Radar and Optical Observations of Asteroid 1998 KY26

Steven J. Ostro,[1]* Petr Pravec,[2] Lance A. M. Benner,[1] R. Scott Hudson,[3] Lenka Šarounová,[2] Michael D. Hicks,[1] David L. Rabinowitz,[1] James V. Scotti,[4] David J. Tholen,[5] Marek Wolf,[6] Raymond F. Jurgens,[1] Michael L. Thomas,[1] Jon D. Giorgini,[1] Paul W. Chodas,[1] Donald K. Yeomans,[1] Randy Rose,[1] Robert Frye,[1] Keith D. Rosema,[1] Ron Winkler,[1] Martin A. Slade[1]

Observations of near-Earth asteroid 1998 KY26 shortly after its discovery reveal a slightly elongated spheroid with a diameter of about 30 meters, a composition analogous to carbonaceous chondritic meteorites, and a rotation period of 10.7 minutes, which is an order of magnitude shorter than that measured for any other solar system object. The rotation is too rapid for 1998 KY26 to consist of multiple components bound together just by their mutual gravitational attraction. This monolithic object probably is a fragment derived from cratering or collisional destruction of a much larger asteroid.

The population of asteroids with a diameter range of 10 to 100 m is thought to number $\sim 10^7$ in Earth-crossing orbits and $\sim 10^9$ in the main belt (*1, 2*). However, only a few dozen objects of several decameters size have been discovered, and little is known about their spin states, shapes, compositions, surface characteristics, or interiors, much less their origins and collisional histories. Spacecraft flyby observations of several much larger objects (*3*) help to constrain the collisional evolution of those objects and the asteroid population as a whole (*4*), but even for those objects, definitive information about interior configuration (and hence collisional history) is lacking: Are they coherent solid rocks or gravitationally bound, multicomponent agglomerates?

Here, we report observations that provide a detailed look at a solar system object smaller than 100 m. The discovery of 1998 KY26 was announced on 1 June 1998 (*5*), 1 week before it passed 2.10 lunar distances (8.061×10^5 km) from Earth. Part of a recently recognized, potentially abundant subpopulation of small near-Earth asteroids (NEAs) (*1*), it is more accessible to a spacecraft rendezvous than any of the other ~25,000 known asteroids with secure orbits (*6*).

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109–8099, USA. [2]Astronomical Institute, Academy of Sciences of the Czech Republic, CZ-25165 Ondřejov, Czech Republic. [3]School of Electrical Engineering and Computer Science, Washington State University, Pullman, WA 99164–2752, USA. [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. [5]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA. [6]Astronomical Institute, Charles University Prague, V Holešovičkách 2, CZ-18000 Prague, Czech Republic.

*To whom correspondence should be addressed. E-mail: ostro@reason.jpl.nasa.gov

During 6 through 8 June 1998, we observed the asteroid with the Goldstone X-band (8510 MHz, 3.5 cm) radar, using waveforms that provided various degrees of resolution in time delay (range) and Doppler frequency (radial velocity). During 2 through 8 June, we observed the asteroid photometrically with the Ondřejov (Czech Republic) 0.65-m telescope, the Steward 0.9-m Spacewatch telescope (Arizona), the Mauna Kea 0.61-m telescope (Hawaii), and the Table Mountain 0.6-m telescope (California), obtaining CCD (charge-coupled device) lightcurves and broadband colors (*7*).

The asteroid's rapid spin rate was revealed by extreme Doppler broadening of spatially resolved radar echoes and shortly thereafter was measured precisely by Fourier analysis of time series formed from disk-integrated optical brightness measurements. The echoes' bandwidth B (in hertz) satisfies $B = 5.945\ D \cos(\delta)/P$, where P (in minutes) is the instantaneous apparent spin period, D (in meters) is the width of the plane-of-sky projection of the asteroid's pole-on silhouette, and δ is the subradar latitude. B is at least 11 Hz for all our echo spectra (Fig. 1). Waveforms with time-delay resolution of 125 ns (19 m in range) produced echoes confined to a single range cell, placing an upper limit of 19 m on the asteroid's visible range extent and an upper limit of 40 m on the asteroid's physical range extent (*8*). Therefore, the radar data require $P \leq 22$ min. Our spectra show no prominent asymmetries or features and only subtle bandwidth variations, precluding more precise radar estimation of P. However, analysis of our finest-time-resolution photometric light curves (Fig. 2) yields an unambiguous estimate of the period, $P = 10.7015 \pm 0.0004$ min (*9*).

The average of all known asteroid rotation periods is of the order of 10 hours (*10*). Among unambiguously determined rotation periods, the shortest period is 136 min for 1566 Icarus (*11*). Asteroid 1998 KY26 would need a bulk density of the order of $39{,}000/P^2$ g cm^{-3} (*12*), or about 340 g cm^{-3}, for it to consist of pieces held together just by their mutual gravitational attraction. This asteroid's rapid spin thus reveals it to be a monolithic body bound by tensile strength alone (*13*).

With the calculated period known, the echo spectra could be inverted (*14*) to estimate the asteroid's shape. The spheroidal model (Fig. 3) has a mean diameter of 26 m/cos(δ). In the absence of prominent variations in echo bandwidth over a 54° sky arc, it is unlikely that any of our observations were within a few tens of degrees of a pole-on view. The Doppler-based model and the range-resolved data therefore bound 1998 KY26's effective diameter: 20 m $\leq D_{eff} \leq$ 40 m.

Whereas the asteroid's relative topographic relief is subdued, roughness at centimeter-to-decimeter scales is revealed by the ratio of echo power in the same sense of circular polarization as transmitted (the SC sense) to that in the opposite (OC) sense. A perfectly smooth surface would reflect echoes with SC/OC = 0. Asteroid 1998 KY26's mean value of SC/OC, 0.5 ± 0.1, exceeds 90% of the values measured for near-Earth asteroids (*15*). Because the asteroid is spinning too fast to retain any loose particulate material (a regolith) except perhaps near the poles, most of its surface is exposed bare rock that has been roughened, probably at least in part by meteoroid bombardment (*16*).

Our photometry yields an estimate of 1998 KY26's mean, absolute V magnitude, $H = 25.5 \pm 0.3$ (*17*). That estimate and our D_{eff} interval bound the asteroid's visual albedo (*18*): $0.05 \leq p_v \leq 0.37$. Cluster analysis of values of p_v and visible to near-infrared colors of hundreds of asteroids has defined taxonomic classes (*19*) that may correspond to different mineralogical compositions, most of which have meteoritic analogs. Our color indices (B-R = 0.083 ± 0.070, V-R = 0.058 ± 0.055, and R-I = 0.088 ± 0.053, with solar colors subtracted) reveal a neutral reflectance spectrum that excludes all classes except six (B, C, F, G, D, P) that are associated with mixtures of carbonaceous material and mafic silicates, and one (M) that corresponds to NiFe metal or to mixtures of metal and spectrally neutral silicates. Our p_v interval encompasses all values for asteroids with unambiguous B, G, or M classifications and about half of the values for asteroids with unambiguous P, F, D, or C classifications.

The asteroid's composition is also constrained by (i) comparison of its radar reflectivity with values for asteroids whose taxonomic classes are known and (ii) implications of its reflectivity for its surface bulk density. The asteroid's OC radar cross section (25 ± 10 m^2), its SC/OC ratio, and our D_{eff} interval bound its radar albedo $\hat{\sigma}$ (that is, radar cross section divided by $\pi D_{\mathrm{eff}}^2/4$) in the OC and total-power (T = OC + SC) polarizations: $0.012 \le \hat{\sigma}_{\mathrm{OC}} \le 0.11$ and $0.018 \le \hat{\sigma}_{\mathrm{T}} \le 0.17$. The means and standard deviations of $\hat{\sigma}_{\mathrm{T}}$ for radar-observed main-belt asteroids (*20*) are 0.10 ± 0.06 for nine objects classified B, G, F, or P; 0.17 ± 0.05 for eight C objects; and 0.32 ± 0.12 for four M objects. Among NEAs for which $\hat{\sigma}_{\mathrm{T}}$ has been measured, it equals 0.10 and 0.18 for the two C objects and 0.63 for the sole M object. Thus, 1998 KY26's radar albedo is consistent with B/C/F/G/D/P classification but not with M classification.

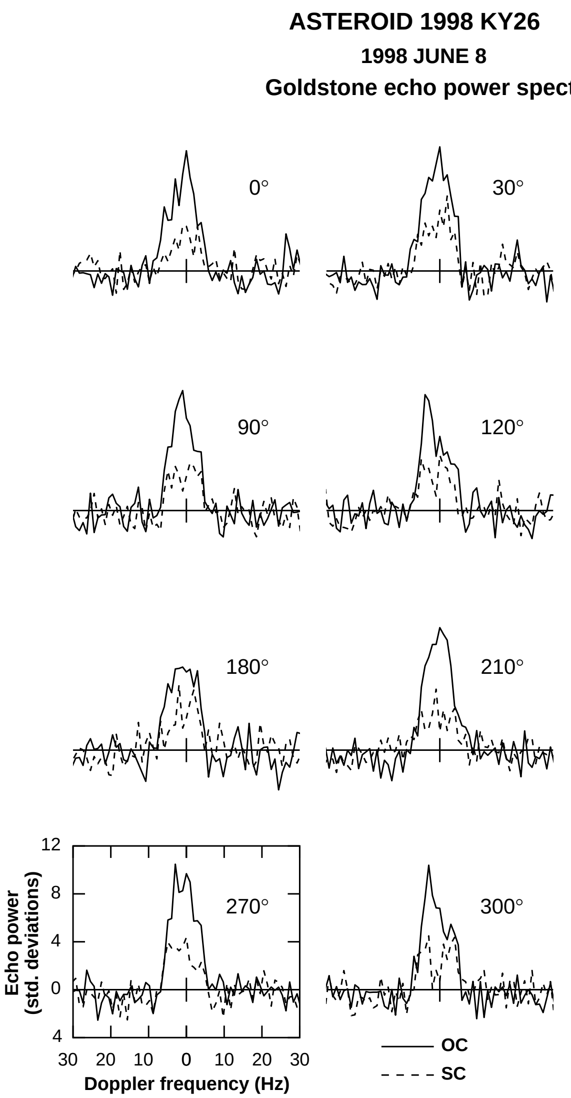
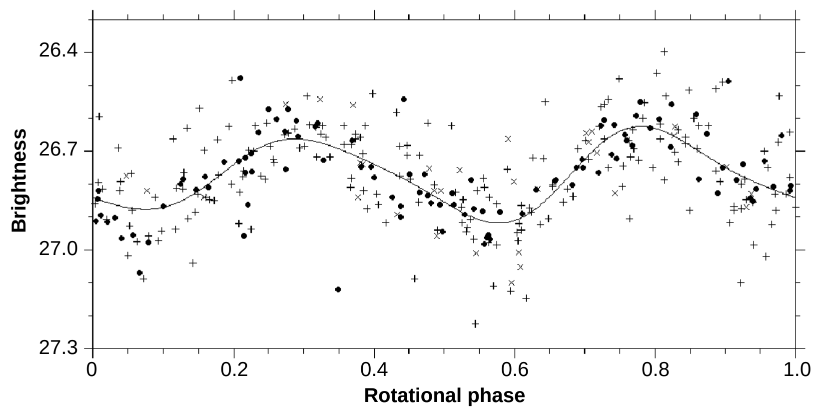


Fig. 1. Our strongest echo spectra from June 8, sorted into rotation-phase bins 30° wide. Our analyses used 15° bins. Each spectrum is a one-dimensional image equivalent to a scan of radar brightness measured through a slit parallel to the asteroid's projected apparent pole. The frequency resolution, 1 Hz, corresponds to a slit width of 1.8 m/cos δ, with δ the subradar latitude. The rotation phase origin is at 1998 June 8.2600.

For a smooth sphere, $\hat{\sigma}_{\mathrm{sc}}$ would equal zero and $\hat{\sigma}_{\mathrm{OC}}$ would equal R, the smooth-surface reflection coefficient, which for materials of asteroidal interest depends primarily on surface bulk density d. For a target with a nonspherical shape or with moderate surface roughness at scales much greater than the wavelength, one could write $R = \hat{\sigma}_{\mathrm{OC}}/g$, where plausible values of the backscatter gain g are between 1.0 and 1.5. With wavelength-scale roughness, some echo power would be shifted to the SC polarization, and only part of the OC power would arise from smooth-surface echoes. For 1998 KY26, such roughness is present and the shape is not perfectly spherical. In this situation, the upper bound on the total-power albedo can be taken as an upper bound on R, and the corresponding value of $d(R)$ can be taken as an upper bound on the surface's average bulk density. The most widely used empirical relation for $d(R)$ (*21*) predicts $d(R = 0.17) = 2.8$ g cm^{-3}. Meteoritic analogs of M-class asteroids include irons and enstatite chondrites, which have mean specific gravities of 7.6 and 3.6 g cm^{-3}, respectively. C/B/G/F asteroids appear analogous to CI1/CM2/CM3 carbonaceous chondrites (*22*), which are primitive, unmelted, volatile-rich samples of solar nebula condensates (*23*) and whose mean specific gravities (2.2 to 2.9 g cm^{-3}) bracket our upper limit on d, supporting identification of 1998 KY26 as carbonaceous chondritic. (D/P asteroids lack meteoritic analogs and may resemble cosmic dust.)

Our optical and radar measurements reveal

Fig. 2. Composite light-curve constructed for $P = 10.7015$ min from clear-filter photometry obtained at Ondřejov on June 2.0 (×) and June 3.0 (+) and at Spacewatch on June 5.3 (●). Brightness is in visual (V) magnitudes, scaled to correspond to geocentric and heliocentric distances of 1 AU and an Earth-asteroid-sun angle of 28.1°. The rotation phase origin is at 1998 June 5.3045. The noise level of individual measurements, about 0.1 magnitude, reflects the asteroid's faintness and our short integration times (20 to 50 s). The light-curve data are represented well by a fourth-order Fourier series (solid curve).



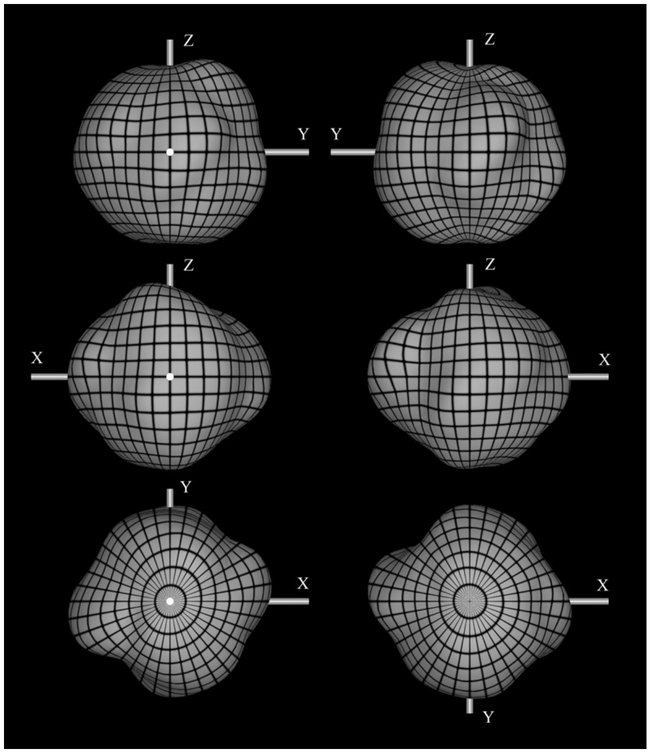


Fig. 3. Asteroid 1998 KY26's shape estimated from least-squares fitting of a 124-vertex polyhedral model to the echo spectra. The effective resolution of the model is 3 m. The model solution depends on the subradar latitude δ, which is not known but probably was at least a few tens of degrees from the pole. This figure shows the solution for an equatorial view (δ = 0). The fractional topographic relief is fairly insensitive to δ. The model's mean diameter is 26 m/cosδ. Principal axes of inertia are labeled *x*, *y*, and *z* (the pole).

an unelongated, monolithic, several-decameter-wide, carbonaceous-chondritic body in a rapid spin state. This combination of characteristics is unique among known objects and sets boundary conditions on theories for the collisional and rotational evolution of individual asteroids and the population as a whole. Asteroids the size of 1998 KY26 are expected to have lifetimes against catastrophic disruption of 10^7 to 10^8 years (*24*); carbonaceous chondrites are the weakest meteorites, so the short end of that interval probably applies here. Therefore, this object may be a nonprimordial collision fragment derived from cratering or destruction of a larger asteroid (*25*). Many asteroids larger than a few hundred meters are thought to be porous, nearly strengthless "rubble piles" (*26*). The size distribution of monolithic subunits in rubble-pile asteroids is unknown, but the existence of 1998 KY26 suggests that they extend up to sizes of at least several decameters.

How did this asteroid's fast spin originate? Laboratory impact experiments (*27*) have shown that rapid rotations are common among spall fragments thrown out from the surface layer surrounding the impact site and that these fragments acquire their spins in the impact-generated shear field (*28*). However, the applicability of experiments on basaltic centimeter-sized targets to carbonaceous chondritic targets 10,000 times larger is not known. Novel approaches to computer simulation of collisions (*29*) may shed light on the source of 1998 KY26's rotation and on how unique it might be among similar-sized collision fragments.

References and Notes

1. D. L. Rabinowitz *et al.*, *Nature* **363**, 704 (1993).
2. D. L. Rabinowitz, E. Bowell, E. Shoemaker, K. Muinonen, in *Hazards Due to Comets and Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, AZ, 1994), pp. 285–312.
3. Spacecraft flybys have imaged four asteroids, all with average overall dimensions between 14 and 58 km.
4. R. Greenberg, M. C. Nolan, W. F. Bottke, R. A. Kolvoord, J. Veverka, *Icarus* **107**, 84 (1994); R. Greenberg *et al.*, *ibid.* **120**, 106 (1996); J. Veverka *et al.*, *Science* **278**, 2109 (1997).
5. G. V. Williams, *Minor Planet Electron. Circ. 1998-L02* (1998). (available at http://cfa-www.harvard.edu/iau/services/MPEC.html)
6. Using simple expressions [E. M. Shoemaker and E. F. Helin, in *Asteroids: An Exploration Assessment*, D. Morrison and W. C. Wells, Eds. (NASA Conf. Publ. 2053, Washington, DC, 1978), pp. 245–256] for the accelerations needed to leave low-Earth orbit and rendezvous with an asteroid, we find that for 1998 KY26 (a = 1.23 AU, e = 0.20, i = 1.5°), the total required change in velocity (ΔV) is 4.2 km s^{-1}. A lunar rendezvous requires 6 km s^{-1}.
7. We used B, V, R, and I color filters of the Johnson-Cousins system, with respective effective wavelengths of 440, 550, 650, and 800 nm [M. S. Bessell, *Publ. Astron. Soc. Pac.* **102**, 1181 (1990)].
8. The physical range extent typically is about twice the visible range extent [R. S. Hudson and S. J. Ostro, *Science* **270**, 84 (1995); A. K. Andrews, R. S. Hudson, D. Psaltis, *Opt. Lett.* **20**, 2327 (1995)].
9. Asteroid 1998 KY26's period was determined unambiguously in independent data from three different stations (Ondřejov, Table Mountain, Spacewatch). Observational techniques and data reduction procedures were similar to those described by P. Pravec, L. Šarounová, and M. Wolf [*Icarus* **124**, 471 (1996)] and by D. Rabinowitz [*ibid.* **134**, 342 (1998)], and used an implementation of the Fourier method developed by A. W. Harris *et al.* [*ibid.* **77**, 171 (1989)].
10. Rotation periods of near-Earth asteroids and similar-sized, main-belt asteroids average about 12 and 7 hours, respectively [D. F. Lupishko and M. DiMartino, *Planet. Space Sci.* **46**, 47 (1998)].
11. The period of 1995 HM has been suggested to be 97.2 or 145.8 min [D. I. Steel, R. H. McNaught, G. J. Garradd, D. J. Asher, A. D. Taylor, *Planet. Space Sci.* **45**, 1091 (1997)].
12. A. W. Harris, *Lunar Planet. Sci.* **27**, 493 (1996).
13. The minimum required tensile strength T for an object of bulk density ρ is of the order of $\pi^2 \rho D^2/P^2$ [D. L. Turcotte and G. Schubert, *Geodynamics Applications of Continuum Physics to Geological Problems* (Wiley, New York, 1982), pp. 85–86, 204]. For this asteroid, T is less than 10^4 dyne cm^{-2}, which is $<10^{-4}$ times values for rocks [J. Suppe, *Principles of Structural Geology* (Prentice-Hall, Englewood Cliffs, NJ, 1985), p. 155]. Thus, 1998 KY26 could be held together by very meager bonds.
14. D. L. Mitchell, R. S. Hudson, S. J. Ostro, K. D. Rosema, *Icarus* **131**, 4 (1998).
15. L. A. M. Benner *et al.*, *ibid.* **137**, 247 (1999); L. A. M. Benner *et al.*, *ibid.* **130**, 296 (1997).
16. For nominal relative velocities of 5 to 10 km s^{-1}, millimeter-sized (~0.01 g) meteoroids would create pits with diameters of the order of 1 cm, probably surrounded by a spall zone in which rock has been shattered or removed, or both [D. E. Gault, F. Horz, J. B. Hartung, *Proc. Third Lunar Sci. Conf., Suppl. 3*, in *Geochim. Cosmochim. Acta* **3**, 2713 (1972)]. The flux of 1-mm meteoroids, of the order of 10^{-12} m^{-2} s^{-1} in the inner solar system [E. Grun, H. A. Zook, H. Fechtig, R. H. Giese, *Icarus* **62**, 244 (1985)] but perhaps an order of magnitude higher in the main belt [D. S. McKay, T. D. Swindle, R. Greenberg, in *Asteroids II*, R. P. Binzel, T. Gehrels, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1989), pp. 617–642], would have roughened much of the asteroid in 10^7 years.
17. We conservatively assume a slope parameter, G = 0.15 ± 0.2, for the asteroid's brightness as a function of solar phase angle.
18. We use the relation: $\log p_v = 12.247 - 2 \log D_{eff} - 0.4 H$, where D_{eff} is in meters [E. F. Tedesco, G. J. Veeder, J. W. Fowler, J. R. Chillemi, *Technical Report PL-TR-92-2049* (Phillips Laboratory, Hanscom AFB, MA, 1992)].
19. D. J. Tholen and M. A. Barucci, in *Asteroids II*, R. P. Binzel, T. Gehrels, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1989), pp. 298–315.
20. C. Magri *et al.*, *Icarus*, in press.
21. J. B. Garvin, J. W. Head, G. H. Pettengill, S. H. Zisk, *J. Geophys. Res.* **90**, 6859 (1985).
22. D. T. Britt and L. A. Lebofsky, in *Encyclopedia of the Solar System*, P. R. Weissman, L.-A. McFadden, T. V. Johnson, Eds. (Academic Press, San Diego, CA, 1999), pp. 585–605.
23. J. Lewis, *Physics and Chemistry of the Solar System* (Academic Press, San Diego, CA, 1997).
24. P. Farinella, D. Vokrouhlický, W. K. Hartmann, *Icarus* **132**, 378 (1998); E. V. Ryan and H. J. Melosh, *ibid.* **133**, 1 (1998).
25. It has been suggested that tidal disruption of rubble-pile asteroids during close planetary encounters might generate large numbers of several-decameter-sized objects [W. F. Bottke Jr., D. C. Richardson, P. Michel, S. G. Love, *Planet. Space Sci.* **46**, 311 (1998)], but such a process seems unlikely to produce ultra-rapid fragment rotation.
26. S. G. Love and T. J. Ahrens, *Icarus* **124**, 141 (1996).
27. A. Fujiwara and A. Tsukamoto, *ibid.* **48**, 329 (1981).
28. Other laboratory experiments indicate that collisionally ejected fragments initially possess excited (non–principal axis) spin states [I. Giblin and P. Farinella, *Icarus* **127**, 424 (1997)]. Our data show no evidence for non–principal axis rotation, but this is not surprising given that the time scale for rotational relaxation of an object with 1998 KY26's size and spin period [A. W. Harris, *Icarus* **107**, 209 (1994)] is only of the order of 10^5 years, much less than the ~3 × 10^7 year dynamical lifetime of objects in Earth-crossing orbits.
29. E. Asphaug *et al.*, *Nature* **393**, 437 (1998).

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