Radar and Optical Observations of Asteroid 1998 KY26

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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 \( \sim 10^2 \) 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 \times 10^5 \text{ 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 \( \sim 25,000 \) known asteroids with secure orbits (6).

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) light-curves 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 \( B = 5.945 \cos(\delta)/P \), 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 \( \delta \) 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 \( P \leq 22 \text{ min} \). 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, \( P = 10.7015 \pm 0.0004 \text{ min} \) (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/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(\delta)). 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 \( \leq D_{\text{eff}} \leq 40 \text{ m} \).

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 \pm 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 \( D_{\text{eq}} \) 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 \pm 0.070, V-R = 0.058 \pm 0.055, and R-I = 0.088 \pm 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 (1) comparison of its radar reflec-
tivity 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 \((25 \pm 10 \text{ m}^2)\), its SC/OC ratio, and our \(D_{\text{eff}}\) interval bound its radar albedo \(\tilde{\sigma}\) (that is, radar cross section divided by \(\pi D_{\text{eff}}^2/(4)\)) in the OC and total-power \((T = \text{OC} + \text{SC})\) polarizations: 
\[
0.012 \leq \tilde{\sigma}_{\text{OC}} \leq 0.11 \quad \text{and} \quad 0.018 \leq \tilde{\sigma}_T \leq 0.17.
\]
The means and standard deviations of \(\tilde{\sigma}_T\) for radar-observed main-belt asteroids \((20)\) are \(0.10 \pm 0.06\) for nine objects classified B, G, F, or P; \(0.17 \pm 0.05\) for eight C objects; and \(0.32 \pm 0.12\) for four M objects. Among NEAs for which \(\tilde{\sigma}_T\) 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.

For a smooth sphere, \(\tilde{\sigma}_{\text{OC}}\) would equal zero and \(\tilde{\sigma}_{\text{OC}}\) would equal \(\bar{R}\), the smooth-surface reflection coefficient, which for materials of asteroidal interest depends primarily on surface bulk density \(d\). For a target with a non-spherical shape or with moderate surface roughness at scales much greater than the wavelength, one could write 
\[
R = \tilde{\sigma}_{\text{OC}}/g,
\]
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 \(\bar{R}\), 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 
\[
d(R = 0.17) = 2.8 \text{ g cm}^{-3}.
\]
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 \(2.9\ \text{g cm}^{-3}\)) 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...
among similar-sized collision fragments. KY26’s rotation and on how unique it might be (10,000 times larger is not known. Novel ap-
sized targets to carbonaceous chondritic targets
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generated shear field (10,000,000 years). Therefore, this
weakest meteorites, so the short end of that
size of 1998 KY26 are expected to have life-
times 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 frag-
ment 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 appli-
cability of experiments on basaltic centimeter-
sized targets to carbonaceous chondritic targets
10,000 times larger is not known. Novel ap-
proaches 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
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pile asteroids during close planetary encounters might generate large numbers of several-decameter-
sized objects [W. F. Bottke Jr., D. C. Richardson, P.
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rapid fragment rotation.
14. Other laboratory experiments indicate that collision-
ally ejected fragments initially possess excited (non-
principal axis) spin states [I. Gubkin and F. Farinella,
Icarus 127, 424 (1997)]. Our data show no evidence
for non–principal-axis rotation, but this is not surpris-
ing 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 × 10^5 year
dynamical lifetime of objects in Earth-crossing orbits.
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