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REPORTS

Radar Imaging of Binary Near-Earth Asteroid (66391) 1999 KW4

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High-resolution radar images reveal near-Earth asteroid (66391) 1999 KW4 to be a binary system. The ~1.5-kilometer-diameter primary (Alpha) is an unconsolidated gravitational aggregate with a spin period ~2.8 hours, bulk density ~2 grams per cubic centimeter, porosity ~50%, and an oblate shape dominated by an equatorial ridge at the object's potential-energy minimum. The ~0.5-kilometer secondary (Beta) is elongated and probably is denser than Alpha. Its average orbit about Alpha is circular with a radius ~2.5 kilometers and period ~17.4 hours, and its average rotation is synchronous with the long axis pointed toward Alpha, but librational departures from that orientation are evident. Exotic physical and dynamical properties may be common among near-Earth binaries.

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The swarm of near-Earth asteroids (NEAs) whose orbits pass close to that of Earth contains about a thousand objects with effective diameters as large as 1 km. Some 840 of these large NEAs have been discovered, and 28 of them have been found by radar and/or photometry to be binary systems (1, 2), which potentially can offer unique insights into NEA origin and evolution. However, detailed information about the physical configurations and dynamical states of NEA binaries is lacking. Here we present decameter-resolution radar images and a detailed model of one of the largest binary NEAs, (66391) 1999 KW4.

KW4 is one of several dozen NEAs whose orbits cross those of Earth, Venus, and Mercury. The asteroid's May 2001 approach to within 0.032 astronomical units (AUs) from Earth was its closest until 2036, and we conducted extended observations using the Goldstone X-band (8560-MHz, 3.5-cm) and Arecibo S-band (2380-MHz, 13-cm) radar systems (table S1). Goldstone is more fully steerable than Arecibo, so the Goldstone image sequences provided our longest continuous coverage (spanning 21 to 29 May, with image sequences up to 6.5 hours long), whereas the Arecibo echoes are an order of magnitude stronger. We also obtained weak, but useful, Arecibo echoes during the asteroid's 0.13-AU approach in June 2002. Our observations used periodic binary phase-coded waveforms to obtain images of the distribution of echo power in time delay (range) and Doppler frequency (line-of-sight velocity) (3, 4). Each of our 279 Arecibo images and 1075 Goldstone images reveal two distinctly separated components (we call the larger one Alpha and the smaller one Beta) and provide excellent orbital phase coverage (Fig. 1).

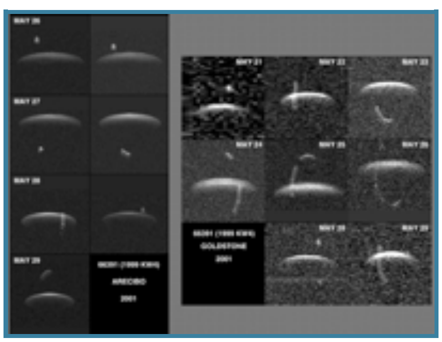

Fig. 1. Single-date, multi-run sums. Sums of delay-Doppler radar images obtained with Arecibo (**left**) and Goldstone (**right**) on each observation date. These sums are long time exposures (table S1) that show the orbital phase coverage of the secondary component (Beta) in each observing sequence. The pairs of Arecibo time exposures on 26 to 28 May correspond to radar setups with slightly different Doppler frequency resolutions (table S1). The radar is toward the top, rotation and orbital motion are counterclockwise, and each image has a height of 5625 m (37.5 μs of roundtrip time delay) and 117.2 cm s^{-1} of line-of-sight velocity (Doppler frequency of 18.6 Hz at Arecibo's 2380-MHz transmitter frequency or 66.9 Hz at Goldstone's 8560-MHz frequency). Vertical smear of the primary component (Alpha) due to motion about the system barycenter is evident in the long

Goldstone exposures. [View Larger Version of this Image (93K GIF file)]

Alpha's echo bandwidths increased from 21 May to a maximum on 25 May and then decreased through 29 May, indicating that our view was closer to equatorial in the middle of the 9-day experiment. In the Arecibo single-date time exposures (Fig. 1), the 26 May image shows a trailing edge where the echo bandwidth reaches a maximum, but during the next 3 days, as our view migrates away from the equator, we see echoes from increasingly beyond that maximum-bandwidth delay, with the bandwidth of those echoes decreasing. This is the progression one would expect for a flattened (oblate) spheroidal target. Alpha's echo edge frequencies vary by only a few percent during the object's several-hour rotation, indicating a nearly circular pole-on silhouette. Analysis of the day-to-day sequence of Alpha's bandwidths constrains the ecliptic (longitude, latitude) of the object's pole direction to be within 20° of either (150°, 60°) or (330°, –60°). A search for sidereal periods P_A consistent with the reappearance times of feature orientations in images on successive days eliminates the first possibility and constrains P_A to be near 2.765 hours. In images showing the components with their trailing edges at similar ranges [and hence their centers of mass (COMs) presumably at approximately similar ranges], the 21 to 29 May variation in the bandwidth from the middle of Alpha to the middle of Beta increases, peaks, and decreases in a manner commensurate with the pattern for Alpha's bandwidth, suggesting that Alpha's equatorial plane and the system's orbit plane are approximately coplanar. When the components are aligned in Doppler frequency or range, Beta's signature is very symmetrical, with the approaching and receding limbs extending to similar delays. However, away from the conjunctions, Beta's limbs extend to distinctly different ranges, with the pattern as expected if the object is at least slightly elongated and if its longest dimension points toward Alpha (fig. S1).

Although a single radar image can be geometrically ambiguous, the delay-Doppler trajectory of any point on the surface of a rotating rigid body is unique if the radar is not in the target's equatorial plane. Therefore (*5*), with a time series of images providing enough echo strength, resolution, and orientational coverage, one can estimate the target's three-dimensional shape, spin state, and radar scattering properties, along with the location of the COM in each delay-Doppler frame.

For each component, our shape estimation used images vignetted to exclude the other component. We summed independent images, attempting to strike a balance between maximizing signal-to-noise ratio and minimizing rotational and translational smear (table S1). The latitude-longitude coverage of the image sets used in the modeling is excellent (fig. S2). Our strategy was to start with an ellipsoid model and proceed first to a model in which surface displacement is expressed as a spherical harmonic series and then proceed to a vertex model, in each case adjusting the free parameters to optimize the resemblance between images synthesized from the shape model and the radar images (*3*, *4*). Ellipsoid models, "harmonic" models, and vertex models were realized as polyhedra with triangular sides. [A triangular polyhedron with V vertices has $(2V-4)$ faces and $(3V-6)$ edges. Larger values of V provide greater spatial resolution and, for ellipsoid and harmonic models, sample the mathematical function more densely, but they also slow the estimation.] We used enough vertices to accommodate the most detailed structure revealed in the data (Fig. 2).

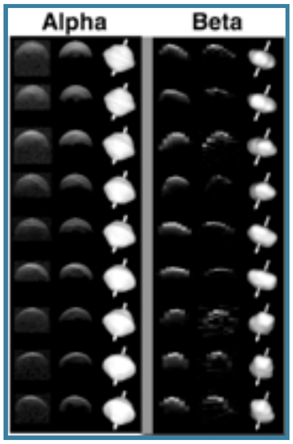

Fig. 2. Examples of images and fit results. Each three-frame horizontal collage shows an Arecibo radar image used in the estimations, the corresponding image synthesized from the shape model, and a plane-of-sky (POS) view of that model. Each three-frame collage consists of three squares with 2.0-km sides for Alpha and 0.8-km sides for Beta. In the delay-Doppler images, the radar is toward the top and the object rotates counterclockwise. In the POS frames, north is toward the top and the arrow represents the spin vector. The Alpha collages (**left**) show images obtained on (top to bottom) 26, 26, 27, 27, 27, 28, 28, 29, and 29 May. The Beta collages (**right**) show images obtained on 26, 26, 27, 27, 28, 28, 29, 29, and 29 May. See (*29*) for tabulation of all images used in the shape modeling and corresponding three-frame collages. [View Larger Version of this Image (53K GIF file)]

To model the components' motion with respect to each other (*1*), we assumed a Keplerian (two-body, point-mass) orbit of Beta's COM with respect to Alpha's COM and used least squares to estimate the orbit elements from the delay and Doppler offsets of Beta's COM from Alpha's COM as determined in the shape reconstructions. Conservative uncertainties, on the order of several times the image resolution, were assigned to the Beta-Alpha offsets. The best-fit solution [postfit root mean square (rms) residuals of 30 m and 0.75 cm s^{-1} (Table 1)] yields an orbital period P_{Orbit} = 17.4223 ± 0.036 hours and a semimajor axis a = 2548 ± 15 m, with the pole at ecliptic (longitude, latitude) = (326°, -62°) ± 5°. P_{Orbit} and a constrain the system's total mass M by Kepler's third law and yield $M = (2.488 \pm 0.054) \times 10^{12}$ kg (*6*).

Table 1. Relative orbit of Beta about Alpha. Least-squares estimates of the elements of the average 2001-2002 relative orbit are given in the J2000 equatorial frame along with their standard errors and correlation matrix. The epoch, T, which corresponds to calendar date 26 May 2001 09:55:00.5, represents the time at which Beta is at pericenter. Ω and i correspond to a pole direction at right ascension = 15.4° ± 3° and declination = −66.1° ± 2°. Our estimate of P_{Orbit} from Beta-Alpha delay-Doppler differences, 1045.34 ± 2.16 min, is marginally compatible with our estimate of P_{Orbit},

1048.18 ± 1.15 min, from modeling of mutual events observed in optical lightcurves during 3 to 12 June 2001 (2) with the orbital pole fixed at the radar estimate (26). [A decrease in the number of revolutions of Beta around Alpha by one between the 2001 and 2002 epochs of the radar measurements corresponds to an increase in orbital period of 2.04 min. There are solutions that fit the radar data with an orbital period of 1047.38 min, but not without a statistically unacceptable increase (25%) in the chi-square value.] MJD, modified Julian date; arg. peri., argument of perihelion.

Parameter	Estimate	P_{ORBIT}	*a*	*T*	Ω	*i*	ω	*e*
P_{Orbit} [period (hours)]	17.4223 ± 0.036	1.00	–0.05	–0.02	–0.02	–0.06	–0.02	0.06
a [semimajor axis (*m*)]	2548 ± 15	−0.05	1.00	0.24	0.52	0.45	0.24	–0.12
T (epoch, MJD)	52055.4132 ± 0.88	−0.02	0.24	1.00	0.18	0.58	1.00	–0.53
Ω [long. asc. node (°)]	105.4 ± 3	−0.02	0.52	0.18	1.00	–0.07	0.18	0.07
i [inclination (°)]	156.1 ± 2	−0.06	0.45	0.58	–0.07	1.00	0.58	–0.30
ω [arg. peri. (°)]	319.7 ± 182	−0.02	0.24	1.00	0.18	0.58	1.00	–0.53
e (eccentricity)	0.0004 ± 0.0019	0.06	–0.12	–0.53	0.07	–0.30	–0.53	1.00
M (total mass)	(2.488 ± 0.054) x 10^{12} kg							

The distances R_A and R_B of the components' COMs from the binary system's barycenter are related to the component masses M_A and M_B by $R_B/R_A = M_A/M_B$. Thus, any candidate mass ratio defines the delay-Doppler location of the bary-center with respect to those of the components' COMs in any given image, and hence yields estimates of the time-delay and Doppler frequency of hypothetical echoes from the barycenter at the receive-time epoch of the image. We estimated the heliocentric orbit of the asteroid in the absolute reference frame of the planetary ephemerides (table S2), using radar and optical astrometry and evaluating the goodness of fit as a function of M_A/M_B. Fits to optical and Goldstone astrometry (7) (table S3) show a sharp chi-square minimum at M_A/M_B = 17.4 ± 2.5 (fig. S3), which with the results in Table 1 yields the component masses in Table 2, as well as a value for the radius of Alpha's orbit about the barycenter: R_A =138±22m.

Table 2. Alpha and Beta model characteristics. The Alpha model has 4586 vertices and 9168 facets, with a mean edge length of 39 m and effective angular resolution of

3°. The Beta model is a spherical harmonics representation of degree and order 8 realized with 1148 vertices and 2292 facets, with a mean edge length of 26 m and an effective angular resolution of 7°. The positive side of Alpha's longest principal axis (+*x*) is on the plane of the sky and approaching Earth on 25 May 2001 at 12:23:21. We assumed uniform internal density and principal-axis rotation about the *z* axis. The dynamically equivalent equal-volume ellipsoid (DEEVE) is the homogeneous ellipsoid having the same moment-of-inertia ratios and volume as the model. The assigned standard errors include our assessment of systematic effects. The uncertainties in the components' individual masses include contributions from the uncertainty in the system's total mass (Table 1) and from the uncertainty in the determination of the mass ratio. Uncertainties in densities and other ratios are calculated with Fieller's theorem (27, 28). Our value for Alpha's spin period agrees with the value, 2.7650 ± 0.0004 hours, derived from lightcurves by (2). Digital versions of the models in Wavefront format are available (29).

		Alpha	Beta
Extents along principal axes (km):	x	1.532 ± 3%	0.571 ± 6%
	y	1.495 ± 3%	0.463 ± 6%
	z	1.347 ± 3%	0.349 ± 6%
Area (km^2)		5.744 ± 6%	0.674 ± 12%
Volume (km^3)		1.195 ± 9%	0.048 ± 18%
Mass (10^{12} kg)		2.353 ± 0.100	0.135 ± 0.024
Density (g cm^{-3})		1.97 ± 0.24	2.81 (+0.82, −0.63)
Moment of inertia ratios:	I_z/I_x	1.187 ± 5%	1.74 ± 10%
	I_y/I_x	1.133 ± 5%	1.18 ± 10%
Equivalent diameter (km) of a sphere with the model's volume		1.317 ± 3%	0.451 ± 6%
DEEVE extents (km):	x	1.417 ± 3%	0.595 ± 6%
	y	1.361 ± 3%	0.450 ± 6%
	z	1.183 ± 3%	0.343 ± 6%
Rotation period (hours)		2.7645 ± 0.0003	17.4223 assumed
Pole direction [ecliptic long., lat. (°)]		(326, −65) ± 3	(326, −62) assumed

Alpha's shape (Fig. 3 and fig. S4) is distinguished by a prominent equatorial bulge whose several-hundred-meter vertical extent is defined in the north by a continuous, very abrupt ridge and in the south by more subtle, discontinuous gradations. Much of the surface appears to have subtle structure with perhaps a few decameters of vertical relief. Some concavities might be interpreted as ~100-m impact craters, but most of the structure looks nondescript.

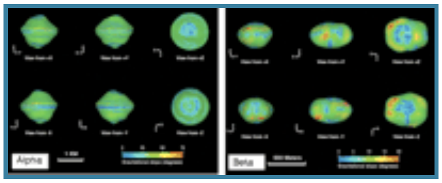

Fig. 3. Principal-axis views of the Alpha (**left**) and Beta (**right**) shape models. Colors indicate effective gravitational slope (the angular deviation from the local downward normal of the total acceleration vector due to gravity and rotation), calculated with the model densities (Table 2). Alpha's slopes average 28° with a maximum of 70°, whereas Beta's average 9° with a maximum of 18°. Beta's +*x* axis points toward Alpha. [View Larger Version of this Image (32K GIF file)]

Alpha's bulk density, 1.97 ± 0.24 g cm^{-3}, and rotation period, P_A = 2.7645 ± 0.0003 hours, reveal this object to be in a highly unusual physical state. Alpha spins fast enough so that the "potential low" of the body is located at its equator. That is, particles allowed to freely move across the surface of Alpha would naturally seek out the equator as the lowest-energy state (Fig. 3). The equatorial band has a very wide variation in slope, due mostly to the total acceleration of particles on the equatorial band being almost zero, but inward. Thus, in the equatorial region, particles are deposited on the surface in a nearly weightless environment and currently are being retained very tenuously. If Alpha's spin were any faster, loose regolith at certain distinct equilibrium points (*8*) would be placed in orbit about Alpha and would eventually reimpact Alpha at some other location. The existence of these equilibrium points just at the surface places the system exactly at the boundary of what a rotating body could sustain.

Alpha's radar polarization ratio, SC/OC = 0.45 ± 0.10, indicates more severe decimeterscale near-surface roughness than on "typical" radar-detected NEAs like 25143 Itokawa and 433 Eros, but specular glints at the leading edges of the images (Fig. 2) show that the surface also possesses a very smooth component. Our modeling used a hybrid, two-term scattering law to accommodate both specular and diffuse scattering, and the parameter values estimated for the specular term correspond to a very shallow rms slope with respect to the model's facets and a near-surface bulk density between 0.6 and 1.2 g cm^{-3}, as might be expected for tenuously held regolith of stony meteoritic material.

The grain density of plausible meteorite matches to the asteroid's S spectral class (*9*) ranges from about 3.7 g cm^{-3} for ordinary chondrites (*10*) to about 5.1 g cm^{-3} for stony irons (*11*). Thus, Alpha's porosity probably is between 40 and 66%, comparable to values for lunar regolith core samples. Our value for Alpha's density is comparable to or lower than other (spacecraft-derived) values for S-class asteroids: 1.95 ± 0.14 g cm^{-3} for the 0.4-km NEA Itokawa (12), 2.67 ± 0.03 g cm^{-3} for the 17-km NEA Eros (13), and 2.6 ± 0.5 g cm^{-3} for the 28-km main-belt asteroid 243 Ida (14). Alpha's porosity apparently exceeds that of the latter two objects but is similar to those of Itokawa and the 58-km C-class main-belt asteroid 253 Mathilde (15) and several other C-class objects (16).

Together, Alpha's size, shape, spin, density, and porosity reveal it to be an unconsolidated gravitational aggregate close to its breakup spin rate, suggesting that KW4's origin involved spinup and disruptive mass shedding of a loosely bound precursor object (1, 2). The disruption may have been caused by tidal effects of a close encounter with a planet (17-20) or by torques due to anisotropic thermal radiation of absorbed sunlight (the YORP effect) (21). The near-circularity of Alpha's pole-on profile further suggests that the disruption may have produced a quasi-circular disk of particles rather than merely a prolate elongated body (22).

Our Beta shape model (Fig. 3 and fig. S4) is about one-third the size of Alpha and more elongated, flattened, and asymmetrical. Our Beta density estimate, 2.81 (+0.82, -0.63) g cm^{-3}, is about 43% larger than our value for Alpha, presumably due to some combination of Beta's different spin, the circumstances of Beta's formation, and the dynamical and collisional evolution of the KW4 system (22). Beta's disk-integrated radar properties are indistinguishable from Alpha's. Analysis of dual-polarization images reveal a drop in the SC/OC ratio toward Beta's leading edge, suggesting the presence of smooth and rough surface components, as with Alpha. Beta's density allows porosities up to 42% if it resembles ordinary chondrites and from 29 to 58% if it resembles stony irons.

Whereas reconstruction of Alpha was very robust, with Beta our estimations were consistent with rotation periods between 17.3 and 17.5 hours but could not discriminate between specific values in that interval. Moreover, values for Beta's rotation period within the range spanned by the May radar and June optical estimates of P_{Orbit} (Table 1) led to indistinguishable harmonic models for which synthesized images fit the boundaries of the delay-Doppler echo distributions but could not fit image fine structure as well as with Alpha. Vertex models were unable to improve upon the image fits; relaxing the requirement of principal-axis rotation did not help. For certain "conjunction epochs" (with both components' COMs at either the same range or the same Doppler), solutions with any candidate period placed Beta's long axis at least several degrees from the Alpha-Beta line. Experiments in which only short subsets of images were centered on those epochs instead of the full Beta data set yielded smaller angular offsets but still are suggestive of Beta's rotation not being exactly synchronous. These results are at odds with our shape modeling assumption of unforced free rotation and suggest that Beta may exhibit sizable librations in longitude.

The dynamics of the KW4 system have unforeseen complexity (22), potentially involving variations in the orbit and Beta's spin state on a variety of time scales due to dynamical excitation from several possible sources. Consequently, our orbit (Table 1) and rotation parameters (Table 2) represent averages corresponding to the geometrical configurations sampled by the radar observations. The gross dimensions and periodicities of the KW4 system are typical of NEA binaries (*2*), so many of them may share KW4's physical and dynamical complexity.

Over time scales of tens of thousands of years, variations in KW4's heliocentric orbit due to planetary perturbations produce configurations with ecliptic crossings near the orbits of Mercury, Venus, or Earth. [The eccentricity varies from 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° ± 20°. This geometric configuration conceivably could be the signature of an extremely recent Earth-flyby origin of the system.

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Supporting Online Material

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Methods

Figs. S1 to S4

Tables S1 to S4

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