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NOTE

Radar Observations of Asteroid 288 Glauke

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The combination of Arecibo radar echoes and available vis/IR data indicates that 288 Glauke is an S-class object slightly smaller and less elongated than 243 Ida, with radar surface properties near the average for S asteroids in the main belt, in an extraordinarily slow (∼50-d) rotation state. © 2001 Academic Press

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1. Introduction. IRAS observations of 288 Glauke (Tedesco *et al.* 1992) yielded an effective diameter of $D_{\rm IRAS} = 32.1 \pm 2.2$ km. That size and Glauke's mean absolute magnitude ($H = 9.84$ mag) and color indices (Zellner *et al.* 1985) are consistent with an S classification (Tedesco *et al.* 1989, Tholen and Barucci 1989). Photometry in Apr.–May 1982 by Harris (1983) showed a period of 1150 ± 50 h, and an analysis by Harris *et al.* (1999) of photometry obtained in Sep.–Nov. 1984 by Binzel (1987) yielded a period of 1296 ± 24 h. Glauke's lightcurve amplitude is about 1 mag, suggesting an elongation near 2.5. This is one of the largest lightcurve amplitudes reported so far for S-class asteroids with $D_{\rm IRAS}$ as large as Glauke's; see http://cfa-www.harvard.edu/iau/lists/LightcurveDat.html. Here we report detection of Glauke radar echoes that are resolved in Doppler frequency and that provide new constraints on the object's physical properties.

At Arecibo's transmitter frequency of 2380 MHz ($\lambda = 13$ cm), the instantaneous bandwidth (Hz) of echo from a rotating rigid object is

$$B = 27.7D\cos(\delta)/P \qquad (1)$$

with P the apparent rotation period (hours) and δ the angle between the line of sight and the asteroid's apparent equatorial plane. D, the apparent breadth (km) of the asteroid's pole-on silhouette, equals the distance between the planes that are tangent to the asteroid and parallel to both the apparent spin vector and the radar line of sight. For $D \sim D_{\rm IRAS}$ and $P \sim 50$ d, Glauke's Arecibo echo bandwidth should be about 1 Hz or less. Since echo signal-to-noise ratio varies inversely as the square root of the echo bandwidth, the concentration of echo power into such a small bandwidth would render Glauke an order of magnitude more radar detectable than if it had a typical main-belt asteroid rotation period of about 10 h.

This logic was the basis for 1991 observations (Ostro *et al.*, unpublished) that produced marginally significant evidence for echoes close to the predicted frequency and with a bandwidth consistent with 50-d rotation. However, evidence for echo was present only in certain subsets of the 1991 data, undermining confidence that echo was detected.

2. Observations. We used the recently upgraded Arecibo Observatory to observe Glauke during March 9–11 and March 19–21, 2000, completing two transmit-receive cycles (runs) on the first and last days and three runs on each of the others (Table I). All runs used a continuous-wave (cw) setup, providing resolution of echoes in Doppler frequency only, and all runs were dual-circular-polarization, permitting simultaneous acquisition of data in the same circular polarization as transmitted (the SC sense) as well as in the opposite circular (OC) sense.

The transmitter was switched between four frequencies 10 kHz apart and centered on 2380 MHz, dwelling 1 min at each, and received signals were sampled at a rate of 62.5 kHz. Power spectra, formed using a 1,250,000-element fast Fourier transform, were sorted into four groups, each of which contained echoes from just one of the transmission frequencies, and then all the spectra in each group were added together. Each of the resultant four sums had echo at a different frequency and thus contained samples of the echo-free noise background at the frequencies of the three other sums' echoes. Such a "frequency-switched" setup permits reliable, efficient background removal and data normalization. The Doppler frequency shift at 2380 MHz was electronically removed from the echoes during the observations, and the additional shifts due to the offsets

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TABLE I
Observations

2000 March	RA (h)	Declination	Distance (AU)	Runs	Time (s)	P_T (kW)
Group 1						
9	10.1	16°	1.35	2	1339	837
10	10.1	16°	1.35	3	1341	810
11	10.1	16°	1.36	3	1354	823
Group 2						
19	10.0	17°	1.39	3	1364	865
20	10.0	17°	1.39	3	1389	903
21	10.0	17°	1.40	2	1393	910

Note. For each observation date we give Glauke's right ascension, declination and distance, the number of runs, and the average integration time and transmitter power. Typical antenna parameters were: system temperature = 30 K and sensitivity = 6.5 K/Jy (gain = 71.5 dB).

of the four transmitter frequencies from 2380 MHz were removed during data reduction, in each case using a Doppler prediction ephemeris based on optical astrometry obtained during 1890–1999.

3. Results. Figure 1 shows weighted sums of echo spectra from each of the two three-day groups of observations and also the six-day grand sum, at a frequency resolution of 0.05 Hz. The frequency origin corresponds to our ephemeris's prediction for echoes from the asteroid's center of mass. Our estimate of the offset of the midpoint of the grand sum OC spectrum is 0.01 ± 0.2 Hz. The formal uncertainty in our Doppler ephemeris was 0.3 Hz, so that result is not surprising.

The Group 1 spectrum appears slightly stronger and perhaps narrower than the Group 2 echoes, but these differences are not significant. Because of the weakness of our echoes, we use the six-day grand sum for our inferences about the asteroid's properties. Our estimate of Glauke's circular polarization ratio is $\mathrm{SC/OC} = 0.17 \pm 0.06$; the uncertainty is due to receiver noise. Our estimate of Glauke's OC radar cross section, $135 \pm 35\ \mathrm{km}^2$, when normalized to the asteroid's projected area $\pi D_{\mathrm{PROJ}}^2/4$, gives an OC albedo equal to 0.17 ± 0.11, where our 65% error bar is intended to encompass uncertainties in D_{PROJ} as well as radar system calibration uncertainty.

The echo edges are obscured by noise. However, based on previous radar investigations of asteroids with well known sizes and shapes (e.g., Ostro *et al.* 1990a) and on experience with various approaches to estimating asteroid echo bandwidths from power spectra with signal-to-noise ratios similar to those of our Glauke spectra (e.g., Magri *et al.* 1999), we adopt

$$0.7 \leq B \leq 1.3 \text{ Hz} \tag{2}$$

as an interval estimate for the echo bandwidth of the sum of our spectra. With this result, Eq. (1) gives

$$21.3 D_{\mathrm{MAX}} \cos(\delta) \leq P \leq 39.6 D_{\mathrm{MAX}} \cos(\delta) \tag{3}$$

where D_{MAX} is the maximum breadth sampled by the radar data.

To proceed further, let us model Glauke as a triaxial ellipsoid with $a/b = a/c = 2.5$, as suggested by the object's lightcurve amplitude. Then, following Magri *et al.* (1999), we write Eq. (1) as

$$\mathrm{B} = 27.7 D_{\mathrm{MAX}} g(\phi) \cos(\delta)/P, \tag{4a}$$

where

$$g(\phi) = [\cos^2\phi + (b/a)^2 \sin^2\phi]^{1/2} \tag{4b}$$

and the rotation phase ϕ is zero at the ellipsoid's maximum-breadth orientation. Now Eq. (3) becomes

$$21.3 D_{\mathrm{MAX}} g(\phi) \cos(\delta) \leq \mathrm{P} \leq 39.6 D_{\mathrm{MAX}} g(\phi) \cos(\delta). \tag{5}$$

Unfortunately, we do not know the lightcurve phases corresponding to eitherthe IRAS flux measurements (G. J. Veeder, personal communication, 2000) or the radar observations. Consistency between the IRAS diameter, the mean visual magnitude, and the broadband color indices makes it seem unlikely that the IRAS diameter was obtained at a lightcurve extremum or near pole-on. Still, there is considerable uncertainty in the asteroid's maximum dimension and hence in D_{MAX}.

From the IRAS diameter, the lightcurve amplitude, the assumed ellipsoid model, and Eqs. (2–4), we obtain constraints on the rotation period P (hours)

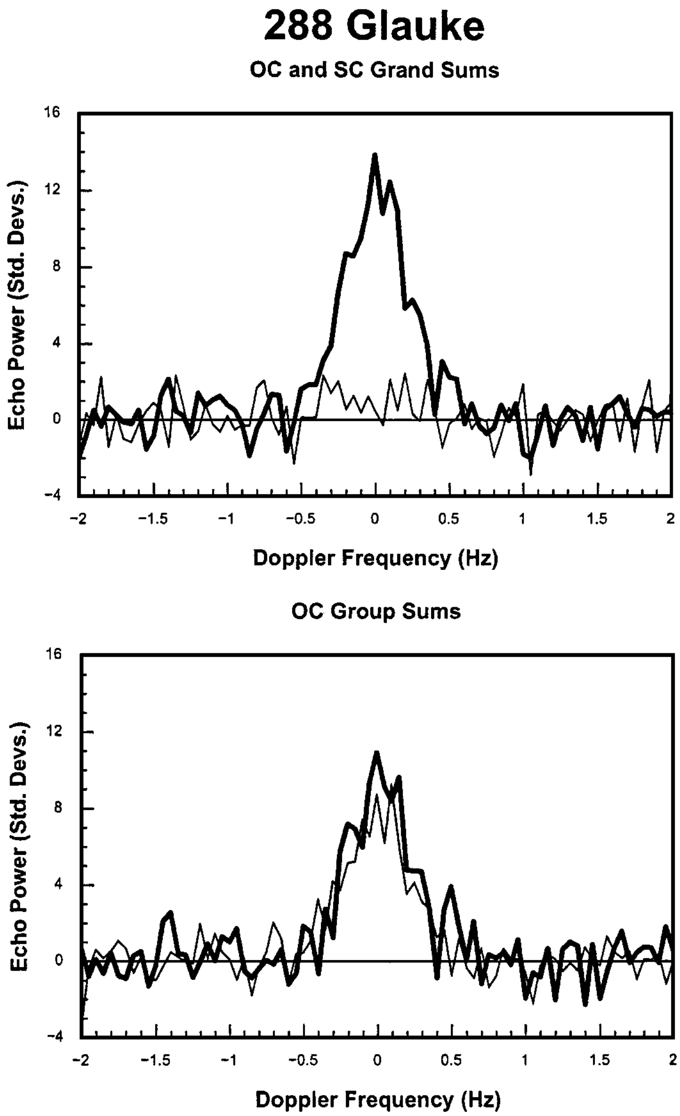

FIG. 1. Glauke echo spectra. Weighted sums of all our OC (heavy curve) and SC (light curve) echo spectra are shown in the top panel, and weighted sums of OC spectra from March 9–11 (heavy curve) and March 19–21 (light curve) are shown in the bottom panel. Echo power (standard deviations) is plotted vs. Doppler frequency (Hz), with 0 Hz corresponding to the ephemeris prediction for echoes from Glauke's center of mass.

TABLE II
Comparison with Other S-Class Asteroids

	Effective diameter (km)	Approximate period (h)	Maximum lightcurve amplitude (mag)	SC/OC	OC albedo
288 Glauke	32.1	∼1200	1.0	0.17 ± 0.06	0.17 ± 0.11
S MBA mean				0.174 ± 0.125	0.147 ± 0.043
243 Ida	28.0	5	0.9	no data	no data
433 Eros	19.4	5	1.49	0.275 ± 0.06	0.30 ± 0.06
1620 Geographos	1.8	5	2.0	0.19 ± 0.05	>0.12
4179 Toutatis	2.7	176	1.1	0.29 ± 0.01	0.24 ± 0.03
4769 Castalia	1.0	4	1.0	0.29 ± 0.01	0.16 ± 0.01
6489 Golevka	0.5	6	1.0	0.23 ± 0.02	0.18 ± 0.09

Note. Arecibo 13-cm observations of Eros (Ostro *et al.* 1991) yielded an OC radar cross section of 75 km^2. From the dimensions determined by NEAR we find that the object's weighted-average projected area during the Arecibo observations (at $\delta = 17^\circ$) was 250 ± 30 km^2, yielding the above albedo. Other references are Magri *et al.* (1999) for S main-belt-asteroid means, Ostro *et al.* (1996) and Hudson and Ostro (2000) for 1620 Geographos, Ostro *et al.* (1999) for Toutatis, Ostro *et al.* (1990b) and Hudson and Ostro (1994) for Castalia, and Hudson *et al.* (2000) for Golevka.

during our observations,

$$1090\, g(\phi) \cos(\delta) \leq P \leq 2100, \tag{6}$$

which is consistent with inferences from optical lightcurves that $1100 \leq P \leq 1320$. Inserting the optical lower bound on P into Eq. (5), we find that δ could not have exceeded 70° during our observations.

4. Discussion. Our echoes are consistent with IRAS and ground-based optical constraints on Glauke's dimensions and rotation. Glauke's circular polarization ratio indicates a fairly smooth surface at cm-to-m scales. That ratio and Glauke's OC radar albedo are close to the mean values for other radar-detected S-class main-belt asteroids (Magri *et al.* 1999). Table II compares Glauke's properties to those of selected asteroids, including the five S-class, near-Earth asteroids (NEAs) for which reliable shape models and radar albedos are published. Those objects' radar albedos straddle Glauke's, and their SC/OC ratios are in the middle of the distribution of NEA values (Lupishko and di Martino 1998), which typically are higher than main-belt asteroid values.

Attempting to understand the long period of Glauke's lightcurve, Harris (1983; see also Harris and Binzel 1985 and Weidenschilling *et al.* 1989) suggested that Glauke might be a binary system, with the observed lightcurve periodicity corresponding to the precession of the primary's spin vector and the normal to the system's orbit. Given the lack of evidence for any shorter-period lightcurve modulation from a putative primary's rotation, that explanation was unconvincing. In any event, our narrowband echoes during two, three-day observation sequences 12 days apart rule out the already remote possibility that we fortuitously captured an almost exactly pole-on orientation of the precessing, rapidly spinning, primary member of a two-object system, and the combination of our spectra and the vis/IR constraints on Glauke's dimensions establishes that the lightcurve periodicity is due to the asteroid's slow rotation.

The two best-studied asteroids in very slow spin states are 253 Mathilde, the 53-km C-class asteroid imaged by NEAR, and 4179 Toutatis, a ∼2.5-km S-class NEA investigated in great detail by radar. There is no evidence for satellites around either object. However, both are in nonprincipal-axis (NPA) spin states, which can be thought of as combining rotation around one axis with precession of that axis about the angular momentum vector. Toutatis' periods are 5.4 and 7.3 d (Hudson and Ostro 1995) and Mathilde's apparently are 17.4 and 31 d (Mottola *et al.* 1995). In that context, and given the possible variation in Glauke's lightcurve period suggested by the disparate optical period estimates, it seems likely that Glauke's spin state is NPA (Harris *et al.* 1999). For Glauke's diameter and rotation period, the damping time scale of NPA rotation to principal-axis rotation is much longer than the age of the Solar System (Harris 1994), so NPA rotation is expected given the slow rotation. The reason for the very slow rotation rate itself remains a mystery.

Characterization of NPA rotation entails estimation of eight parameters. This task is difficult using just optical lightcurves (e.g., Spencer *et al.* 1995) but is straightforward using a time series of strong radar images (as demonstrated for Toutatis; Ostro *et al.* 1995, Hudson and Ostro 1995), ideally in combination with optical lightcurves (Hudson *et al.* 1997). However, for radar echoes to be useful for testing the hypothesis that Glauke's spin is NPA, they should be at least an order of magnitude stronger than ours and must provide a thoroughly sampled time base much longer than two weeks. An intensive series of radar+optical observations during several months surrounding Glauke's 1.20-AU approach in 2014 could offer the best opportunity to clarify the nature of the asteroid's spin until its 1.23-AU approach in 2046.

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REFERENCES

Binzel, R. P. 1987. A photoelectric survey of 130 asteroids. *Icarus* **72**, 135–208.

Harris, A. W. 1983. Slowly rotating asteroids: Evidence for binary asteroids? *Bull. Am. Astron. Soc.* **15**, 828.

Harris, A. W. 1994. Tumbling asteroids. *Icarus* **107**, 209–211.

Harris, A. W., and R. P. Binzel 1985. 288 Glauke and 1220 Crocus: Precessing binary asteroids? *Lunar Planet. Sci. Conf.* **16**, 320–321.

Harris, A. W., J. W. Young, E. Bowell, and D. J. Tholen 1999. Asteroid lightcurve observations from 1981 to 1983. *Icarus* **142**, 173–201.

Hudson, R. S., and S. J. Ostro 1994. Shape of asteroid 4769 Castalia (1989 PB) from inversion of radar images. *Science* **263**, 940–943.

Hudson, R. S., and S. J. Ostro 1995. Shape and nonprincipal axis spin state of asteroid 4179 Toutatis. *Science* **270**, 84–86.

Hudson, R. S., and S. J. Ostro 1999. Physical model of asteroid 1620 Geographos from radar and optical data. *Icarus* **140**, 369–378.

Hudson, R. S., S. J. Ostro, and A. W. Harris 1997. Constraints on spin state and Hapke parameters of asteroid 4769 Castalia using lightcurves and a radar-derived shape model. *Icarus* **130**, 165–176.

Hudson, R. S., and 26 colleagues 2000. Radar observations and physical modeling of asteroid 6489 Golevka. *Icarus* **148**, 37–51.

Lupishko, D. F., and M. di Martino 1998. Physical properties of near-Earth asteroids. *Planet. Space Sci.* **46**, 47–74.

Magri, C., S. J. Ostro, K. D. Rosema, M. L. Thomas, D. L. Mitchell, D. B. Campbell, J. F. Chandler, I. I. Shapiro, J. D. Giorgini, and D. K. Yeomans 1999. Mainbelt asteroids: Results of Arecibo and Goldstone radar observations of 37 objects during 1980–1995. *Icarus* **140**, 379–407.

Mottola, S. A., W. D. Sears, A. Erikson, A. W. Harris, J. W. Young, G. Hahn, M. Dahlgreen, B. E. A. Muller, B. Owen, R. Gil-Hutton, J. Licandro, M. A. Barucci, C. Angeli, G. Neukum, C. Lagerkvist, and J. F. Lahulla 1995. The slow rotation of 253 Mathilde. *Planet. Space Sci.* **43**, 1609–1613.

Ostro, S. J., K. D. Rosema, and R. F. Jurgens 1990a. The shape of Eros. *Icarus* **84**, 334–351.

Ostro, S. J., J. F. Chandler, A. A. Hine, I. I. Shapiro, K. D. Rosema, and D. K. Yeomans 1990b. Radar images of asteroid 1989 PB. *Science* **248**, 1523–1528.

Ostro, S. J., D. B. Campbell, J. F. Chandler, I. I. Shapiro, A. A. Hine, R. Velez, R. F. Jurgens, K. D. Rosema, R. Winkler, and D. K. Yeomans 1991. Asteroid radar astrometry. *Astron. J.* **102**, 1490–1502.

Ostro, S. J., R. S. Hudson, R. F. Jurgens, K. D. Rosema, R. Winkler, D. Howard, R. Rose, M. A. Slade, D. K. Yeomans, J. D. Giorgini, D. B. Campbell, P. Perillat, J. F. Chandler, and I. I. Shapiro 1995. Radar images of asteroid 4179 Toutatis. *Science* **270**, 80–83.

Ostro, S. J., R. F. Jurgens, K. D. Rosema, R. S. Hudson, J. D. Giorgini, R. Winkler, D. K. Yeomans, D. Choate, R. Rose, M. A. Slade, S. D. Howard, D. J. Scheeres, and D. L. Mitchell 1996. Radar observations of asteroid 1620 Geographos. *Icarus* **121**, 44–66.

Ostro, S. J., R. S. Hudson, K. D. Rosema, J. D. Giorgini, R. F. Jurgens, D. Yeomans, P. W. Chodas, R. Winkler, R. Rose, D. Choate, R. A. Cormier, D. Kelley, R. Littlefair, L. A. M. Benner, M. L. Thomas, and M. A. Slade 1999. Asteroid 4179 Toutatis: 1996 radar observations. *Icarus* **137**, 122–139.

Spencer, J. R., and 47 colleagues 1995. The lightcurve of 4179 Toutatis: Evidence for complex rotation. *Icarus* **117**, 71–89.

Tedesco, E. F., D. L. Matson, and G. J. Veeder 1989. Classification of IRAS asteroids. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 290–297. Univ. of Arizona Press, Tucson.

Tedesco, E. F., G. V. Veeder, J. W. Fowler, and J. R. Chillemi 1992. *The IRAS Minor Planet Survey*, Tech. Rep. PL-TR-92-2049. Phillips Laboratory, Hanscomb AFB, MA.

Tholen, D. J., and M. A. Barucci 1989. Asteroid taxonomy. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 298–315. Univ. of Arizona Press, Tucson.

Weidenschilling, S. J., P. Paolicchi, and V. Zappalà 1989. Do asteroids have satellites? In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 643–658. Univ. of Arizona Press, Tucson.

Zellner, B., D. J. Tholen, and E. F. Tedesco 1985. The eight-color asteroid survey: Results for 589 minor planets. *Icarus* **61**, 355–416.