Spin Rate of Asteroid (54509) 2000 PH5 Increasing Due to the YORP Effect
Patrick A. Taylor, et al.
Science 316, 274 (2007);
DOI: 10.1126/science.1139038

The following resources related to this article are available online at www.sciencemag.org (this information is current as of April 13, 2007):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/cgi/content/full/316/5822/274

Supporting Online Material can be found at:
http://www.sciencemag.org/cgi/content/full/1139038/DC1

A list of selected additional articles on the Science Web sites related to this article can be found at:
http://www.sciencemag.org/cgi/content/full/316/5822/274#related-content

This article cites 15 articles, 2 of which can be accessed for free:
http://www.sciencemag.org/cgi/content/full/316/5822/274#otherarticles

Information about obtaining reprints of this article or about obtaining permission to reproduce this article in whole or in part can be found at:
http://www.sciencemag.org/about/permissions.dtl
In a second step, we numerically integrated the secular evolution of the spin state for each of these 1000 particles along their precise orbits (13), with the YORP strength set to our observed value. At 35 My, when 25% of the original clone population remained, the median rotation period was 19 s with a lowest extreme of 5 s (Fig. 3).

Our observational calibration of the YORP effect, in conjunction with orbital and spin integrations, demonstrates that asteroids like PH5 can attain extremely fast rotation rates. Our work also implies the possible 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 WH110 with P = 80 s (16). Light curve observations to date are biased against the 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.

References and Notes
13. See supporting material on Science Online.
17. We thank all the staff at the observatories involved in this study for their support. This work was based on observations at the following observatories: ESO, Chile (PIs 271C-5023 and 073C-O137); Ondrejov Observatory, Czech Republic (grant A0303204); Centro Astronómico Hispano Alemán (Calar Alto, Spain); Liverpool Telescope, La Palma (Canary Islands, Spain); Isaac Newton Group, La Palma; and Faulkes Telescope North (Maui, Hawaii). We also thank the referees for their helpful reviews. Supported by the Leverhulme Trust (O.C.L.), the UK Particle Physics and Astronomy Research Council (A.F.), the Grant Agency of the Czech Republic (P.P. and D.V.), NASA grant NNG04GN31G (P.A.T. and J.-L.M.), and Slovak Grant Agency for Science VEGA grant 1/307406 (A.G.). This work made use of the NASA/JPL HORIZONS ephemeris-generating program.

Spin Rate of Asteroid (54509) 2000 PH5 Increasing Due to the YORP Effect

Patrick A. Taylor,1* Jean-Luc Margot,1* David Vokrouhlický,2 Daniel J. Scheeres,3 Petr Pravec,4 Stephen C. Lowry,5 Alan Fitzsimmons,5 Michael C. Nolan,6 Steven J. Ostro,7 Lance A. M. Benner,7 Jon D. Giorgini,7 Christopher Magri8

Radar and optical observations reveal that the continuous increase in the spin rate of near-Earth asteroid (54509) 2000 PH5 can be attributed to the Yarkovsky-O’Keefe-Radzievskii-Paddack (YORP) effect, a torque due to sunlight. The change in spin rate is in reasonable agreement with theoretical predictions for the YORP acceleration of a body with the radar-determined size, shape, and theoretical predictions for the YORP acceleration of a body with the radar-determined size, shape, and spin state of 2000 PH5. The detection of asteroid spin-up supports the YORP effect as an explanation for the anomalous distribution of spin rates for asteroids under 10 kilometers in diameter and as a binary formation mechanism.

Theory predicts an evolution of the spin state of a small solar system body as a result of the absorption and asymmetric re-emission of sunlight, the so-called YORP effect. The resultant radiation torques are thought to realign the spin vector while changing the spin rate of the object (1). Lowry et al. (2) report an increase in the spin rate of 2000 PH5. Here we present, with radar and optical observations and modeling of 2000 PH5, the best evidence to date that the YORP effect is responsible for changing the spin rate of an asteroid.

For objects with finite thermal conductivity, especially fast-rotating asteroids (<1 km in diameter that lack regolith, YORP torques tend to force the spin vector to 0° or 180° obliquity (parallel or antiparallel to the orbit normal) and cause the spin rate to increase or decrease with equal probability (3) on time scales proportional to the square of the diameter D (4). Therefore, YORP may explain
the observed excess of slow and rapid rotators among asteroids <10 km in diameter (4). Continuous spin-up by the YORP effect could result in a binary system from the shedding of mass as centrifugal forces overcome self-gravity and internal strength. Thus, along with spin-up from close planetary encounters (5–8) and subcatastrophic collisional fission (9), the YORP effect may be responsible for producing a fraction of the near-Earth asteroid binary systems (10).

Near-Earth asteroid (54509) 2000 PH5, hereafter referred to as PH5, was discovered by the Massachusetts Institute of Technology Lincoln Laboratory’s near-Earth asteroid search program (LINEAR) (11) on 3 August 2000 at a geocentric distance of 0.04 astronomical units (AU). PH5 (semimajor axis $a = 1.00$ AU, eccentricity $e = 0.23$, inclination $i = 1.8^\circ$) (fig. S1) is one of only a handful of objects known to be co-orbital companions of Earth (12–14). Annual close approaches from 2001 to 2005, as close as 5 lunar distances, were conducive to radar observations and allow us to present a spin-state description and detailed shape model (15) of PH5.

We conducted radar observations of PH5 (table S1) using the 70-m antenna and 450 kW, 3.5 cm wavelength transmitter at Goldstone on 27–28 July 2001 (16) and the 305-m antenna and 900 kW, 12.6 cm wavelength transmitter at Arecibo on 27–28 July 2004 and 24–26 July 2005. The radar echo is Doppler broadened by the rotation of the target (17), and the amount of broadening constrains the spin axis. Daily sums of Doppler-only spectra (fig. S2) determine the radar reflection properties of PH5 (table S2), which are similar to terrestrial planet surfaces (18).

Range-Doppler images (19) constrain the shape by resolving the radar echo in two orthogonal dimensions: distance from the observer and rotational Doppler shift. High-resolution images of PH5 from Arecibo (Fig. 1, first and fourth columns) with 7.5 m (0.05 $\mu$s) resolution reveal an echo 60 to 75 m deep, as well as an array of leading-edge features: convex, linear, and concave, as PH5 rotates. Visual inspection of the range-Doppler images suggests a rotation period of ~12 min, consistent with light-curve observations (2).

The limb-to-limb bandwidths of Doppler-only spectra (20) covering a full rotation of the target produce a bandwidth curve (fig. S3) whose amplitude variation is due to the changing breadth of the rotating nonspherical target on the sky. The mean bandwidth grows from 2001 to 2005, so the line of sight was moving away from the spin axis (21). Fits to individual Doppler-only spectra from 2001, 2004, and 2005 with simple ellipsoid and spherical harmonic shape models (22) constrain the spin vector to lie within 10° of ($180^\circ$, $-85^\circ$) in J2000 ecliptic coordinates at an...
obliquity of 173° from the orbit normal. This retrograde pole is adopted for shape modeling and translating between the observed light curve and intrinsic sidereal periods in the light-curve analysis (2). A prograde pole fits the observed bandwidths equally well but cannot fit bandwidth curves and light curves simultaneously.

A change in sidereal spin rate is necessary to fit the radar data over time. However, light-curve data alone provide a more accurate determination of the required change than does analysis of the range-Doppler imagery. To produce initial conditions for the spin state of our most detailed shape model, we fit synthetic light curves based on a simple spherical harmonic shape model to the 2001 light-curve data (2), which consist of three epochs over 24 hours, a time frame over which the change in spin rate is negligible. We then include the remaining light-curve data from 2002 to 2005 (2), allowing for an arbitrary phase shift for each light curve to match the shape of the model’s synthetic light curves. The resulting phase shifts (Fig. 2) necessary to link the light curves are well fit by a quadratic function in time; in other words, the spin rate is increasing linearly with time. The use of a linear change in the spin rate rather than a constant spin rate yields improvement by a factor of ten in the reduced $\chi^2$ value of a spherical harmonic fit to the entire collection of light-curve data.

For pole coordinates of (180°, −85°), the sidereal spin rate necessary to fit the light curve data are $42582.41 \pm 0.02$ deg/day (12.17-min period) at the initial epoch of $0^\circ$ UT on 27 July 2001, and the necessary change in spin rate is $(2.0 \pm 0.2) \times 10^{-4}$ deg/day$^2$. This determination of a continuous increase in spin rate precisely matches the discrete spin-period changes observed in (2). The fractional change in spin period is $1.72 \times 10^{-5}$ (±10%) per year. Accelerations determined by this method for poles less than 10° from (180°, −85°) lie within 8% of the nominal acceleration, indicating relative insensitivity of the acceleration to precise pole location.

The shape models (22) of PH5 are 288-vertex polyhedra with 572 triangular facets giving the models 12° resolution in longitude, twice the amount PH5 rotated by during the exposure time for each range-Doppler image. We produced a family of models with a range of surface “roughness” based upon large-, medium-, and small-scale topography (22) to determine both the shapes that best fit the combined radar and light-curve data and how roughness affects the YORP acceleration calculations. All models produced have similar silhouettes, with much of the variation coming from the smoothness of the surface and the length of the shortest principal axis of inertia. The best PH5 shape model shows very good agreement with all range-Doppler images, reproducing the various convex, linear, and concave leading edges of the echoes (Fig. 1).

The shape of PH5 (fig. S4) is distinguished by its flattened northern hemisphere with a linear edge and prominent concavity that are clearly visible in the radar images.

The phase agreement between the rotating model and the entire set of range-Doppler images, as well as the ability to link the light curves from the 4-year optical photometry campaign (2), is due to the inclusion of a linear change in the intrinsic spin rate of PH5 (23). Harder to reproduce is the large amplitude of the PH5 light curves (fig. S5). The discrepancy may be due to unresolved topography, shadowing effects from concavities, albedo variations, or deficiencies in the photometric model used in the shape modeling software.

The rapid rotation of PH5, the increasing spin rate, and the near-180° obliquity are consistent with simulations of a body subjected to YORP torques (3). YORP torques can change the spin state of PH5 on less than million-year time scales (2), shorter than the dynamical (2, 24) and collisional lifetimes (25) of about 10 million and 1 billion years, respectively, that would reorient the spin vector or disrupt the asteroid. Despite the repeated close encounters between PH5 and Earth, planetary tidal torques are not strong enough (2) to cause the observed change in spin rate. Without other plausible causes, the YORP effect is the most viable mechanism for explaining the observations.

Using the PH5 spin state and shape models, two independent YORP acceleration models (3, 26) predict changes in spin rate, in terms of the fractional change in spin period ($\Delta P/P_0$) per year, 2 to 7 times as large as those observed (Table 1). Smooth models, those with less facet-scale topography, produce changes in spin rate closer by a factor of 2 to the observed value as models with rougher surfaces. Several factors may account for the discrepancy between observed and theoretical values. The incomplete surface coverage by radar and light-curve data. Several factors could account for the discrepancy between observed and predicted values.

Table 1. Summary of shape models and predictions for the change in spin period due to the YORP effect. Shape A (rough) is the best-fit shape model depicted in Fig. 1, and the other shape models sample the 1-σ formal uncertainty region for the fit. “Smooth” and “rough” describe the amount of facet-scale topography the shape models allow. $a$, $b$, and $c$ are the extents of the shape model along the principal axes of inertia. $D$ is the diameter of a sphere with the same volume as the shape model. The YORP predictions are given by the factor by which they overestimate the observed change in spin period. Shape models with smoother surfaces result in predicted changes in spin period more consistent with observation than do rough surfaces, which provide better fits to the radar and light-curve data. Several factors could account for the discrepancy between observed and predicted values.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Type</th>
<th>$abc$ (m)</th>
<th>$D$ (m)</th>
<th>$\Delta P/P_0$ per year factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Smooth</td>
<td>150/128/93</td>
<td>114.2</td>
<td>2.86</td>
</tr>
<tr>
<td>B</td>
<td>Rough</td>
<td>149/134/96</td>
<td>112.8</td>
<td>6.18</td>
</tr>
<tr>
<td>B</td>
<td>Smooth</td>
<td>149/130/91</td>
<td>113.2</td>
<td>2.95</td>
</tr>
<tr>
<td>C</td>
<td>Rough</td>
<td>147/132/91</td>
<td>111.7</td>
<td>4.56</td>
</tr>
<tr>
<td>C</td>
<td>Smooth</td>
<td>149/129/97</td>
<td>115.1</td>
<td>2.63</td>
</tr>
<tr>
<td>C</td>
<td>Rough</td>
<td>149/131/99</td>
<td>113.0</td>
<td>4.74</td>
</tr>
</tbody>
</table>

Observed $\Delta P/P_0$ per year $(2) = -1.72 \times 10^{-6}$

References and Notes

Analyses of Soft Tissue from *Tyrannosaurus rex* Suggest the Presence of Protein

Mary Higby Schweitzer,1,2,3* Zhiyong Suo,4 Recep Avci,4 John M. Asara,5,6 Mark A. Allen,7 Fernando Teran Arce,4,8 John R. Horner3

We performed multiple analyses of *Tyrannosaurus rex* (specimen MOR 1125) fibrous cortical and medullary tissues remaining after demineralization. The results indicate that collagen I, the main organic component of bone, has been preserved in low concentrations in these tissues. The findings were independently confirmed by mass spectrometry. We propose a possible chemical pathway that may contribute to this preservation. The presence of endogenous protein in dinosaur bone may validate hypotheses about evolutionary relationships, rates, and patterns of molecular change and degradation, as well as the chemical stability of molecules over time.

It has long been assumed that the process of fossilization results in the destruction of virtually all original organic components of an organism, and it has been hypothesized that original molecules will be either lost or altered to the point of nonrecognition over geological time. Analyses of specific organic constituents may persist across geological time.

1Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA. 2Department of Anatomy, School of Medicine, University of North Carolina at Chapel Hill, Chapel Hill, NC 27514, USA. 3Division of Signal Transduction, Beth Israel Deaconess Medical Center, Boston, MA 02215, USA. 4Department of Pathology, Harvard Medical School, Boston, MA 02115, USA. 5Department of Chemistry and Biochemistry, Montana State University, Bozeman, MT 59717, USA. 6Center for Nanomedicine, Pulmonary and Critical Care Medicine, Department of Medicine, University of Chicago, Chicago, IL 60637, USA. *To whom correspondence should be addressed. E-mail: schweiter@ncsu.edu

---

17. The Doppler broadening of the radar echo due to rotation of the target is $B = (4\pi D P \sin \alpha)$, where $D$ is the limb-to-limb bandwidth of the echo, $P$ is the spin period of the target, and $\alpha$ is the inclination of the spin axis to the line of sight.
19. Resolution in time delay, and equivalently range, is achieved by transmitting a time-dependent signal and analyzing the received signal according to arrival time.
20. We typically define the limb-to-limb bandwidth as the full width of the radar echo at the level of twice the root mean square (RMS) of the off-DC, off-target noise. The exception is the strong 2004 Arecibo data, for which we use 10 times the RMS as the threshold to avoid contributions from frequency sidebands.
21. This assumes PHS is a principal axis (PA) rotator where the spin axis remains fixed in inertial space and aligned with the axis of maximum moment of inertia. The spin axis of PHS must then be oriented such that the angles it makes with the lines of sight satisfy the observed bandwidths (17). The damping time scale (20) to PA rotation for PHS is of order 0.1 million years.
22. Materials and methods are available as supporting material on Science Online.
23. The spin state solution is also validated by the phase agreement of infrared lightcurves from the Spitzer Space Telescope with synthetic lightcurves produced with our shape (27).