0.68 to 0.81 and the inclination varies from 39° to 14° (*23*, *24*)]. Thus, the KW4 binary system could have originated in a close flyby past any of those planets. Currently, KW4's orbit is close to the ($e = 0.68$, $i = 39°$), state and the ascending node is very close to Earth's semimajor axis. Within the nearly two-millennium window (1179 to 2946) of accurate close-approach prediction (table S4) allowed by available radar plus optical astrometry, KW4 makes 186 close Earth approaches and no approaches to any other planet. With Alpha's current pole direction assumed, the sub-Earth latitude at closest approach is generally equatorial, with mean and rms of $-7° \pm 20°$. This geometric configuration conceivably could be the signature of an extremely recent Earth-flyby origin of the system.

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Dynamical Configuration of Binary Near-Earth Asteroid (66391) 1999 KW4

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Dynamical simulations of the coupled rotational and orbital dynamics of binary near-Earth asteroid 66391 (1999 KW4) suggest that it is excited as a result of perturbations from the Sun during perihelion passages. Excitation of the mutual orbit will stimulate complex fluctuations in the orbit and rotation of both components, inducing the attitude of the smaller component to have large variation within some orbits and to hardly vary within others. The primary's proximity to its rotational stability limit suggests an origin from spin-up and disruption of a loosely bound precursor within the past million years.

Binary systems in the near-Earth asteroid (NEA) population appear to be common (*1*). Because of their small sizes, binary NEAs' dynamical states and evolutionary histories may be very unlike those of other binaries in the solar system (the Earth-Moon and Pluto-Charon systems, large mainbelt asteroid binaries, and binary Kuiper Belt objects). Previous analyses of binary-system dynamics (*2*) have not considered situations with nonspherical components and strong coupling between translational and rotational motion. Radar images have characterized binary NEA (66391) 1999 KW4 in detail (*3*), and here we explore the full dynamics of the KW4 system with numerical simulations that solve the equations of motion for the coupled evolution of orbit and rotation.

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Our simulations model the orbital dynamics as the relative motion between the body centers of mass and model the rotational dynamics using Euler's and attitude kinematic equations for each body (*4*). The system conserves total angular momentum and energy in the absence of external perturbations but may lose energy through internal dissipation. The coupled rotational and orbital dynamics are driven by the system's mutual gravitational potential, which is an explicit function of the relative position and attitude of the two bodies. The mutual potential between the radar-derived models of KW4's primary and secondary components (Alpha and Beta) are computed using a mutual potential expansion specialized for polyhedral models (*5*–*7*). Propagation of the system's dynamical evolution over several-month time scales has been made tractable by using a variational integrator (*8*) and a parallel computer with up to 256 processors (*9*).

Ostro *et al*. (*3*) find that the average relative orbit is nearly circular with a period of 17.4 hours and a separation of 2.54 km, that Beta's rotation is synchronous on average, and that Alpha's rotation pole and the binary orbit normal are separated by between 0 and 7.5°, with a nominal separation of 3.2°. Our simulations identify an energetically relaxed configuration for the coupled orbit and rotational dynamics, with the orbit and Alpha angular momentum vectors aligned, Beta rotating synchronously with small departures of its long axis from the Beta-Alpha line, and modest dynamical variations (Figs. 1 and 2). The eccentricity of the relaxed orbit, ~0.0113, is nonzero because of the nonspherical mass distributions of Alpha and Beta. Nevertheless, the system traces out a nearly circular path as the true anomaly librates about zero with a few degree amplitude, whereas the argument of periapsis increases secularly with a period equal to the orbit period.

A relaxed configuration is expected in the absence of any external perturbations, but during each perihelion passage gravitational perturbations from the Sun excite the system. Numerical simulations indicate that KW4's orbit pole can shift by more than 0.5° per periapsis passage for the current perihelion distance of 0.2 astronomical units (AU) and by more than 1.0° when the perihelion is at 0.12 AU, the minimum perihelion expected as a result of *N*-body perturbations and the Kozai resonance (*10*). During each perihelion passage, solar perturbations cause the eccentricity to vary up to 0.002 at a perihelion of 0.2 AU and 0.005 at a perihelion of 0.12 AU, producing excitation in the pole and eccentricity that should persist given the high frequency of perihelion passages. KW4 makes frequent Earth approaches (*3*): An approach within 20 Earth radii can excite the system (*11*), and flybys within 5 Earth radii can disrupt it (*12*).

An excited energy state can be simulated by parametrically varying the initial osculating eccentricity *e*. To explore the range of possible excitations, we performed a number of simulations at different initial eccentricities. Figures 1 and 2 show two cases, one chosen with relaxed initial conditions and the other starting from $e = 0$ (to produce an excited state), both of which lie within the uncertainties (*3*).

Because of the 4% variation in Alpha's equatorial radius, there are fluctuations of the mutual orbit semimajor axis and eccentricity that drive a longer-term oscillation with a period equal to the orbit period (Fig. 1). These excite Beta's free precession, causing oscillations in its rotation and orbit with a period of ~188 hours (about four times Beta's 48-hour free precession period). The oscillation amplitude in Beta's rotation rate changes from near zero to a maximum value, causing the attitude to vary by several degrees relative to uniform rotation during some orbits but to maintain nearly uniform rotation during others (Fig. 2).

Thus, Beta experiences persistent shaking, with angular accelerations up to 2×10^{-10} rad/s^2 in the relaxed state and substantially more in the excited configurations (Fig. 2), which are much more energetic than that due to free precession (*13*). Such shaking would drive material toward a minimum-energy, compact configuration, lowering the body's porosity, and possibly producing Beta's low gravitational slopes. This hypothesis is consistent with the fact that Beta's density estimate is larger than Alpha's (*3*).

The system's total angular momentum budget receives a 75% contribution from Alpha's rotation, 25% from the relative orbit, and less than 0.1% from Beta's rotation. As a result of conservation, the system's total angular momentum vector lies between Alpha's and the orbit's angular momentum vectors, so that the three are in a plane, except for the deviations that Beta allows. Beta's angular momentum is locked

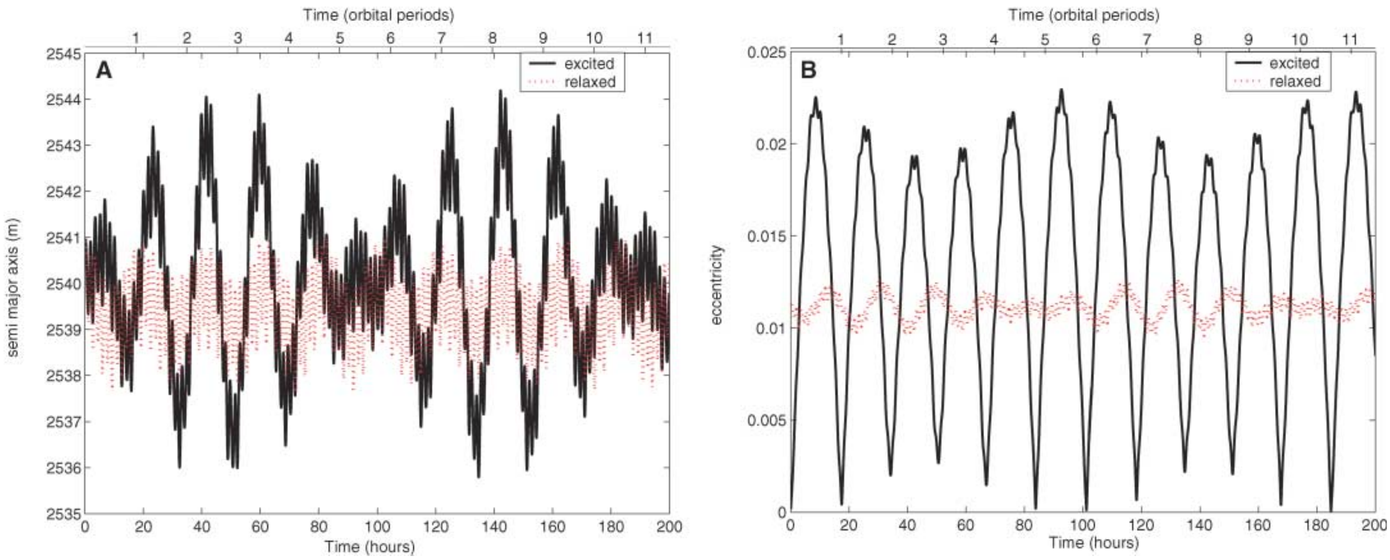

Fig. 1. Evolution of KW4's orbit (**A**) semimajor axis and (**B**) eccentricity over 200 hours, computed for the relaxed and excited system.

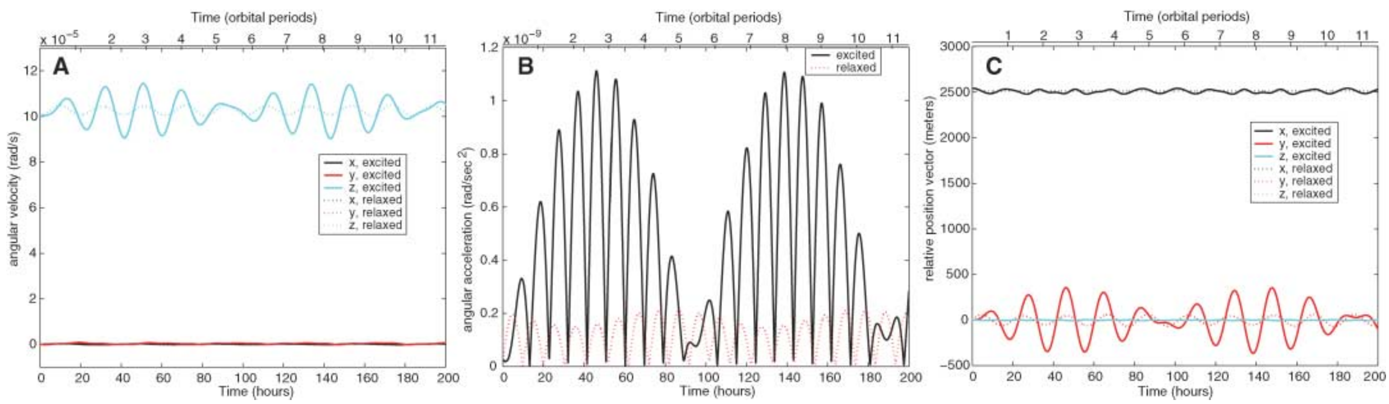

Fig. 2. (**A**) Rotational angular velocity and (**B**) total angular acceleration of Beta, shown in the Beta fixed frame, for the relaxed and excited cases. (**C**) Alpha's orbit in a Beta-fixed frame. The large *y* variations are due primarily to Beta's attitude libration about the Beta-Alpha line.

within a small-scale variation about the orbit angular momentum vector and is captured on average in a Cassini state (*14*) with fluctuations due to perturbations from the component's shapes. The minimum energy configuration is for the angular momentum vectors to be aligned, consistent with the estimated offset between the vectors of 3.2° with an uncertainty ranging up to 7.5° (*3*). However, solar perturbations at perihelion indicate that a minimum offset on the order of 1° should exist. The actual offset between these vectors will be constant between perihelion passages because the components' mutual potential induces equal precession rates of the orbit plane and Alpha's spin pole (*2*, *15*), with a period of ~90 days. Over half a precession period, the inertial directions of the estimated orbit and Alpha poles will vary by 4.8° and 1.6°, respectively, less than the uncertainty in the determined pole direction using data from the 2001 and 2002 observations.

Portions of Alpha's surface are only 7 m from an altitude at which a free particle would be placed into orbit about the body. A rotation period 1.3% shorter would place portions of Alpha's surface at orbital speeds. A particle at such a point would be in a circular synchronous orbit (Fig. 3), and if Alpha rotated faster would be at periapsis of an elliptical orbit and would rise off the surface.

Because of its rapid rotation, Alpha's minimum geopotential is located along the equator rather than at its poles, the usual case for more slowly rotating bodies (*16*), so loose material preferentially migrates toward the equator (fig. S2). Thus, Alpha's equatorial bulge can be understood as the redistribution of loose, unconsolidated regolith toward the lowest point on the object, consistent with recent observations of asteroid Itokawa, where loose regolith was preferentially located in the potential lows of that body (*17*).

At Alpha's high rotation rate, previously compacted granular material could seek out lower-energy, higher-porosity configurations that do not exist on slowly rotating bodies. Consider an ellipsoid resting on a rotating sphere: For slow rotation, the minimum energy configuration has the ellipsoid's shortest axis normal to the surface and pointing at the body center. For sufficiently rapid rotation, an orientation with the long axis normal to the surface is the minimum energy configuration, increasing the "mean radius" (*18*). Such minimum energy states in an unconsolidated gravitational aggregate can create a porous distribution of material, perhaps producing the lower density found for Alpha (*3*). Furthermore, material on Alpha is subject to minimal compression due to the small surface accelerations (fig. S3) and can exist at high porosities that are impossible on Beta because of its shaking.

We can constrain KW4's formation age by considering the semimajor axis increase due to tides raised on Alpha by Beta. For the nominal KW4 model, if the orbit semimajor axis were 0.238 km (9.4%) smaller, conservation of angular momentum would bring Alpha's surface to the disruption limit. For idealized elastic bodies, the time scales depend linearly on the product μQ, where μ is the shear modulus of the material and Q is the tidal dissipation factor (*19*, *20*). Because of evidence for decreased rigidity at small overburden pressures and in fragmented rock (*21*), and because tidal damping is likely to be strong in a gravitationally bound aggregate as a result of friction between constituent particles, we estimate that KW4's formation age is less than 10^6 years (*22*).

The proximity of Alpha's surface to its instability limit may be due in part to the Yarkovsky-O'Keefe-Raszievskii-Paddack (YORP) effect (*23*, *24*), in which recoil from thermal reradiation of absorbed sunlight induces a net torque that alters the spin. The YORP effect on Alpha generates rotational accelerations on the order of 3×10^{-11} rad/s per year (*25*) that may induce a cycle of orbiting and reimpacting regolith when Alpha reaches an extreme rotation rate. Because of the presence of Beta, particles spun off Alpha are trapped within a zero-velocity surface [defined in the context of the restricted three-body problem for the Alpha, Beta, and particle system (*26*)], so neither escape from Alpha nor impact on Beta is allowed. Thus, material spun off Alpha will eventually reimpact and migrate toward the equator, where it may be spun off again. This cycle self-regulates Alpha's spin rate near the surface disruption limit and expands the orbit by transferring angular momentum from Alpha to the orbit. Alpha's surface lies completely outside the rotational Roche Lobe that usually envelopes asteroids (*27*), which is expected if the surface particles fell directly from orbit onto the body surface. At the current rate of YORP acceleration, the semimajor axis expands ~200 m/10^5 years, faster than the estimated time scale for the orbit to evolve as a result of tidal dissipation.

The dynamical and physical characteristics of the KW4 system suggest possible formation and evolution mechanisms but do not point to a single, unambiguous scenario. Below we consider explanations that are consistent with the current system.

Did KW4 form during a close planetary flyby? KW4 seems similar to binaries produced in tidal disruption simulations (*28*); however, such simulations consistently predict primary spin periods ~50% longer than Alpha's 2.8-hour value (*29*). Alpha's rapid rotation could have resulted if a debris disc formed simultaneously with Beta, was trapped inside Beta's orbit, and then collapsed onto Alpha. During tidal acceleration at closest approach to Earth, the largest blocks on the progenitor achieve orbital speeds before smaller particles because, on average, the center of mass of a large block on the surface is farther from Alpha's center and thus has a lower circular speed than a smaller block (*18*). The collapse of a disc returns angular momentum to Alpha and increases its spin: Accelerating Alpha from a period of 4 hours to its current value requires approximately 5% of Alpha's mass to collapse from the current orbit radius of 2.5 km, 10% of Alpha's mass to collapse from 1.4 km, or 20% from 1 km. Such a collapse could leave some of Alpha's surface at the disruption limit and form a raised equatorial structure. Most tidal binary formation simulations to date have employed equal-sized particles with spheres (*28*), ellipsoids (*30*), or simple polyhedra (*31*). Simulations with a distribution of particle sizes are more realistic and may elucidate formation by tidal breakup.

KW4 may have formed by rotational fission, which occurs if the asteroid spins fast enough for the largest blocks on the surface to enter orbit (*32*, *18*). KW4's progenitor would need to rotate with a period of 4.2 hours for a block the size of Beta to enter orbit, 3.8 hours if Beta were composed of two equal-sized blocks, 3.5 hours for four blocks, and so forth. Continued acceleration of Alpha from a 3.5-hour period to its current

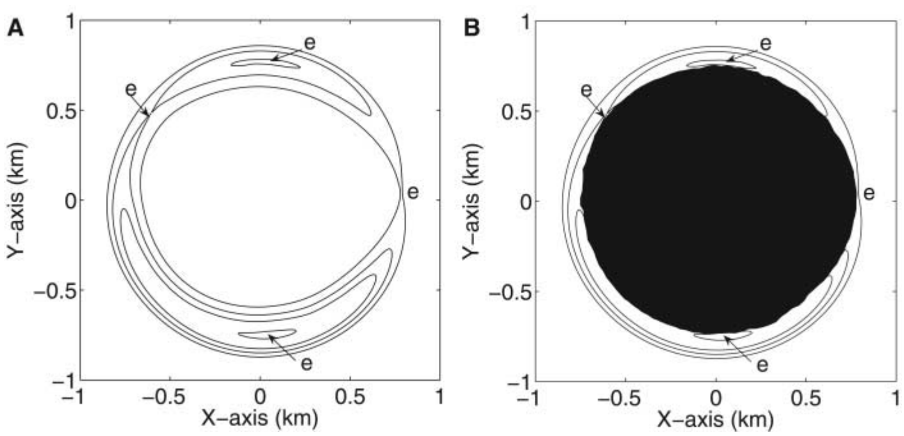

Fig. 3. Curves of constant geopotential about Alpha (**A**) without and (**B**) with Alpha's pole-on shape superimposed. Four equilibrium points, orbits that are stationary in the frame rotating with Alpha, are indicated by "e" and lie just at the body's surface. Alpha's surface lies outside the innermost curve, defined for the equilibrium point with the lowest potential value.

period in less than a million years would require a YORP acceleration rate a factor of five times as high as at present, which is plausible if Alpha's initial mass distribution were less symmetric than it is now. Once Beta formed, continued rotational acceleration of Alpha would be regulated as described previously, the resurfacing making the system more symmetric and diminishing YORP's effectiveness over time.

Could KW4 have formed in the main asteroid belt and subsequently migrated into an Earth-crosser? Recent discoveries reveal a substantial population of small, inner main-belt binaries with characteristics similar to near-Earth binaries (*33*). Collisions and YORP can form binaries within the main belt, but formation by tidal flybys is extremely unlikely. If KW4 formed in the main belt, then its age must be on the order of 10^8 years and it must have survived multiple close-Earth approaches (*3*) that could have strongly excited it while avoiding any that could disrupt it. Thus, formation of KW4 in a near-Earth orbit through some combination of tidal and YORP torques seems more likely.

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Ongoing Buildup of Refractory Organic Carbon in Boreal Soils During the Holocene

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Radiocarbon ages of vascular plant wax–derived *n*-alkanes preserved in well-dated Holocene sediments in an anoxic fjord (Saanich Inlet, Canada) were found to be not only substantially older than the depositional age but increasingly so during the Holocene. Assuming that *n*-alkanes serve as a proxy for recalcitrant terrigenous organic matter, this indicates that the accumulation of refractory organic carbon in soils that developed after the deglaciation of the American Pacific Northwest is ongoing and may still be far from equilibrium with mineralization and erosion rates.

Estimated at ~1500 Pg, soil organic carbon (SOC) constitutes the largest active OC pool on the globe (*1*, *2*), and consequently the fluxes of OC to and from this reservoir are important for the carbon budgets in the bio- and geosphere (*1*, *3*). Refractory organic matter makes up approximately half of the SOC pool because of its resistance to degradation (*4*), and it is this pool that is ultimately responsible for long-term terrestrial carbon storage (*1*, *5*). However, our understanding of the long-term buildup of SOC is largely derived from studies of present-day soils, and there is a paucity of temporal records of SOC dynamics. Because of its complex and heterogeneous nature, the accumulation, erosion, and especially mineralization rates of refractory SOC are hard to determine, which hinders modeling of fluxes to and from this carbon pool (*1*, *3*, *4*, *6*). For instance, the extent to which the higher-latitude soils and peats have been, or still are, expanding and/or changing in composition after their initial buildup after the most recent deglaciation remains an open question (*1*, *3*, *5*, *6*). Data to substantiate hypotheses about the global carbon cycle over millennial time scales are very limited, and for the terrigenous component of this cycle, depend mainly on soil chronosequences (*7*, *8*); mass balance studies of various SOC pools, aided by radiocarbon analysis (*6*); vegetation reconstructions coupled with soil carbon content (*9*); and models (*4*). A limiting factor in these studies is that they rely on inventories of biomass and active soil, whose properties have probably changed over time.

Coastal and lake sediments contain a temporal record of soil organic matter delivered from adjacent watersheds, and these records may

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