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ScienceDirect

Icarus 188 (2007) 425–429

ICARUS

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The effect of YORP on Itokawa

D.J. Scheeres [a,*], M. Abe [b], M. Yoshikawa [b], R. Nakamura [c], R.W. Gaskell [d], P.A. Abell [e]

[a] Department of Aerospace Engineering, The University of Michigan, Ann Arbor, MI 48109-2140, USA
[b] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan
[c] National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8568, Japan
[d] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[e] National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, TX 77058, USA

Received 9 June 2006; revised 8 December 2006

Abstract

The effect of solar radiation on the near-term rotation rate of Asteroid Itokawa via the YORP effect is predicted using the detailed shape model, rotation pole, mass estimate, and optical properties derived from the Hayabusa mission to Itokawa. Based on these estimates Itokawa is decelerating at a rate which will halve its rotation rate in only 50–90 thousand years, a large deceleration that should be detectable in a future appartion. The implications of such a large deceleration for Itokawa's past history are discussed and related to possible seismic shaking.

Keywords: Asteroids; Rotational dynamics

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1. Introduction

An evaluation of the effect of solar radiation on the rotation state of Asteroid Itokawa is given. The change in rotation rate due to this effect is known as the Yarkovsky–O'Keefe-Radzievskii–Paddack or "YORP" effect, and was introduced to the small body community by Rubincam (Rubincam, 2000). For the evaluation of the effect given here we use the estimated Itokawa shape, spin pole, mass, and optical properties derived from the Hayabusa mission to that asteroid (Fujiwara et al., 2006). Relevant values for this body are reported in Table 1.

The current work focuses on two specific items. First is to make a prediction for when the YORP effect should be observable for Itokawa. This has been studied earlier by Vokrouhlický et al. (2004) using pre-rendezvous models of the asteroid. The current predictions use the model estimated by the Hayabusa mission. A second aspect of this work is to explore the implications of the predicted YORP acceleration for Itokawa. For the predicted YORP acceleration rates we note that Itokawa most likely was rotating rapidly within the last few hundred thousand years, a situation that could have lead to reconfiguration of the system and possible mutual orbit of its main components followed by a low-speed impact between the asteroid components. Such a past provides an additional mechanism for seismic shaking.

2. Effect of YORP on the rotation rate

In Rios-Reyes and Scheeres (2005) a general form for the total differential force acting on a surface element of a body is derived that is only an algebraic function of the body shape and a unit vector defining the location of the Sun, with the optical coefficients appearing as explicit multipliers. The differential force elements are integrated over the body surface, and the resulting moment is separately averaged over one rotation period and over one orbit period about the Sun. Performing these two averages separately is valid due to the small size of the YORP torque as compared to the asteroid's rotation rate, and due to the large time scales between the asteroid rotation rate and its orbital rate.

Our main interest is in changes in the spin rate which can be determined from the equation:

$$\dot{\omega}_z = \frac{M_z}{I_z}, \tag{1}$$

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[*] Corresponding author.
E-mail address: scheeres@umich.edu (D.J. Scheeres).

0019-1035/$ – see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2006.12.014

where ω_z is the rotation rate of the asteroid about its maximum moment of inertia (assumed to be its rotation pole), $\dot{\omega}_z$ is the time rate of change in this quantity, M_z is the averaged component of the solar torque along the body's rotation pole and I_z is the body's maximum moment of inertia.

Resulting from these we find the predicted evolution of the spin rate:

$$\dot{\omega}_z = \alpha_0 + B\big[(1-s)\rho + \kappa(1-\rho)\big]\alpha_1 + \rho s \alpha_2, \tag{2}$$

where $\rho < 1$ is the albedo of the body, $s < 1$ is the fraction of reflected light that is reflected specularly, $\kappa < 1$ represents the reduction in emission due to finite thermal conductivity, and B is the Lambertian scattering coefficient (Rios-Reyes and Scheeres, 2005). The constants α_i have units of radians per second squared and are directly computed from the asteroid shape, moments of inertia and current rotation pole orientation relative to its orbital plane.

Table 2 summarizes values of α_i computed for different versions of the Itokawa shape model evaluated at the current orbit and rotation pole. For consistency we used the same (final) asteroid mass and moments of inertia for each case (Demura et al., 2006; Gaskell et al., 2006), allowing for comparisons between the effect of using different shape models alone. The pre-encounter model is described in detail in Ostro et al. (2005). The positive angular acceleration of Itokawa for the pre-encounter shape agrees with the computation given in Vokrouhlický et al. (2004). Note that the given acceleration rate in Vokrouhlický et al. (2004) was stated incorrectly and should have been positive (personal communication from D. Vokrouhlický). The different versions of the Hayabusa shape model were produced at different epochs of the mission, and in general start from being similar to the pre-encounter model and subsequently morph to the final Itokawa shape. The shift from a positive acceleration coefficients to negative coefficients coincides with the modeling of the large concavity in the south pole region of Itokawa (Saito et al., 2006). This clearly indicates the sensitivity of the YORP effect to global properties of the shape. After this major change, however, the coefficients continue to vary and indicate the sensitivity of the YORP coefficients to smaller shifts in the body's shape and to different resolutions for the modeling of the surface. It is important to note that these coefficients do not uniformly converge as the resolution is increased. This indicates that the topography resolution of the model is still far from the level of precision necessary to completely model the geometry of the interaction between solar radiation and the surface.

Table 1
Physical elements of the Itokawa model, data taken from Abe et al. (2006), Gaskell et al. (2006), Demura et al. (2006)

Rotation period	12.132370 (h)
Obliquity	178.3°
Semi-major axis	1.3236 (AU)
Eccentricity	0.280
Total mass	3.58×10^{10} (kg)
Mean radius	0.162 (km)
Moments of inertia:	
I_x/M	6.31×10^{-3} (km^2)
I_y/M	2.06×10^{-2} (km^2)
I_z/M	2.17×10^{-2} (km^2)

The x, y, and z axes correspond to the principal axes of Itokawa.

Evaluating the YORP coefficients for a recent Itokawa shape model (Gaskell et al., 2006) and sampling the surface at different resolutions (excluding the lowest resolution model and incorporating shadowing where computationally feasible), these parameters range over:

$$\alpha_0 = 0 \rightarrow -0.060 \times 10^{-16}\ \mathrm{rad/s^2}, \tag{3}$$

$$\alpha_1 = -0.383 \rightarrow -0.700 \times 10^{-16}\ \mathrm{rad/s^2}, \tag{4}$$

$$\alpha_2 = -2.091 \rightarrow -2.734 \times 10^{-16}\ \mathrm{rad/s^2}. \tag{5}$$

The zero values of α_0 occur when shadowing by portions of the asteroid that are above the local horizon for every facet are not taken into account. For the highest resolution models, we currently cannot handle these precision shadowing models as the number of computations needed using our current algorithm grows too great. We also note that shadowing becomes important for these high resolution models, as the degree of variability in the local surface orientation will in general lead to a large increase in shadowing. When carrying out computations for very high resolution shape models it will also be necessary to modify our relatively simple algorithm to incorporate secondary reflec-

Table 2
Computed coefficients α_i for different Itokawa models

Model epoch	Facets	α_0 (rad/s^2)	α_1 (rad/s^2)	α_2 (rad/s^2)
Pre-encounter	3688	8.033×10^{-18}	1.633×10^{-16}	4.396×10^{-16}
10/2005	13,064	8.080×10^{-18}	2.475×10^{-16}	6.722×10^{-16}
11/2005	13,064	-0.486×10^{-18}	-0.872×10^{-16}	-3.219×10^{-16}
12/2005	13,064	-5.253×10^{-18}	-1.302×10^{-16}	-4.258×10^{-16}
02/2006	3464	-5.778×10^{-18}	-0.953×10^{-16}	-2.906×10^{-16}
02/2006	13,064	-5.986×10^{-18}	-0.700×10^{-16}	-2.698×10^{-16}
02/2006 No shadowing	13,064	0.000×10^{-18}	-0.649×10^{-16}	-2.734×10^{-16}
02/2006	50,696	-4.54×10^{-18}	-0.501×10^{-16}	-2.372×10^{-16}
02/2006 No shadowing	50,696	0.000×10^{-18}	-0.383×10^{-16}	-2.328×10^{-16}
02/2006 No shadowing	199,688	0.000×10^{-18}	-0.676×10^{-16}	-2.091×10^{-16}

Each computation uses the same total mass and moments of inertia for comparison purposes.

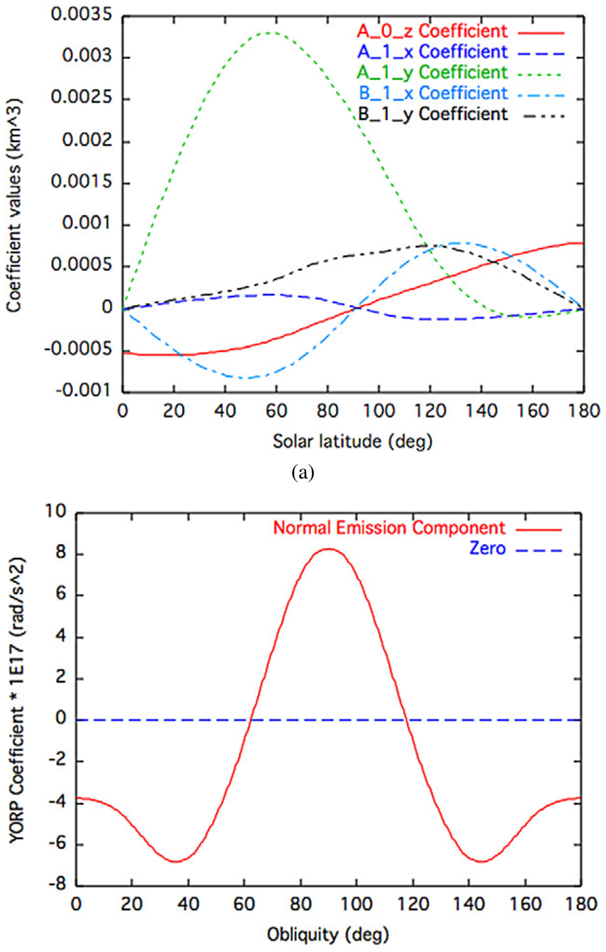
tions and heating, physical details that are currently ignored in our model.

The albedo has been estimated to be $\rho \sim 0.2$ in Müller et al. (2005), however if we assume $s = 0$ and $\kappa = 1$ this removes dependence of the result on albedo. If we make these assumptions for definiteness and assume $B = 2/3$, the ideal value for Lambertian scattering and used in previous analyses (Vokrouhlický et al., 2004), the predicted deceleration in the spin rate for the current Itokawa state ranges from 2.5 to 4.5×10^{-17} rad/s^2, or a rate of increase in rotation period of 0.66–1.19 $\times 10^{-4}$ h/year. We note that, given the relative uncertainty of the optical parameters and the small scale surface, these values should be assigned a relatively large uncertainty.

We have also studied the effect of YORP torques on the obliquity of Itokawa. To do this we model the torque acting on the asteroid using a Fourier series representation of the form $P(R)[\mathbf{A}_0 + \mathbf{A}_1 \cos(\lambda) + \mathbf{B}_1 \sin(\lambda)]$, where $P(R)$ is the solar radiation pressure at a distance R from the Sun, and the 3-dimensional vector coefficients $\mathbf{A}_0$, $\mathbf{A}_1$ and $\mathbf{B}_1$ represent the variation of the YORP torques in the body-fixed frame as a function of solar longitude λ and are tabulated as functions of the solar latitude. For this model we only considered the effect of normal emission, and multiplied the above torque by the parameter B. The Fourier coefficients are shown in Fig. 1a as a function of solar latitude. Solving the equations of motion for the rotational evolution of the asteroid's spin pole (Greenwood, 2003) we find that the obliquity only has a small change as a function of time, decreasing from its initial value at a rate of 0.1 degrees per 1K years. In Fig. 1b the value of the α_1 parameter for Itokawa as a function of obliquity is shown. For the obliquity computations we chose the 2/2006, 50K facet model without shadowing. We expect the qualitative obliquity variations to be unchanged across the different models. We note that Itokawa with its near 180° obliquity is currently at a local minimum in its rotational deceleration, and that any change away from this obliquity will initially cause it to decelerate more rapidly. Furthermore, the obliquity must change by almost 60° before it enters an acceleration phase. Based on this we assert that the change in obliquity will not affect the deceleration of the asteroid rotation rate significantly over time-spans on the order of 100K years.

3. Detection of YORP

In Vokrouhlický et al. (2004) a detailed discussion of the measurement possibilities of Itokawa's rotation rate are given, as are the effect of very recent Earth flybys on the asteroid's rotation rate. From these analyses, and consistent with the above large prediction of the net deceleration of Itokawa's rotation rate, a precise measurement of the YORP effect on this asteroid should be possible at a future observing opportunity.



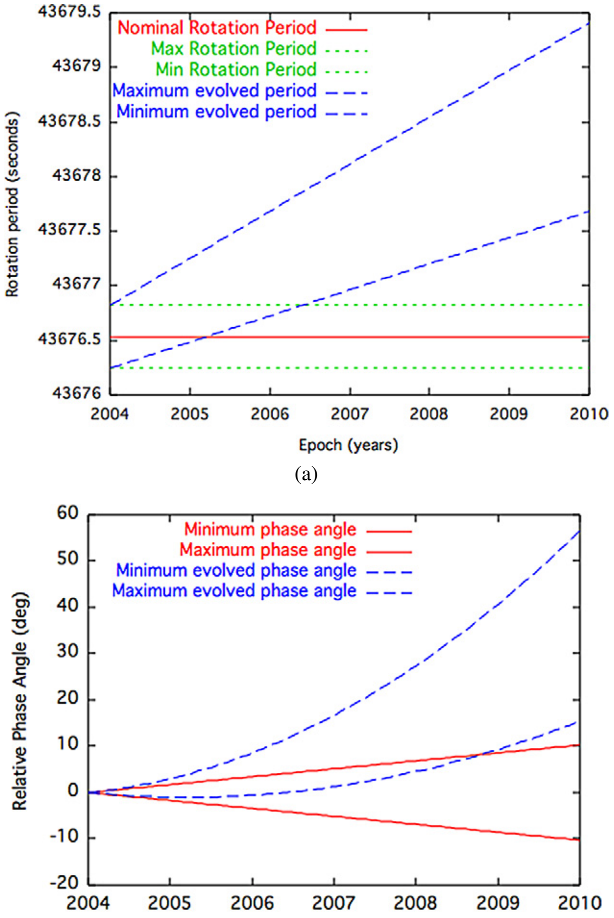
(a)

(b)

Fig. 1. (a) Variation in the normal emission YORP torque Fourier coefficients as a function of solar latitude in the Itokawa-fixed frame. Only those terms important for the rotational evolution of the asteroid are shown. (b) Variation in the coefficient α_1 as a function of asteroid obliquity, the coefficient values are multiplied by 1×10^{17}. The current Itokawa obliquity is near 180°.

The current uncertainty in the spin period determination corresponds to an uncertainty in spin rate of $\pm 1 \times 10^{-9}$ rad/s. Given the range in estimates of the secular deceleration, such a shift in spin rate would occur in 0.7–1.3 years. To be detectable, and assuming similar data quality is obtainable as for the 2004 apparition, at least two of these time scales should pass for an unambiguous detection to occur. Fig. 2a shows the current uncertainty in rotation period and the maximum and minimum evolved periods consistent with the range of values found from the different resolutions of the shape models. We note that the poorly characterized radiative properties of the asteroid will induce even larger uncertainties.

Alternatively, detection may also occur by measuring the shift in phase angle of the asteroid, as compared to the previously measured rotation rate and phase angle. For the current uncertainty in asteroid spin rate, this level of uncertainty corresponds to a change in asteroid phase angle of 5.4° in three years, or an uncertainty in phase angle of ±5.4°. The range of decelerations we consider due to different resolutions in the shape model predict a shift in phase angle of −0.7°–1.3° in one year and −6.3°–11.5° in three years, decreasing quadratically in time. This indicates that differences between predicted and measured light curve phase angles are marginally detectable over this time span. Apparitions occurring in subsequent opportunities (which should occur with an approximate frequency of 3 years) will be commensurately larger and should provide a



(a)

(b)

Fig. 2. Uncertainty in the Itokawa rotation period and relative phase angle due to variations in the predicted acceleration as a function of shape model resolution. (a) Uncertainty in rotation period and maximum and minimum limits in the YORP evolved rotation period over time. (b) Uncertainty in relative phase angle change and maximum and minimum limits in the YORP evolved relative phase angle over time.

much clearer determination of the magnitude of the YORP effect. Fig. 2b shows the current uncertainty in propagated phase angle given the uncertainty in rotation period (all relative to the nominal rotation period) and the maximum and minimum evolved phase angles consistent with our theory and the current uncertainty in rotation period.

4. Implications

Given the current Itokawa rotation period, the computed angular deceleration of Itokawa corresponds to a halving of its spin rate, sometimes called the YORP timescale, in 50–90 thousand years. This is an extremely rapid rotation rate evolution, and if verified would imply that YORP rotational acceleration is a dominating effect for small NEAs.

Such a large deceleration rate for Itokawa has strong implications for the recent history of this body, implying that ∼100–180 thousand years ago Itokawa was spinning at a rate of 6.5 h. This rotation rate is fast enough for the "head" and "body" of Itokawa, as defined in Demura et al. (2006), to go into mutual orbit about each other (Scheeres, 2006b), and at least would be spinning fast enough to allow them to reconfigure themselves in order to decrease the total energy of the system (Scheeres, 2006a). We note that relatively small shifts in the body can result in changes of the size and sign of the YORP coefficients, as evident in Table 2, and may transition a body from a configuration where YORP accelerates the rotation rate to one where it decelerates the rate.

Thus, we may imagine that a few hundred thousand years ago Itokawa may have had a positive YORP acceleration, driving the system to a faster rotation rate. As the rotation period approaches an approximate value of 6.5 h, the two main components of the asteroid would seek out lower energy configurations (Scheeres, 2006a). If, in one of these configurations, the YORP coefficient takes on negative values, the system will evolve away from this rapid rotation rate and enter a situation where it decelerates. If the YORP coefficients do not change sign during this period of reconfiguration, then the system rotation rate may increase to the point where the two main components go into orbit about each other. For the sizes and shapes of these two components, however, the synchronous orbit that they would naturally enter is highly unstable and would not evolve into a stable configuration. Neither would it evolve into an escaping orbit, as the total energy of that system is negative (Scheeres, 2002), meaning that the system is bound. Thus, it is probable that the system would re-impact at the relatively low orbital speeds for that system (on the order of 10 $\mathrm{cm\,s^{-1}}$ or less) and reconfigure itself. Such reconfigurations or impacts would supply significant seismic energy that could be related to Itokawa's current surface state and regolith distribution, which shows a dearth of craters and evidence for regolith migration to the potential lows of that body (Fujiwara et al., 2006). Eventually, the system could enter a configuration that provides a negative acceleration coefficient for its rotation rate, which would take it from this rapid rotation rate towards its current state. Alternately, if the head and body achieved orbit about each other, the force due to incident and reemitted solar photons acting on the smaller member could also have led the system to a low-speed re-impact (Ćuk and Burns, 2005). While these scenarios are speculative, they are entirely consistent with simple and basic physical laws of mechanics and motion.

Over this same time period, however, it is also possible that Itokawa had a close approach to the Earth, based on Michel and Yoshikawa (2005) which predicts a near unity probability of impact with the Earth for Itokawa over a million years about the current epoch. Thus, it may not be valid to uniformly extrapolate the Itokawa spin state backwards in time, as a close Earth passage could have changed its spin state (Scheeres et al., 2000), and even its YORP coefficients if mass redistribution occurred (Richardson et al., 1998). Even though we cannot rule this out, given the general order of magnitude of the predicted YORP effect it becomes likely that a similar YORP-induced interaction as discussed above may have occurred at some point in the past.

This specific scenario can be generalized, as there is nothing intrinsically unique about Itokawa, and would imply that NEAs and small main belt asteroids may experience relatively many transitions between rapid rotation, from which binary asteroids may be formed and shapes reconfigured, and periods of deceleration. The formation of binary asteroids via rapid rotation, or fission, is discussed in Harris (2002), Scheeres (2006a). This scenario also leads to periods of slow rotation and, potentially, reversals in spin direction that could then lead to an acceleration of the body to a fast spin rate, starting the cycle all over again.

Acknowledgments

We gratefully acknowledge the helpful reviews of D.P. Rubincam. D.J.S. acknowledges support by a fellowship from the Japan Society for the Promotion of Science and a grant from NASA's Planetary Geology and Geophysics Program.

References

Abe, S., Mukai, T., Hirata, N., Barnouin-Jha, O.S., Cheng, A.F., Demura, H., Gaskell, R.W., Hashimoto, T., Hiraoka, K., Honda, T., Kubota, T., Matsuoka, M., Mizuno, T., Nakamura, R., Scheeres, D.J., Yoshikawa, M., 2006. Mass and local topography measurements of Itokawa by Hayabusa. Science 312, 1344–1347.

Ćuk, M., Burns, J.A., 2005. Effects of thermal radiation on the dynamics of binary NEAs. Icarus 176, 418–431.

Demura, H., Kobayashi, S., Nemoto, E., Matsumoto, N., Furuya, M., Yukishita, A., Muranaka, N., Morita, H., Shirakawa, K., Maruya, M., Ohyama, H., Uo, M., Kubota, T., Hashimoto, T., Kawaguchi, J., Fujiwara, A., Saito, J., Sasaki, S., Miyamoto, H., Hirata, N., 2006. Pole and global shape of (25143) Itokawa. Science 312, 1347–1349.

Fujiwara, A., Kawaguchi, J., Yeomans, D.K., Abe, M., Mukai, T., Okada, T., Saito, J., Yano, H., Yoshikawa, M., Scheeres, D.J., Barnouin-Jha, O., Cheng, A.F., Demura, H., Gaskell, R.W., Hirata, N., Ikeda, H., Kominato, T., Miyamoto, H., Nakamura, A.M., Nakamura, R., Sasaki, S., Uesugi, K., 2006. The near-Earth Asteroid Itokawa observed by Hayabusa: Its possible structure and history. Science 312, 1330–1334.

Gaskell, R., Saito, J., Ishiguro, M., Kubota, T., Hashimoto, T., Hirata, N., Abe, S., Barnouin-Jha, O., Scheeres, D., 2006. Global topography of Asteroid 25143 Itokawa. Lunar Planet. Sci. XXXVII. Abstract 1876.

Greenwood, D.T., 2003. Advanced Dynamics. Cambridge, Cambridge, UK, chap. 3.

Harris, A.W., 2002. On the slow rotation of asteroids. Icarus 156, 184–190.

Michel, P., Yoshikawa, M., 2005. Earth impact probability of the Asteroid (25143) Itokawa to be sampled by the spacecraft Hayabusa. Icarus 179, 291–296.

Müller, T.G., Sekiguchi, T., Kaasalainen, M., Abe, M., Hasegawa, S., 2005. Termal infrared observations of the Hayabusa spacecraft target Asteroid 25143 Itokava. Astron. Astrophys. 443, 347–355.

Ostro, S.J., Benner, L.A.M., Magri, C., Giorgini, J.D., Rose, R., Jurgens, R.F., Yeomans, D.K., Hine, A.A., Nolan, M.C., Scheeres, D.J., Broschart, S.B., Kaasalainen, M., Margot, J.-L., 2005. Radar observations of Itokawa in 2004 and improved shape estimation. Meteor. Planet. Sci. 40 (11), 1563–1574.

Richardson, D.C., Bottke, W.F., Love, S.G., 1998. Tidal distortion and disruption of Earth-crossing asteroids. Icarus 134, 47–76.

Rios-Reyes, L., Scheeres, D.J., 2005. A generalized model for solar sails. J. Spacecraft Rockets 42 (1), 182–185.

Rubincam, D.P., 2000. Radiative spin-up and spin-down of small asteroids. Icarus 148, 2–11.

Saito, J., Miyamoto, H., Nakamura, R., Ishiguro, M., Michikami, T., Nakamura, A.M., Demura, H., Sasaki, S., Hirata, N., Honda, C., Yamamoto, A., Yokota, Y., Fuse, T., Yoshida, F., Tholen, D.J., Gaskell, R.W., Hashimoto, T., Kubota, T., Higuchi, Y., Nakamura, T., Smith, P., Hiraoka, K., Honda, T., Kobayashi, S., Furuya, M., Matsumoto, N., Nemoto, E., Yukishita, A., Kitazato, K., Dermawan, B., Sogame, A., Terazono, J., Shinohara, C., Akiyama, H., 2006. Detailed images of Asteroid 25143 Itokawa from Hayabusa. Science 312, 1341–1344.

Scheeres, D.J., 2002. Stability of binary asteroids. Icarus 159 (2), 271–283.

Scheeres, D.J., 2006a. Stability of binary asteroids formed through fission. Lunar Planet. Sci. XXXVII. Abstract 1632.

Scheeres, D.J., 2006b. Relative equilibria for general gravity fields in the sphere-restricted full 2-body problem. Celest. Mech. Dynam. Astron. 94 (3), 317–349.

Scheeres, D.J., Ostro, S.J., Asphaug, E., Hudson, R.S., Werner, R.A., 2000. Effects of gravitational interactions on asteroid spin states. Icarus 147, 106–118.

Vokrouhlický, D., Čapek, D., Kaasalainen, M., Ostro, S.J., 2004. Detectability of YORP rotational slowing of Asteroid 25143 Itokawa. Astron. Astrophys. 414, L21–L24.