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SCIENCE DIRECT®
Icarus 178 (2005) 281–283
ICARUS
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Abrupt alteration of Asteroid 2004 MN4's spin state during its 2029 Earth flyby

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Received 16 March 2005; revised 2 June 2005

Available online 22 July 2005

Abstract

We predict that when Asteroid 2004 MN4 passes 5.6 ± 1.4 Earth radii from Earth's center on April 13, 2029, terrestrial torques during the flyby will alter its spin state in a dramatic manner that will be observable using groundbased telescopes. Although the asteroid will most likely not undergo catastrophic disruption, it may be subject to localized failure across its surface and interior, providing a unique opportunity to measure otherwise inaccessible mechanical properties of an asteroid.
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Keywords: Asteroids; Rotational dynamics; Rotation; Dynamics; Radar

The ∼0.4 kilometer diameter Asteroid 2004 MN4 will pass 35900 ± 8980 km (5.6 ± 1.4 Earth radii) from Earth's center on April 13, 2029 (Benner et al., 2005; Giorgini et al., 2005).[1] It has been demonstrated that gravitational interactions during close planetary encounters can alter an asteroid's spin state, and hence, along with collisions, play a role in the rotational evolution of near-Earth asteroids (NEAs) (Scheeres et al., 2000, 2004). Here we present results of simulations that predict that terrestrial torques in 2029 will alter 2004 MN4's spin state in a dramatic manner that should be easily observable in real time using groundbased telescopes.

We explored the parameter space of possible spin-state changes by conducting Monte Carlo simulations that model the asteroid as a tri-axial ellipsoid with a length-to-width ratio of 1.4 and rotating uniformly about its shortest axis with a period of 30.62 h (R. Behrend, personal communication). To complete the tri-axial asteroid shape we assumed a height-to-width ratio of 0.8. We sampled a million asteroid orientations for the nominal and three-sigma closest and farthest possible flyby distances using the methodology outlined in Scheeres et al. (2004).

Our Monte Caro simulation code uses an analytic approximation for the change in rotation state. The analytical model predicts the change in an object's rotational angular momentum as a function of flyby distance (periapsis radius of the hyperbolic trajectory), eccentricity (or hyperbolic excess speed), flyby geometry in the body fixed space (specification of the hyperbola's longitude of ascending node, inclination, and argument of periapsis), and the moments of inertia and the initial rotation state of the asteroid (Scheeres, 2001). The relative orientation of the asteroid is crucial in controlling whether the body's rotational angular momentum and kinetic energy is increased, decreased, or left unchanged. Even if the net change in angular momentum and kinetic energy are zero, the body will still experience significant angular accelerations and decelerations during the flyby.

Fig. 1 shows a sample of our results, parameterized by the effective rotation period (P_{eff}) and the rotation index (I_R). We define the effective rotation period of a nonprincipal-axis (NPA) spin state as the rotation period of a sphere with the same kinetic energy and angular momentum as the rotating body; this generalizes to the simple spin period for a principal-axis rotator. The rotation index I_R is defined to equal 1 for rotation about the maximum moment of inertia (short axis), 0 for rotation about the intermediate moment of inertia, and -1 for rotation about the minimum moment of inertia (long axis); all other values indicate NPA rotation. The P_{eff} histogram will shift one-to-one with a change in initial rotation period. The I_R histogram will shift away from unity if the body is initially in an NPA rotation state, resulting in minor changes to the P_{eff} histogram. The distributions become wider as the length-to-width ratio increases. Changing the height-to-width ratio does not have a strong effect on the results.

The histograms in Fig. 1 suggest that the overwhelmingly likely outcome of the flyby will be NPA rotation with a distinctly different value of P_{eff}. We note that the resulting P_{eff} distribution has two peaks strongly

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[1] All trajectory values are taken from JPL orbit Solution 91, available at the JPL Horizons web-site: http://ssd.jpl.nasa.gov/horizons.html.

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doi:10.1016/j.icarus.2005.06.002

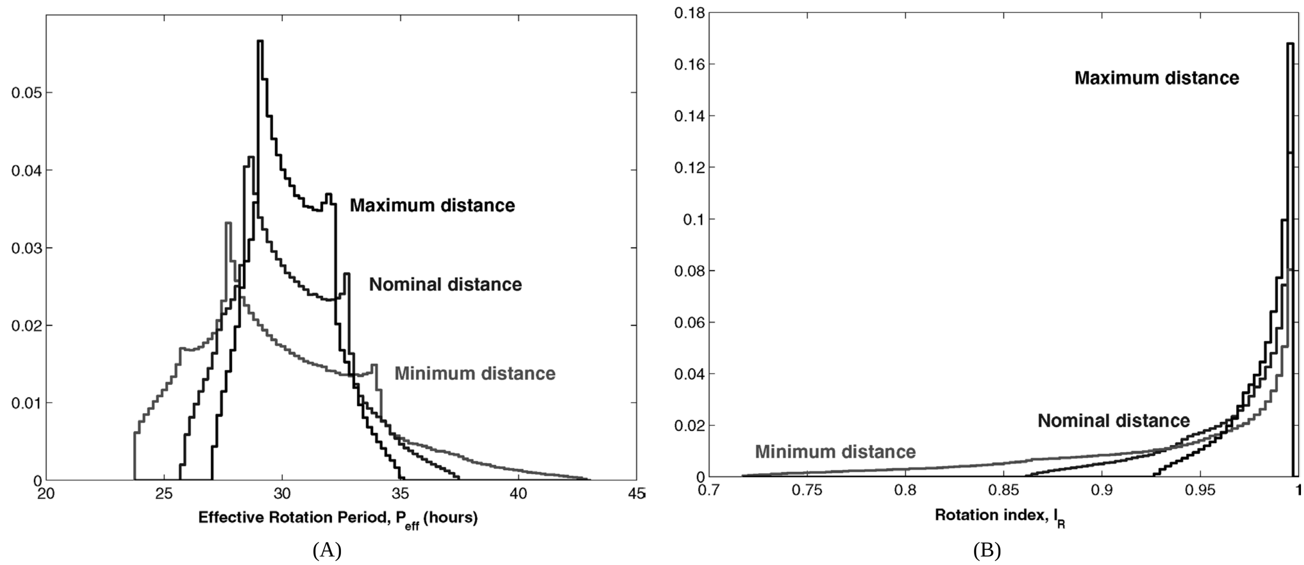

Fig. 1. Histograms of 2004 MN4's effective rotation period (A) and rotation index (B) following the 2029 flyby.

shifted from the initial spin period in both increasing and decreasing directions. We also note that over 88% of the flybys (for the nominal distance) leave the asteroid in a nonprincipal axis rotation state. Cases with minimal change in $P_{\rm eff}$ generally correspond to nearly pole-on geometries at closest approach, and for these the tidal torques force the object into a strongly NPA state, toward the lower tail of the rotation index histogram. The short-period and long-period tails of the $P_{\rm eff}$ histogram generally are accompanied by only small changes in $I_{\rm R}$ and correspond to simulations in which Earth is near the asteroid's equatorial plane at closest approach with the longest principal axis 45° from the asteroid-Earth line. Cases with a minimal change in both parameters correspond to equatorial flybys with the longest principal axis parallel or perpendicular to the asteroid-Earth line. Even in these cases, however, the asteroid is subject to appreciable rotational accelerations and decelerations near closest approach.

The analytical formulae we use for our Monte Carlo simulations are conservative in that they under-estimate the possible change in the spin state (Scheeres et al., 2004). Performing a similar Monte Carlo analysis with precise numerical integrations is not feasible, however, due to the computation time needed to simulate the flybys. We have performed a limited set of precise numerical simulations of the equations of motion to establish the extreme outcomes possible for $P_{\rm eff}$. These generally occur for flybys in the equatorial plane. From these we find that the post-flyby $P_{\rm eff}$ for the nominal case could be as short as 19 h or as long as 57 h.

The spin-state alteration occurs almost entirely during a one-hour interval centered on the closest-approach epoch, 2029 April 13 21:45:34 UTC, when the asteroid will brighten to naked-eye visibility (3rd magnitude). Radar imaging using today's Goldstone and Arecibo systems would be able to determine the pre- and post-flyby spin states.

If the asteroid's bulk density is greater than 1 $\mathrm{g\,cm^{-3}}$ then it will remain outside of the classical Roche limit and most likely will not disrupt catastrophically. For densities less than this, some portion of the closest approach uncertainty ellipse lies within the asteroid's Roche limit; at a density of 0.44 $\mathrm{g\,cm^{-3}}$ the nominal flyby distance is at this limit. Terrestrial torques will cause angular accelerations as strong as 1×10^{-8} $\mathrm{rad/s^2}$ (7.5 $\mathrm{deg/h^2}$), and particles on the surface will experience fractional changes in local gravity as large as 0.1 for an asteroid density of 2 $\mathrm{g\,cm^{-3}}$, or correspondingly larger for a lower density body. If 2004 MN4 has a very low density and is a gravitationally bound agglomerate, then global reshaping or disruption could occur (Richardson et al., 1998). If the asteroid has a density similar to values estimated for other NEAs (>1.5 $\mathrm{g\,cm^{-3}}$, Britt et al., 2002) we do not expect it to undergo extensive tidal reshaping or disruption. However, the accelerations and torques could still be great enough to cause localized shifts on the asteroid's surface and within its interior. Specific predictions about such shifts are difficult to make, given our lack of understanding of the interior structure of asteroids. If 2004 MN4 is a shattered or fractured object, following the classification schemes used in (Richardson et al., 2002), there is a possibility for localized shifts in the interior and surface of the body due to the long-term stress associated with an Earth flyby.

The closest approach conditions are amenable to the placement of accelerometers or seismometers on the surface, as they most likely will not be lifted off the asteroid surface. Measurement of any structural shifts by devices placed on the surface prior to the flyby could reveal otherwise inaccessible mechanical properties of the asteroid (Scheeres et al., 2003). Therefore, the 2004 MN4 flyby constitutes an unprecedented opportunity to gain insight into asteroid interiors.

NEAs undergo nongravitational Yarkovsky accelerations (Chesley et al., 2003; Giorgini et al., 2002) that depend on the spin state. Alteration of 2004 MN4's spin state in 2029 will change its Yarkovsky accelerations, its subsequent heliocentric motion, and thus the proximity of future close Earth approaches.

Acknowledgments

This material is based upon work supported by the National Aeronautics and Space Administration (NASA) under the Science Mission Directorate Research and Analysis Programs. Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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