DIRECT DETECTION OF THE ASTEROIDAL YORP EFFECT. S. C. Lowry[1] and A. Fitzsimmons[1], P. Pravec[2], D. Vokrouhlicky[3], H. Boehhardt[4], P. Taylor[5], J. Margot[5], A. Galad[6], M. Irwin[7], J. Irwin[7], and P. Kushnirak[2], [1]School of Mathematics and Physics, Queen's University Belfast, Belfast, BT7 1NN, UK (s.c.lowry@qub.ac.uk), [2]Astronomical Institute, Academy of Sciences of the Czech Republic, Fricova 1, CZ-25165 Ondrejov, Czech Republic, [3]Institute of Astronomy, Charles University, V Holesovickach 2, 18000 Prague 8, Czech Republic, [4]Max-Planck-Institut fur Sonnensystemforschung, Max-Planck-Strasse 2, 37191 Katlenburg-Lindau, Germany, [5]Department of Astronomy, Cornell University, Ithaca, NY 14853, USA, [6]Department of Astronomy, Physics of the Earth, and Meteorology, FMPI, Comenius University, 842 48 Bratislava, Slovakia, [7]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA.

Introduction: For decades, it has been suggested that YORP should exist on asteroidal surfaces and meteorites. More recently, several remarkable effects have been reported in this field that can only be explained if an as-yet undetected torque is acting upon these bodies, for which the YORP effect is the only realistic mechanism.

Likely manisfestations of YORP torques are the non-random grouping of the spin-states of the larger Koronis-family asteroids [1], as well as the evolution of orbital semi-major axes of small members in asteroid families toward extreme values [2]. YORP is also an important component in delivery models for near-Earth asteroids from the main asteroid belt [3]. Finally, there exists a distinct population of small very fast spinning asteroids known as the Monolithic Fast Rotators (MFR) [4]. If the orbits of such bodies are stable over million-year timescales, then the YORP effect is highly likely to place these asteroids into this category.

Without the necessary internal strength, YORP could cause small asteroids to spin up so fast that they are forced to morph into new shapes or even shed mass. Indeed, YORP may supersede tidal disruption and collisions as the main formation mechanism for binary asteroids in the planet-crossing population [5][6]. Conversely, YORP can act to reduce the spin rate and so could explain the very long (> 40 days) rotation period of some main belt asteroids and their tumbling states.

Despite its importance, YORP has never been directly measured and the only clues we have of its presence come from the indirect evidence mentioned above. Its companion effect, known as the Yarkovsky effect, was recently detected for the first time on asteroid Golevka using radar data spanning 10 years [7].

Near-Earth Asteroid (54509) 2000 PH5: A candidate for YORP detection: The importance of YORP derives from its ability to secularly modify the rotation rate and obliquity of small bodies. Unfortunately, the obliquity effect is too small to be detected with ground-based or even space-based measurements. It is the rotation rate change that may be detected if very precise observations, such as high-quality asteroid lightcurves, are obtained over a long enough timespan [8][9]. We selected the small near-Earth asteroid (54509) 2000 PH5. This is one of the few known Earth co-orbitals in a near 1:1 mean-motion resonance with Earth. The characteristics of its horseshoe orbit results in periodic close Earth approaches, roughly every July-August, making it a good target for regular monitoring over yearly timescales, using either photometric or radar observing techniques [10].

2000 PH5 is small, with a radar-derived mean radius of ~57 m, and any size-related YORP effect is therefore likely to be relatively high. Initial measurements on the spin-rate gave a period of 12.17 minutes, making this a very practical target for observations from Earth-based telescopes, in the sense that full and consecutive nights of observation are not required for accurate period determination. Within 2 hours we could continuously sample the lightcurve over ~10 full revolutions, more than adequate for our purposes. This small size and fast rotating nature puts 2000 PH5 into the MFR asteroid group, and so YORP may have been significantly affecting its spin rate for some time, and it is reasonable to assume that it is susceptible to YORP torques.

Data Acquisition and Lightcurve Analysis: In 2001, we initiated a large-scale observational photometric monitoring campaign of 2000 PH5 which spanned over 4 years. Many observatories from various countries contributed, including 1-2m optical telescopes at Calar Alto Observatory (Spain), Ondrejov Observatory (Czech Republic) and the European Southern Observatory (Chile) among others. On occasions where the brightness of the asteroid fell below the detection limits of the above facilities, we secured access to the large 3.5m telescope at Calar Alto, the 3.5m New Technology Telescope and the 8.2m Very Large Telescope at ESO. Each telescope was equipped with modern CCD imaging detectors, and standard broadband optical filters were used (normally either V or R filters, centered at wavelengths of 550 nm and 697 nm, respectively).

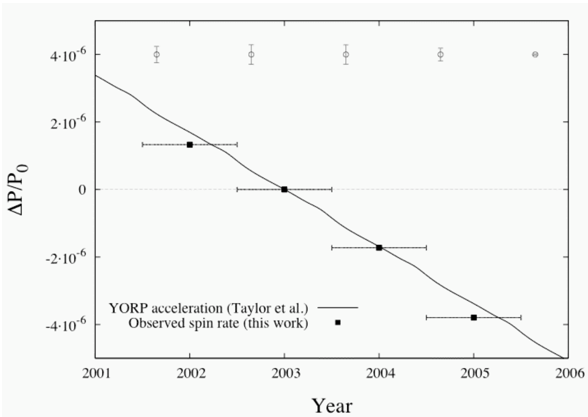

Figure 1: The observed inter-year change in sidereal rotation period for asteroid 2000 PH5. The solid curve is the theoretical prediction from [10].

Imaging sequences were obtained and the asteroid's rotational lightcurve were extracted at each epoch. Lightcurves were then grouped according to date; the 2001 and 2002 lightcurves were taken together, then the 2002-2003, 2003-2004, and finally the 2004-2005, so that each data set had a 1 year time-base. After normal geometry corrections were applied to the data-point times, we applied fitted for the sidereal period of each grouped data set. This method requires knowledge of the spin-axis orientation, which was determined using a combination of radar data plus our optical lightcurves from [10].

Over the 4 year observing period, the sidereal rotation period was unambiguously seen to decrease at an average rate of $\Delta P/P = -1.7*10^{-6}$ (± 9\%) per year, (Fig. 1). This result was robustly confirmed using an independent analysis method on the combined radar and lightcurve data [10]. This value can be matched to theoretical expectations for the YORP effect based on the shape and spin orientation of PH5 is presented in [10]. Earth encounter effects were modeled and safely excluded as a cause for the sidereal rotation period variation.

Long Term Spin Evolution of Asteroid (54509) 2000 PH5: The fast rotation of 2000 PH5 could imply this asteroid underwent a significant YORP evolution in the past. Also, our result suggests that YORP may significantly change the rotation state of 2000 PH5 in the future. From this value we may expect YORP will cause structural changes, mass shedding or even fission of this object at some point in the future, depending on its internal strength.

To probe this idea, we numerically propagated orbits of 2000 PH5 and its 999 close clones within the current orbital uncertainty ellipsoid. For this work we used the numerical package SWIFT-RMVS3 which is a state-of-the-art N-body symplectic code for long-term planetary dynamics that allows close encounters of test particles and planets [11]. We found a median dynamical lifetime before particle removal from the simulation, by solar or planetary impacts, of ~13 My. The longest-lived clones of 2000 PH5 (about 6 %) survived 100 My of orbital evolution.

In a second step, we numerically integrated the secular evolution of the spin state for each of these 1000 particles along their precise orbits. The initial rotation state was that of 2000 PH5 today and the YORP strength as calibrated by our observation. At 14.8 My, when half of the population were still on heliocentric orbits, the rotation periods decreased such that their median was 40 s with extreme values as small as 12 s. At 35 My, when 25% of the original clone population was still surviving, we had a median rotation period of 19 s and lowest extremes of 5 s.

Our observational calibration of the YORP effect, in conjunction with orbital and spin integrations, therefore demonstrates that asteroids like 2000 PH5 can attain extremely fast rotation rates. Our work implies the existence of a population of 100 m asteroids with rotation periods of ~20 s, significantly faster than the most rapidly rotating asteroid of this size, 2000 WH10 with P ~ 80 s [12]. Lightcurve observations to date are biased against detection of such short periods, and hence the number of such bodies is unconstrained at present. If no such objects are found, then the most likely explanation is eventual significant mass shedding or rotational fission before they reach this value of P. We are a major step closer to understanding the origins and evolution of the MFR asteroid population and the binary asteroids.

References:

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