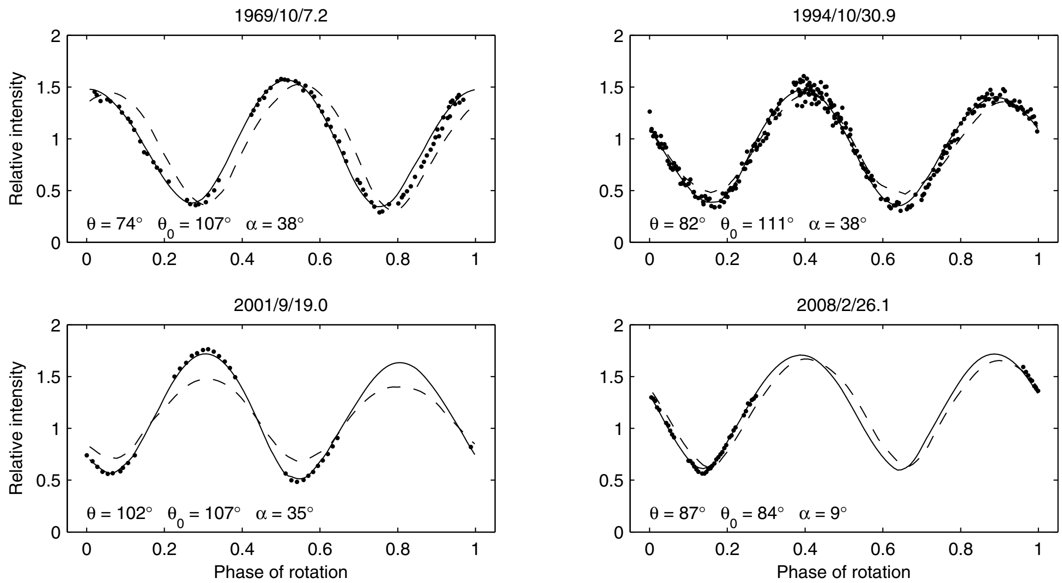

Fig. 2. Examples of Geographos' lightcurves fitted with synthetic ones based on the convex shape model. The solid curve corresponds to the best model with the rotation rate accelerated by $\upsilon = 1.15 \times 10^{-8}$ rad d^{-2} while the dashed curve corresponds to the best constant-period model with $\upsilon = 0$. The viewing and illumination geometry is given by the aspect angle θ, the solar aspect angle θ_0, and the solar phase angle α.

by global shape features. We thus covered our convex shape models with small-scale topography that was extracted from the Itokawa shape model containing 49 152 surface facets[2]. Small-scale features did not significantly affect the YORP value. For different rough models we always found an acceleration within 5% of the nominal value for the corresponding smooth model. Thus the small-scale surface features on Geographos do not seem to be as important as for Itokawa and the YORP torque is dominated by Geographos' global topography. Nevertheless, we conclude that while the largest uncertainty in the YORP prediction derives from the details of the shape model, all derived models were consistent with acceleration of Geographos' rotation and typically provided predicted values of $\mathrm{d}\omega/\mathrm{d}t$ within a factor of two of the observed value.

We also used the shape model derived from radar and optical data by Hudson & Ostro (1999)[3]. The best-fit value of υ based on this model was almost the same as that based on the convex shape. However, the theoretical YORP value computed for the radar model predicts that the rotation rate should decelerate as $\mathrm{d}\omega/\mathrm{d}t \sim -3 \times 10^{-8}$ rad d^{-2}, which is not consistent with the observations.

Similarly to Ďurech et al. (2008), we also examined the maximum change $|\Delta\omega|$ of the rotation rate during Geographos' close encounter (0.033 AU) with the Earth in Aug. 25, 1994. Using numerical integration of the Euler equations we found $|\Delta\omega|$ was less than $\sim 2 \times 10^{-8}$ rad d^{-1}. This implies that we could have neglected this effect in our analysis of the lightcurve observations.

3. Conclusions

Using the lightcurve inversion method on photometric data spanning almost forty years, we have detected an acceleration of Geographos rotation $\upsilon = (1.15 \pm 0.15) \times 10^{-8}$ rad d^{-2}. This corresponds to the change in rotation period 0.1 s between 1969 and 2008, or a secular rotation-period decrease with a 2.7 ms yr^{-1} pace. Interestingly, this value is larger than for the small asteroid (54 509) YORP for which the period decreases by 1.25 ms yr^{-1} only (while the intrinsic YORP strength is obviously larger for the latter). This shows that it is more complicated to change the rotation rate of already fast-rotating objects (the rotation period of (54 509) YORP is ~0.2 h). In Geographos' case, the formal phase shift in $\Delta T \simeq 39$ years produced by the YORP term is $\simeq \upsilon(\Delta T)^2/2 \simeq 64°$. However, because for $\upsilon = 0$ the optimization procedure finds a period that minimizes phase differences, the real maximum shift between the best-fit model and the best-fit constant-period model is ~20°. This is close to the expected value $\simeq \upsilon(\Delta T)^2/8 \simeq 16°$ with the small difference produced by an unequal distribution of the photometric observations in time. The observed difference still makes the effect clearly noticeable (Fig. 2). The large formal phase shift also means that the exact timing of observations from 1969 (Dunlap 1974) that could be disputed due to the difficulty of verifying the data accuracy and the lack of independent measurements from the same apparition is not crucial for YORP detection. Even if there was a systematic shift of ±10 min in their timing it would lead to only ~30% change of the υ value and any model with $\upsilon = 0$ would not give a good fit to the dataset.

Of the three asteroids for which YORP was detected, Geographos is the largest one and the strength of the YORP υ is the smallest. Our detection of YORP here shows that moderately large size is not an obstacle (Geographos is one of the largest near-Earth asteroids) if the photometric data cover a long-enough period of time. This supports the search for further YORP detections even outside the near-Earth population of objects, namely small Hungarias and/or inner main belt asteroids.

We find it interesting that for all three asteroids for which YORP was detected, the rotation rate is accelerated (recall that attempts to detect YORP on Itokawa have failed so far). While no conclusions could be drawn from this sample of three objects, detection of an asteroid for which YORP decelerates the rotation rate will be the next important step in confirmation of the YORP theory.

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[2] http://hayabusa.sci.isas.jaxa.jp

[3] The shape model is available at http://www.psi.edu/pds (Planetary Data System).

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References

Čapek, D., & Vokrouhlický, D. 2004, Icarus, 172, 526
Čapek, D., & Vokrouhlický, D. 2005, in Dynamics of Populations of Planetary Systems, ed. Z. Knežević, & A. Milani, IAU Colloq., 197, 171
Dunlap, J. L. 1974, AJ, 79, 324
Ďurech, J., Vokrouhlický, D., Kaasalainen, M., et al. 2008, A&A, 488, 345
Hudson, R. S., & Ostro, S. J. 1999, Icarus, 140, 369
Kaasalainen, M., Torppa, J., & Muinonen, K. 2001, Icarus, 153, 37
Kaasalainen, S., Piironen, J., Kaasalainen, M., et al. 2003, Icarus, 161, 34
Kaasalainen, M., & Ďurech, J. 2007, in Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, ed. A. Milani, G. B. Valsecchi, & D. Vokrouhlický (Cambridge: Cambridge University Press), 151
Kaasalainen, M., Ďurech, J., Warner, B. D., Krugly, Y. N., & Gaftonyuk, N. M. 2007, Nature, 446, 420
Kitazato, K., Abe, M., Ishiguro, M., & Ip, W.-H. 2007, A&A, 472, L5
Krugly, Y. N., Belskaya, I. N., Chiorny, V. G., Shevchenko, V. G., & Gaftonyuk, N. M. 2002a, in Asteroids, Comets, and Meteors: ACM 2002, ed. B. Warmbein, ESA SP, 500, 903
Krugly, Y. N., Belskaya, I. N., Shevchenko, V. G., et al. 2002b, Icarus, 158, 294
Krugly, Y. N., Gaftonyuk, N. M., & Shevchenko, V. G 2008, Icarus, submitted
Lagerkvist, C.-I., Piironen, J., & Erikson, A. 2001, Asteroid photometric catalogue, fifth update, Uppsala Astronomical Observatory
Lowry, S. C., Fitzsimmons, A., Pravec, P., et al. 2007, Science, 316, 272
Magnusson, P., Dahlgren, M., Barucci, M. A., et al. 1996, Icarus, 123, 227
Pravec, P., Harris, A. W., Vokrouhlicky, D., et al. 2008, Icarus, in press
Rubincam, D. P. 2000, Icarus, 148, 2
Scheeres, D. J., Abe, M., Yoshikawa, M., et al. 2007, Icarus, 188, 425
Slivan, S. M. 2002, Nature, 419, 49
Taylor, P. A., Margot, J.-L., Vokrouhlický, D., et al. 2007, Science, 316, 274
Vokrouhlický, D., & Čapek, D. 2002, Icarus, 159, 449
Vokrouhlický, D., Nesvorný, D., & Bottke, W. F. 2003, Nature, 425, 147
Walsh, K. J., Richardson, D. C., & Michel, P. 2008, Nature, 454, 188