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Letter to the Editor

Detectability of YORP rotational slowing of asteroid 25143 Itokawa

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Abstract. We predict that the YORP thermal-emission effect can be directly detected through a measurable increase in the rotation period of the several-hundred-meter near-Earth asteroid 25143 Itokawa. The fractional change of Itokawa's rotation rate in between 2001 and 2004 should be $(1-2) \times 10^{-4}$, significantly larger than its currently estimated uncertainty $\simeq 5 \times 10^{-5}$. The corresponding change of sidereal rotation phase, normalized to unity in a cycle, is $\simeq(0.09-0.25)$ in January 2004, producing $\simeq(1-3)$ h delay of lightcurve maximum.

Key words. solar system: minor planets, asteroids – radiations mechanisms: thermal

1. Introduction

Torques produced by the reflection and thermal re-emission of sunlight from an asteroid's surface can alter its spin state. This Yarkovsky-O'Keefe-Radzievskii-Paddack or YORP effect (Rubincam 2000; Vokrouhlický & Čapek 2002; Vokrouhlický et al. 2003) is related to the Yarkovsky effect, by which the anisotropic re-radiation of absorbed sunlight causes object's orbital semimajor axis to drift at a rate that depends on the object's physical properties, especially its mass, its spin state and its surface's thermal characteristics (Bottke et al. 2002). YORP torques depend on these factors and especially on the shape; energy re-radiated from an irregularly shaped body allows the YORP effect to change the spin period and the obliquity, while there would be no net YORP torques on a homogeneous sphere or ellipsoid.

Whereas the obliquity effect is unlikely to be measureable with ground-based astronomical techniques, rotation rate variations could in principle accumulate rapidly enough to be detectable over time scales as short as several years. Here we argue that precise measurements of the rotation period of the small near-Earth asteroid 25143 Itokawa (1998 SF36) may yield, for the first time, a direct detection of the YORP effect.

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2. YORP effect

Solar energy absorbed by an asteroid and re-radiated at thermal wavelengths causes an infinitesimal pressure on each surface element. If conditions for a nonuniform distribution of surface temperature are satisfied, the resulting net force $\boldsymbol{F}$ and torque $\boldsymbol{T}$ from the thermal re-radiation are nonzero. This torque alters the asteroid's angular velocity ω at a rate (see Rubincam 2000; Vokrouhlický & Čapek 2002)

$$\tau = T_s/C = \boldsymbol{T} \cdot \boldsymbol{s}/C, \tag{1}$$

where $\boldsymbol{s}$ is the unit vector along the spin axis and C is the largest proper value of the moment of inertia. This simplified model assumes a body rotating along its shortest axis (a condition well satisfied for Itokawa; Kaasalainen et al. 2003; Ostro et al. 2003). As a result, the rotation rate changes as

$$\omega = \omega_0 + \delta\omega, \tag{2}$$

with

$$\delta\omega(f) = \frac{\eta^3}{n} \int_{f_0}^{f} \frac{\tau(f')\,\mathrm{d}f'}{(1 + e\cos f')^2}. \tag{3}$$

Here f is the orbit's true anomaly, ω_0 is a reference value of the rotation rate at f_0, e is the orbit's eccentricity, n its mean orbital motion and $\eta = \sqrt{1-e^2}$. Variation $\delta\omega$ of the rotation rate produces a variation $\delta\Phi$ of the sidereal rotation phase Φ defined as

$$\Phi = \frac{1}{2\pi} \int_{t_0}^{t} \omega\,\mathrm{d}t = \Phi_0 + \delta\Phi, \tag{4}$$

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where Φ_0 is a linearly increasing nominal value of the phase corresponding to the constant rotation rate ω_0 (note in this paper the rotation phase is always normalized to unity in a rotation cycle). With Eq. (3) we thus have

$$\delta\Phi(f) = \frac{\eta^3}{2\pi n}\int_{f_0}^{f}\frac{\delta\omega(f')\,\mathrm{d}f'}{(1+e\cos f')^2}. \qquad (5)$$

Note that any (linear) secular change in the rotation rate translates into a quadratic change in the rotation phase, hence propagating faster than observation uncertainty (see also Fig. 3).

3. Results for 25143 Itokawa

Itokawa's orbit, not far from the 3/2 exterior resonance with the Earth, is favorable for detection of YORP modification of the asteroid's spin period. During Itokawa's 2004 close approach, its photometric observability mimics that during its 2001 apparition even though the approach occurs near the descending node. Itokawa will be observable with small and medium size telescopes during two periods: January through March 2004 and June through September 2004; Fig. 1 shows Itokawa's path on the sky during the apparition. It starts January 1 in the upper right corner, turns back around March 15, swoops very fast through the southern latitudes in June/July during the closest approach, and approaches the plane of the ecliptic again in late September. Itokawa's elongation is smaller than 60° between May 20 and June 25 (about when its solar phase angle exceeds 110°). After this, Itokawa is a bright target from late June (when it reaches very high phase angles) until early August. The visual magnitudes in Fig. 1 are estimated from Itokawa's solar phase curve in Kaasalainen et al. (2003); those in May–June at high phases are wide extrapolations and thus uncertain. A similar situation then occurs also in 2007, after it is visited by the Japanese spacecraft Hayabusa during June–November 2005 (Fujiwara et al. 1999; Farquhar et al. 2003). Below we show that this sequence of observation opportunities, their expected precision of rotation period determination, and the estimated strength of the YORP effect imply detectability of the effect.

We have carried out a numerical simulation using the model by Vokrouhlický & Čapek (2002) generalized to include effects of finite surface thermal inertia. The assumed surface parameters are as follows: thermal conductivity $K = 0.05$ W/m/K, heat capacity $C = 800$ J/kg/K and surface density $\rho_{\rm surf} = 2$ g/cm^3, consistent with Itokawa's value of thermal inertia derived from infrared observations (Ishiguro et al. 2003) and with radar observations reported by Ostro et al. (2003). The assumed thermal conductivity and surface density correspond to appropriate for L chondrites with about (10−20)% surface porosity (Yomogida & Matsui 1983) and the assumed heat capacity, which is very dependent on temperature, corresponds to the mean temperature along the orbit. However, we note that, unlike for the Yarkovsky effect, results of this paper do not depend critically of the value of the surface thermal inertia so that uncertainty in this parameter contributes very little to the error budget of our YORP effect prediction. We assume the value for Itokawa's geometric albedo of ≃(0.23–0.35) from infrared observations reported by Sekiguchi et al. (2003) and Ishiguro et al. (2003). We include the effect of both the torque due to the thermally radiated energy (the "proper" YORP effect) as well as the torque due to radiation reflected in optical. For that component we assume diffuse reflection on the surface and mean geometric albedo of 0.3. The bulk density is taken to be 2.5 g/cm^3 consistent with Itokawa's spectral type S; see e.g. Yeomans et al. (2000) and Ostro et al. (2003). We use the radar-derived shape model from Ostro et al. (2003), which assumes the pole and rotation period of Kaasalainen et al. (2003). (Itokawa's high obliquity (≃172°) contributes to the strength of the YORP effect.) As a check, we also used the shape model derived by Kaasalainen et al. (2003) from analysis of 2001 optical photometry, rescaling its dimensions to make it 18% larger in order to give it the same volume and mass as the radar shape model. The YORP torque from the photometrically derived shape model is about 15% larger than that from the radar shape model.

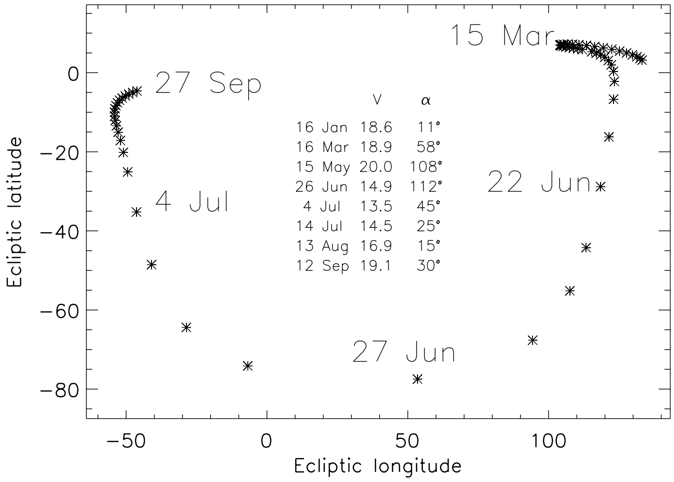

Fig. 1. Itokawa's motion in the sky during most of 2004 (ecliptic longitude and latitude in degrees on axes); legend gives visual magnitude (V) and phase angle (α) on selected dates.

Figure 2 shows time evolution of the relative change $(P - P_0)/P_0$ of Itokawa's rotation period P due to the YORP effect relative to the value $P_0 = 12.132$ h determined during its 2001 apparition. We estimate an uncertainty of 30% in the nominal model prediction, with the following principal components: (i) uncertainty in the shape model (we created 10 "clone" Itokawa models by slight shape variations and verified that the resulting YORP torque does not change by more than 15%); (ii) uncertainty in linear size of Itokawa of ≃10% (Ostro et al. 2003; note that such linear rescaling implies a quadratic rescaling of the YORP torques); (iii) uncertainty in Itokawa's bulk density of ≃10%; (iv) uncertainty in the pole position; and (v) uncertainty in the surface optical and thermal parameters. Even in the worst case, the difference between the YORP modified rotation period in 2004 and that determined in 2001 amounts to about ≃2 standard deviations (expressed in the 2001 uncertainty). Assuming Gaussian statistics, there is about 0.04 probability that such fluctuation would happen in the constant rotation rate model; the probability drops to 0.003 for the result of the nominal YORP model that differs by as much as ≃3 standard deviations from the constant rotation model. Therefore we

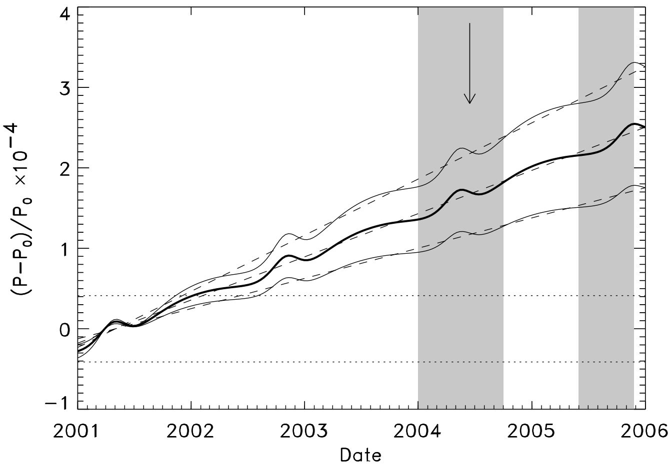

Fig. 2. Relative change of the rotation period P, referred to a nominal value $P_0 = 12.132$ h in MJD = 52 000 (Kaasalainen et al. 2003), as a function of time due to the YORP effect. The thick solid curve corresponds to a nominal model described in the text, and the thin solid curves are results for YORP torques varied by ±30% from the nominal model. Solid curves show the complete expected variation of Itokawa's rotation period, and dashed lines show the mean linear rate of rotational slowing. The dotted lines indicate the formal uncertainty of the rotation period determination from the 2001 campaign. The shaded intervals correspond to future optical observing opportunities, notably in 2004 from Earth and in 2005 from Hayabusa. The arrow shows the asteroid's close encounter with the Earth, during which the rotation period may fractionally change by 3.1×10^{-5} at maximum due to the effect of Earth's gravitational torque (see the text).

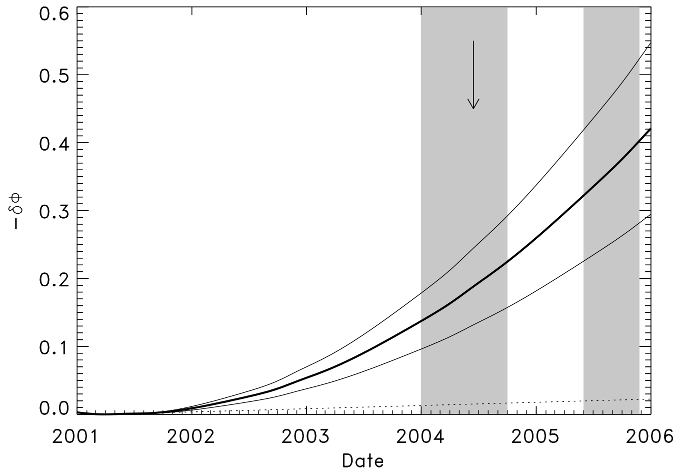

Fig. 3. Change of the rotation phase $\delta\Phi$, with an arbitrary zero value at MJD = 52 000 (Kaasalainen et al. 2003), as a function of time due to the YORP effect; notation as in Fig. 2. The formal uncertainty of the previous determination of asteroid's rotation rate causes a linear increase of the uncertainty in phase (dotted line), while the YORP effect signature in $\delta\Phi$ is quadratic and hence easily observable in the future.

argue that the 2004 observations should be able to detect YORP rotational slowing of Itokawa.

The Hayabusa observations, if comparable in accuracy to those of the NEAR/Shoemaker spacecraft (Yeomans et al. 2000; Konopliv et al. 2003), should be able to contribute importantly to the YORP effect measurement. First, the shape model and thermal properties of the asteroid will be determined more accurately than by the Earth-based observations (though significant refinements of Itokawa's shape model will be also obtained from radar imaging in June 2004 and optical observations throughout 2004). Additionally, Hayabusa measurements should in principle be accurate enough to themselves reveal the YORP-induced deceleration of the asteroid rotation. A link to the previous (and possible future) observations should then give a superb probe of the thermal effects on this body (independently, Ostro et al. 2003, also demonstrate that Hayabusa radio ranging should be also able to detect the Yarkovsky effect affecting Itokawa's orbit around the Sun).

Figure 3 shows the accumulated change $\delta\Phi$ of Itokawa's sidereal rotation phase due to the YORP effect. As expected, $\delta\Phi$ propagates quadratically with time, much faster than the growth in its uncertainty, and by January 2004 the YORP-induced $\delta\Phi$ dominates. The expected value of at least $\simeq$0.09 translates into a delay of lightcurve maximum by $\simeq$1 h, which should be easily detectable.

An asteroid's spin state can also be modified by gravitational torques during close approaches (CA) to planets. Scheeres et al. (2000) investigated the effect of a planetary flyby along a hyperbolic orbit on rotation of a quasi-rigid body. With their results we estimate maximum relative change of Itokawa's rotation rate during a flyby as

$$\left(\frac{\delta\omega}{\omega}\right)_{\rm CA} \simeq \frac{1}{2}\frac{B-A}{C}\frac{GM}{q^2 v_\infty}, \qquad (6)$$

where $A \leq B \leq C$ are proper values of the inertia tensor, G the gravitational constant, M planetary mass, q is minimum distance to the planet during the approach and v_∞ is relative velocity at large distance. For Itokawa we estimate $(B-A)/C \simeq 0.6$. With $v_\infty \simeq 7$ km s^{-1} and $q \simeq 0.013$ AU appropriate for the 2004 encounter (Ostro et al. 2003 and Fig. 2), we thus obtain a maximum impulsive change of Itokawa's rotation rate of about $(\delta\omega/\omega)_{\rm CA} \simeq 3.1 \times 10^{-5}$. The exact value, and its sign, depends on rotation phase at pericenter of the Earth flyby. Though not negligible, the effect of gravitational torques is small compared to YORP.

We noted above that measurement of the YORP-induced slowing of Itokawa's rotation is uncertain due several unknown parameters, principally the asteroid's precise shape, size and mass, but once detected these parameters may be in turn determined. Since the scheduled radar and optical observations during 2004 should reduce uncertainty in shape and size of Itokawa, YORP detection would result mainly in constraining its mass (as it is the case of the Yarkovsky effect detection; Chesley et al. 2003).

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References

Bottke, W. F., Vokrouhlický, D., Rubincam, D. P., & Brož, M. 2002, in Asteroids III, ed. W. F. Bottke, et al. (Tucson: The University of Arizona Press), 395

Chesley, S. R., Ostro, S. J. Vokrouhlický, D., et al. 2003, Science, 302, 1739

Dermawan, B., Nakamura, T., Fukushima, H., et al. 2002, PASJ, 54, 635

Farquhar, R., Kawaguchi, J., Russell, C. T., et al. 2002, in Asteroids III, ed. W. F. Bottke, et al. (Tucson: The University of Arizona Press), 367

Fujiwara, A., Mukai, T., Kawaguchi, J., & Uesugi, K. T. 1999, Adv. Space Res., 25, 231

Ishiguro, M., Abe, M., Ohba, Y., et al. 2003, PASJ, 55, 691

Kaasalainen, M., Kwiatkowski, T., Abe, M., et al. 2003, A&A, 405, L29

Konopliv, A. S., Miller, J. K., Owen, W. M., et al. 2002, Icarus, 160, 289

Ostro, S. J., Benner, L. A. M., Nolan, M. C., et al. 2003, Meteor. Planet. Sci., submitted

Rubincam, D. P. 2000, Icarus, 148, 2

Scheeres, D., Ostro, S. J., Werner, R. A., Asphaug, E., & Hudson, R. S. 2000, Icarus, 147, 106

Sekiguchi, T., Abe, M., Boehnhardt, et al. 2003, A&A, 397, 325

Vokrouhlický, D., & Čapek, D. 2002, Icarus, 159, 449

Vokrouhlický, D., Nesvorný, D., & Bottke, W. F. 2003, Nature, 425, 147

Yeomans, D. K., Antreasian, P. G., Barriot, J.-P., et al. 2000, Science, 289, 2085

Yomogida, K., & Matsui, T. 1983, J. Geophys. Res., 88, 9513