ITOKAWA, YORP AND SEISMIC SHAKING. D.J. Scheeres, *U. Michigan, Ann Arbor (scheeres@umich.edu)*, R.W. Gaskell, *PSI*, M. Abe, R. Nakamura, M. Yoshikawa, *JAXA/ISAS*, P.A. Abell, *NASA-JSC*.

One unexpected consequence of the YORP effect acting on Itokawa is the occurrence of a period of seismic shaking that occurred on the order of a few hundred thousand years ago, and perhaps many times prior to that. These occurrences are due in part to Itokawa's small size and characteristic contact binary structure.

This abstract presents the results of an evaluation of the Yarkovsky-O'Keefe-Raszievskii-Paddack (YORP) effect [1] on the rotation state of asteroid Itokawa and the implications of this effect for the observed morphology of Itokawa. For the evaluation of the effect we use the estimated Itokawa shape, spin pole, mass, and optical properties derived from the Hayabusa mission to that asteroid [2]. This work has been accepted for publication in Icarus [3], this abstract provides a summary of these results plus some additional observations.

Itokawa observations The Hayabusa spacecraft visited asteroid Itokawa for a three month period in the Fall of 2005. During this period data was obtained that resulted in a precise shape of the asteroid [4,5], a total mass estimate [6], and observations of the surface features of the asteroid [2,7]. Of the many scientific results, some of the more intriguing observations were that the asteroid's surface is largely devoid of craters, the asteroid is a rubble pile distribution of boulders, the finest grained regolith lies in the gravitational lows of the asteroid, and that the asteroid is a contact binary with each component being roughly ellipsoidal in shape. The paucity of craters has been taken as an indication of a young surface for this asteroid. While such a recent surface could result from an extremely close flyby of Itokawa to the Earth, or be due to a recent large impact, we also find that such a fresh surface may naturally arise as a consequence of the YORP effect acting on the body's rotation rate.

Of relevance to the following discussion are the following measured Itokawa values inferred from the Hayabusa mission, and earlier observations reported in [8, 9]. The rotation period is 12.132370 hours, the obliquity is 178.3°, the total mass is 3.58×10^{10} kg, the mean radius is 0.162 km, and the principal moments of inertia, normalized by the mass, are 6.31×10^{-3}, 2.06×10^{-2}, and 2.17×10^{-2} km^2.

Effect of YORP on the rotation rate To evaluate the effect of YORP on the rotation state of Itokawa we apply the analysis method detailed in [10]. When combined with the precision shape model now in existence for Itokawa [5], this provides a prediction of the rotational acceleration of the asteroid and for the migration of its obliquity. Despite the precision model there is a large degree of uncertainty in the YORP predictions, due to unmeasured optical and thermal properties and to the fact that the solar radiation interactions occur at small scales not precisely modeled in the existing shape model.

As detailed in [3], the Itokawa spin rate is currently decreasing, with the predicted deceleration on the order of 3.5×10^{-17} radians/s^2, or a rate of increase in rotation period of 0.9×10^{-4} hours/year. The current uncertainty in the spin rate is on the order of $\pm 1 \times 10^{-9}$ rad/s, and was determined in 2004 [9]. Given the range in estimates of the secular deceleration, a detectable shift in spin rate should occur in less than 3 years. Thus, assuming similar data quality is obtainable as for the 2004 apparition, detection may occur in its current apparition. 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 degrees in three years, or an uncertainty in phase angle of ± 5.4 degrees. The range of decelerations considered in [3] due to different resolutions in the shape model predict a shift in phase angle of $-0.7 \rightarrow -1.3$ degrees in one year and $-6.3 \rightarrow -11.5$ degrees in three years, decreasing quadratically in time. This indicates that differences between predicted and measured light curve phase angles are marginally detectable at the current apparition, but in subsequent opportunities (which should occur with an approximate frequency of 3 years) will be commensurately larger and could provide a precise determination of the magnitude of the YORP effect.

The effect of YORP torques on the obliquity of Itokawa has also been computed, using the methodology detailed in [10]. For the current computation we ignored the effect of thermal inertia, which can be important. We find that the obliquity is decreasing from its current value at a rate of 0.1 degrees per 1K years. 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 from the present.

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 less than 100K years. More importantly, such a large deceleration rate for Itokawa has strong implications for the recent history of this body, implying that less than 200K years ago Itokawa was spinning at a rate of 6.5 hours. This rotation rate is fast enough for the "head" and "body" of Itokawa, as defined in [4], to go into mutual orbit about each other [11]. Even prior to achieving orbital speeds, these high spin rates place the system into an excited state where the components can decrease the total energy of the system by reconfiguring themselves [12]. We note that relatively small shifts in the body can result in changes of the size and sign of the YORP coefficients and may transition a body from a configuration where YORP accelerates the rotation rate to one where it decelerates the rate[3].

Thus, as we review the recent history of Itokawa and move backwards in time, we find it likely that the system went through a period where its "head" and "body" were energetically able to shift relative to each other to shed excess energy, and may even have been in orbit with subsequent low-speed impacts (on the order of cm/s). Moving even further back to before this epoch, we may imagine that Itokawa had a positive YORP acceleration, driving the system to a faster rotation rate. As the rotation period approached an approximate value of 6.5 hours, the two main components of the asteroid would seek out lower energy configurations [12]. 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, such as we have today.

If the YORP coefficient of Itokawa does 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 would most likely be negative [13], 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 centimeters per second or less) and reconfigure itself. 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 [14]. 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.

Such a period of 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 [2]. It is significant to note that the mechanical interactions between the bodies are of relatively low energy. The total kinetic energy of the two components, if they were in a circular orbit at their current separation, is less than 5% of the total gravitational potential energy of the entire system [15]. The relative speeds involved with reconfiguration or mutual orbit are much less than this and would in general be much less than 1% of the total potential energy of the system, and would be unable to disrupt or disperse the system.

Such interactions would be able to generate local slope failures of the system, however, such as the region of high slopes over the face of Itokawa's head, as discussed in [2]. They would also supply a sustained period of relatively gentle shaking of the body that would encourage regolith transport and erase older surface structures. If the two body components roll across each other during such reconfigurations it may also be possible for boulder material from one body to be deposited on the surface of the other, thoroughly mixing the surface material between the two bodies and potentially covering or uncovering material on each body. In [2] it is noted that the Western hemisphere of Itokawa has an apparent surplus of large blocks. If the head of Itokawa had rolled across this region such a deposit of larger blocks could easily have occurred.

Over this same time period, however, it is also possible that Itokawa had a close approach to the Earth, based on [16] 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 and even its YORP coefficients if mass redistribution occurred. 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 spin-up to a fast rate where reconfigurations can energetically occur may have happened 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 [17, 12]. 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.

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