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ICARUS

Icarus 166 (2003) 271–275

www.elsevier.com/locate/icarus

Radar detection of Asteroid 2002 AA29

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Received 24 June 2003; revised 27 August 2003

Abstract

Radar echoes from Earth co-orbital Asteroid 2002 AA29 yield a total-power radar cross section of 2.9×10^{-5} km^2 ±25%, a circular polarization ratio of $\mathrm{SC/OC} = 0.26 \pm 0.07$, and an echo bandwidth of at least 1.5 Hz. Combining these results with the estimate of its visual absolute magnitude, $H_\mathrm{V} = 25.23 \pm 0.24$, from reported Spacewatch photometry indicates an effective diameter of 25 ± 5 m, a rotation period no longer than 33 min, and an average surface bulk density no larger than 2.0 g cm^{-3}; the asteroid is radar dark and optically bright, and its statistically most likely spectral class is S. The H_V estimate from LINEAR photometry (23.58 ± 0.38) is not compatible with either Spacewatch's H_V or our radar results. If a bias this large were generally present in LINEAR's estimates of H_V for asteroids it has discovered or observed, then estimates of the current completeness of the Spaceguard Survey would have to be revised downward.

Keywords: Asteroids; Radar; Photometry

1. Introduction

This asteroid was discovered by the MIT Lincoln Near Earth Asteroid Research (LINEAR) Project (MPEC 2002-A92) and was found to be in a "classical" Earth horseshoe orbit (Connors et al., 2002), the first example of this dynamical category. As noted in that reference, 2002 AA29 ($a = 1.0007$ AU, $e = 0.01222$, $i = 10.7°$) is essentially co-orbital with our planet, librating over 350° of relative orbital longitude between the leading and trailing sides of the Earth, always avoiding passage through inferior conjunction or opposition. On 2003 January 8, the object reached its minimum close approach distance of 0.039 AU on the leading side of the Earth and began its long libration towards the trailing side; the libration period is 190 years. This behavior will continue for at least several centuries. Integrations suggest that at some of its future libration extrema, the object may temporarily become a quasi-satellite of the Earth for several decades before reentering the horseshoe orbit (Connors et al., 2002).

The long-term stability of Earth horseshoe orbits was demonstrated by Hollabaugh and Everhart (1973), and 2002 AA29's orbit is remarkably similar to the prototypical Earth horseshoe orbit shown in Fig. 1 of that reference. Although both 3753 Cruithne (Wiegert et al., 1997) and 2002 AA29 are in 1 : 1 resonances with Earth, Cruithne's large eccentricity and potential interactions with Venus and Mars make its current horseshoe-like orbital behavior short-lived. 2002 AA29 is the first known object that can become a quasi-satellite of the Earth and is the first object known to follow a prototypical heliocentric horseshoe orbit.

2002 AA29 would be an energetically attractive target for a flyby mission, because the heliocentric distances of the orbit's ascending and descending nodes are both near 1 AU (C. Sauer, personal communication). Launch energies and flight times for flybys will remain low during the next seven years, but then will increase as the asteroid recedes from Earth on its horseshoe orbit.

An initial estimate of 2002 AA29's absolute visual magnitude, $H_\mathrm{V} = 23.9$, based primarily on the photometry reported by LINEAR, was reported in MPEC 2002-A92. If the optical geometric albedo were 0.18 (a typical S-class value), then an H_V of 23.9 would suggest a diameter near 50 m,

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doi:10.1016/j.icarus.2003.09.001

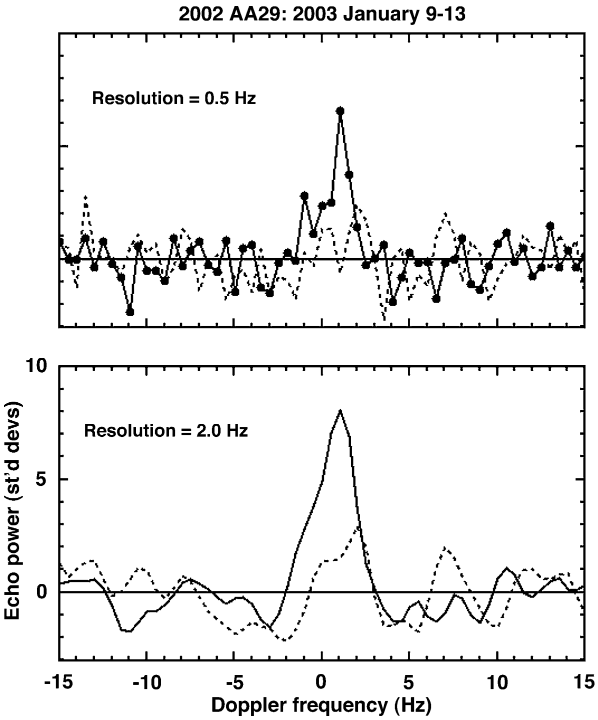

Fig. 1. Weighted sums of 2002 AA29 echo spectra in the OC and SC polarizations (solid and dashed curves), shown at resolutions of 0.5 and 2.0 Hz. In the 0.5-Hz-resolution spectrum, the OC radar cross section equivalent of one standard deviation is 1.15×10^{-6} km^2. The top and bottom figures have identical axes. The frequency origin corresponds to the prediction ephemeris (JPL solution #11) used during the observations.

which would be expected to make its echoes detectable at Arecibo at a signal-to-noise (SNR) of at least 200 per date in January 2003. This prediction assumed a rotation period of 2 h, an equatorial view, and a radar albedo of 0.1, and would underestimate the SNR if the period were longer or the view were nonequatorial.

2. Observations

We used Arecibo's S-band (2380-MHz, 12.6-cm) radar to observe 2002 AA29 daily during January 9–13, 2003 (Table 1). Our observations used a circularly polarized transmission followed by simultaneous reception in the same and opposite senses of circular polarization (SC and OC); back-reflections from an ideal smooth surface would be entirely OC, so the SC/OC ratio is a measure of wavelength-scale roughness.

Thanks to successful efforts to recover the object optically by Jim Scotti at Spacewatch, the three-sigma pointing and Doppler uncertainties in our observing ephemeris (JPL orbit solution #11) were only 1.8 arcsec and 0.6 Hz. Our strategy was to start with a handful of transmit–receive cycles (runs) using transmission of a continuous wave (cw), for resolution just in Doppler frequency, and then to do some runs using "ranging" waveforms that would furnish time-delay measurements. Then we would use the resultant radar astrometry to refine the orbit and, with the more accurate ephemeris, devote the rest of the experiment to imaging with 7.5-m range resolution.

Table 1
Observations

2003 January	RA	Dec.	Dist. (AU)	Runs	UTC start–stop (hhmmss–hhmmss)	TX power (kW)	Echo strength (sigma)
9	183°	19°	0.040	39	092201–104722	919	3
10	186°	23°	0.040	32	091706–105122	920	2
11	189°	27°	0.041	99	083533–104823	925	5
12	192°	30°	0.042	50	094443–105303	924	3
13	195°	34°	0.043	50	092523–103647	910	3

Note. All observations used JPL orbit solution #11 and used a continuous wave (cw) transmission at a frequency of 2380 MHz + 200 Hz. Data were sampled in a 5 kHz bandwidth. During the observations, the maximum antenna gain was 73.5 dB (10.3 K Jy^{-1}) and the minimum system temperature was within 1 K of 25 K in each channel. The last column gives the strength of a weighted sum of echo spectra reduced at a resolution of 1 Hz.

3. Results

The first cw runs on January 9 showed no echo. We continued integrating, and ultimately a weighted sum of all 39 runs from that day yielded a three-sigma signal overlapping the expected frequency. This experience was repeated on each of the next four dates (last column of Table 1).

Figure 1 shows OC and SC weighted sums of all five dates' data at 2.0-Hz resolution, which optimizes the strength of the spectral peak, and also at 0.5-Hz resolution. From the full width at half power of the latter, we place a lower bound of 1.5 Hz on the echo's edge-to-edge bandwidth B_{echo}. We find that the offset, 1.0 ± 1.0 Hz, of the spectral peak from the frequency origin (i.e., from our prediction ephemerides) is unfortunately not useful in refining the orbit of this object because of the measurement's coarse precision relative to the small uncertainties in our observing ephemeris.

Integration and calibration of our spectra yields the following estimates for the OC, SC, and total-power (TC = OC + SC) radar cross sections and the circular polarization (SC/OC) ratio:

$$\sigma_{\mathrm{OC}} = 2.3 \times 10^{-5}\ \mathrm{km}^2 \pm 25\%, \tag{1}$$

$$\sigma_{\mathrm{SC}} = 6.1 \times 10^{-6}\ \mathrm{km}^2 \pm 25\%, \tag{2}$$

$$\sigma_{\mathrm{TC}} = 2.9 \times 10^{-5}\ \mathrm{km}^2 \pm 25\%, \tag{3}$$

$$\mathrm{SC/OC} = 0.26 \pm 0.07. \tag{4}$$

4. Discussion

How can we understand the unexpected weakness of our echoes? We have no reason to believe that the telescope was incorrectly pointed or that the radar system was malfunctioning, because all indications from monitoring of the telescope pointing and radar hardware were that the entire system was

Table 2
Estimates of absolute visual magnitude

Observatory	#	Phase angle	Band	H_{V} ($G = 0.15$) mean ± std.dev	$G(H_{\text{V}} = 25.2)$
LPL/Spacewatch II	6	65°–66°	V	25.23 ± 0.24	0.14
Great Shefford	1	67°	R	24.80	0.36
Powell observatory	23	65°–77°	R	24.04 ± 0.44	1.05
LINEAR	14	65°–67°	B	23.58 ± 0.38	1.75
	44			24.07 ± 0.66	

Note. The number of published apparent magnitude measurements from each reporting site is shown along with the reported passband (visual, red, or blue) and the phase angle range over which they were made. We applied mean color corrections of $V{-}R = 0.4$ and $B{-}V = 0.8$ (A.W. Harris and P. Pravec, personal communications) to produce equivalent visual magnitudes. Then we assumed a nominal slope parameter, $G = 0.15$, and used the IAU two-parameter or "H, G" magnitude system (Bowell et al., 1989), and the numerically integrated orbit, to compute the mean absolute visual magnitude H_{V}. This magnitude system has been scaled such that $G \sim 0$ for steep phase curves (low-albedo bodies, generally) and $G \sim 1$ for shallow phase curves (high-albedo bodies). The last column gives the value of G required to produce $H_{\text{V}} = 25.2$ (a value compatible with both radar and Spacewatch results) for each site's data; see text.

performing in an optimum manner. Furthermore, observations of 1993 OM7 immediately before the 2000 AA29 runs and observations of 2002 CQ11 on two of the same dates produced echoes consistent with expectations.

One possibility is that 2002 AA29 is significantly smaller than its reported apparent magnitude measurements might lead one to infer. To explore this possibility, we independently solved for the object's absolute visual magnitude H_{V} using all published photometry [Minor Planet Electronic Circulars (MPEC) 2002-A92, 2002-B17, 2002-B24, 2002-B35, 2003-A17, 2003-A26, 2003-A51, 2003-A70, 2003-A72, 2003-A77] and obtained $H_{\text{V}} = 24.07 \pm 0.66$ (Table 2, discussed in detail below). This is the same weighted-mean value reported by the JPL Horizons system (Giorgini, 2003). The Minor Planet Center currently reports $H_{\text{V}} = 24.3$ as a result of reducing the weighting of LINEAR data so much that it is effectively excluded from the photometric solution when other photometry is present (G. Williams, personal communication).

In Table 3, we list the visual geometric albedo p_v for several values of H_{V}, calculated as a function of diameter with the equation (Zellner, 1979; see also Fowler and Chillemi, 1992):

$$\log p_v = 6.224 - 2 \log D - 0.4 H_{\text{V}}, \tag{5}$$

where D is the diameter in km. Table 3 also lists for each diameter the total-power radar albedo $\hat{\sigma}_{\text{TC}}$, defined as σ_{TC} divided by the target's projected area, and the maximum value P_{max} of the asteroid's rotation period that is consistent with an echo bandwidth of at least 1.5 Hz and a constant equatorial diameter D.

For a smooth sphere, SC power would equal zero and the OC albedo ($\hat{\sigma}_{\text{OC}}$) would equal $R_\perp$, the Fresnel power reflection coefficient at normal incidence, 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: $R_\perp = \hat{\sigma}_{\text{OC}}/g$, 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 hypothetical smooth-surface echoes.

Table 3
Properties' dependence on diameter

D (m)	Visual geometric albedo (p_v) $H_{\text{V}} = 24$	$H_{\text{V}} = 25$	$H_{\text{V}} = 26$	$\hat{\sigma}_{\text{TC}}$	d_{max} ($\text{g}\,\text{cm}^{-3}$)	P_{max} (min)
16	> 1	0.654	0.260 S	0.144 R	2.56	18
17	> 1	0.580	0.231 S	0.128 R	2.39	19
18	> 1	0.517	0.206 S	0.114 R	2.25	20
19	> 1	0.464	0.185 S	0.102 R	2.12	21
20	> 1	0.419	0.167 S	0.092 R	2.01	22
21	0.954	0.380	0.151 S	0.084 R	1.91	23
22	0.869	0.346	0.138 S	0.076 R	1.82	24
23	0.795	0.317	0.126 S	0.070 R	1.73	25
24	0.730	0.291 S	0.116 S	0.064 R	1.66	27
25	0.673	0.268 S	0.107 S	0.059 R	1.59	28
26	0.622	0.248 S	0.099 S	0.055 R	1.54	29
27	0.577	0.230 S	0.091 C	0.051 R	1.50	30
28	0.537	0.214 S	0.085 C	0.047 R	1.48	31
29	0.500	0.199 S	0.079 C	0.044 R	1.45	32
30	0.467	0.186 S	0.074 C	0.041 R	1.42	33
31	0.438	0.174 S	0.069 C	0.038	1.40	34
32	0.411	0.164 S	0.065 C	0.036	1.38	35
33	0.386	0.154 S	0.061 C	0.034	1.37	37
34	0.364	0.145 S	0.058 C	0.032	1.35	38
35	0.343	0.137 S	0.054 C	0.030	1.34	39
40	0.263 S	0.105 S	0.042 C	0.023	1.28	44
50	0.168 S	0.067 S	0.027 C	0.015	1.21	55
60	0.117 S	0.047	0.019	0.010	1.17	67

Note. For each value of 2002 AA29's diameter D, we list the visual geometric albedo p_v corresponding to three values for the absolute visual magnitude H_{V}, the total-power radar albedo $\hat{\sigma}_{\text{TC}}$, the maximum surface bulk density d_{max} allowed by that radar albedo, and the maximum rotation period P_{max} consistent with D and our lower bound, $B_{\text{echo}} \geqslant 1.5$ Hz, for the radar echo bandwidth. A "C" flags each value of the visual albedo p_v within the range of the central 90% of values for asteroids with a *low*-albedo taxonomic class according to Table 2 of Cellino et al. (2002), and an "S" flags each value of the visual albedo p_v within the range of the central 90% of values for asteroids with a *moderate*-albedo taxonomic class. An "R" flags values of the total-power radar albedo (σ_{TC}) within the range of 100% of asteroid values. See text.

For 2002 AA29, some small-scale roughness is indicated by the SC/OC ratio and the shape is unlikely to be perfectly spherical. In this situation, the upper bound on the total-power radar albedo $\hat{\sigma}_{\text{TC}}$ can be taken as an upper bound on $R_\perp$, and the corresponding value of $d(R_\perp)$ can be taken as an upper bound on the smooth surface component's average bulk density. Table 3 lists the larger of the densities calculated from empirical rules given by Ostro et al. (1985) and Garvin et al. (1985). That is, for any given diameter, the average density of 2002 AA29's surface cannot be higher than the listed value and almost certainly would be much lower.

All reported asteroid total-power radar albedos ($\hat{\sigma}_{\text{TC}}$) are larger than 0.04 (Magri et al., 2001). Among the more than

690 asteroids in the JPL Horizons database that list both a spectral type and a value for the visual geometric albedo p_v, only 11 have p_v as large as 0.4 and only 26 have a p_v as large as 0.3. 90% of all S-type asteroids have p_v between 0.1 and 0.3, and 90% of C-type asteroids have p_v between 0.03 and 0.09. In Table 3, a "C" flags each value of the visual albedo p_v within the range of the central 90% of values for asteroids with a low-albedo taxonomic class according to Table 2 of Cellino et al. (2002), and an "S" flags each value within the range of the central 90% of values for asteroids with a moderate-albedo taxonomic class.

If 2002 AA29's radar albedo is not less than other reported asteroidal values, then its effective diameter is no larger than 30 m, its rotation period is 33 minutes or less, its absolute visual magnitude H_V cannot be as low as 24, and further constraints on the object's properties depend on H_V as indicated in Table 3. For example, moderate (e.g., S-class) visual albedos are admissible for H_V at least ~ 25, but H_V must be at least ~ 26 for low (e.g., C-class) visual albedos to become admissible.

Note that observations from LINEAR are 1.6 magnitudes brighter on average than those reported by Spacewatch, when corrected for color (see Table 2 caption). Among the sites publishing photometry, only the data reported by Spacewatch (the single site reporting visual-band data) and Great Shefford (red band) are consistent with our radar-derived diameter. Spacewatch measurements indicate a fairly typical slope parameter of $G = 0.14$, which in turn suggests a fairly typical visual albedo.

However, the color-corrected photometric dataset is internally inconsistent, and we cannot reconcile our results with data from LINEAR or Powell. This may be due to equipment-specific circumstances requiring non-standard color index calibrations of $V-R$ and $B-V$, but which have not been determined by the reporting sites. As listed in the last column of Table 2, implausibly high values of G (and hence of p_v) would be required for the LINEAR and Powell data to yield an H_V that is compatible with radar, Spacewatch and Great Shefford measurements.

The absolute magnitude, defined as the apparent magnitude at zero phase and unit heliocentric and geocentric distances, is notoriously difficult to estimate from high-phase-angle measurements alone, because of effects from the shadowing of the asteroid's unknown shape and from the surface's scattering behavior (e.g., Karttunen and Bowell, 1989; Bowell et al., 1989). (Our observations are too weak to shed light on how irregular 2002 AA29's shape might be.) However, the optical observations were all made at similarly high phase angles, so this factor cannot explain inconsistencies between different observatories' results.

The comments by Jedicke et al. (2002, p. 84) on inconsistencies in the reporting of asteroid absolute magnitudes are relevant here. Furthermore, since LINEAR is responsible for more than half of the discoveries of Potentially Hazardous Asteroids (http://cfa-www.harvard.edu/iau/lists/Dangerous.html, http://neo.jpl.nasa.gov/missions/stats.html), the question arises as to whether the 1.6-magnitude bias evident for 2002 AA29 might be indicative of a general, systematic bias in absolute magnitudes from LINEAR. If this were so, then the Spaceguard Survey's completeness vs. magnitude curve (Jedicke et al., 2003) would be significantly lower than would be surmised if LINEAR H_V estimates generally were unbiased. Clearly, the case for follow-up of LINEAR discoveries with accurate photometric and radar observations is strong.

5. Implications for 2002 AA29

Let us assume that the Spacewatch absolute magnitude, $H_V = 25.23$, is correct. Then the asteroid is radar dark and optically bright, its statistically most likely spectral class is S, and the bulk density of its smooth-surface component does not exceed 2.0 g cm^{-3}. However, this upper bound does not necessarily pertain to the average bulk density of, say, the top meter of the surface which, given our circular polarization ratio must contain rocks or some other sort of decimeter-scale structure in addition to a putative smooth-surface component. Nor does it necessarily pertain to the asteroid's internal bulk density. Still, since the meteoritic analogs of S-class asteroids have typical grain densities of more than 3 g cm^{-3} (Britt et al., 2002), we suspect that 2002 AA29 contains substantial porosity. Following the methodology and assumptions of Magri et al. (2001), we find that 2002 AA29's macroporosity is likely to be at least 25% and could easily be as high as 50%.

The minimum required tensile strength $T_{\min}$ for an object of bulk density d, diameter D, and spin period P is (Turcotte and Schubert, 1982) of order $d(\pi D/P)^2$. For 2002 AA29, we find that even if the spin period were only a minute, $T_{\min}$ would still be much less than the tensile strength of unsaturated soils (i.e., damp dirt): 200–300 kPa, or about 2×10^6 dyne cm^{-2}, or about two bars (Tang and Graham, 2000). For comparison, values for terrestrial rocks are typically at least two orders of magnitude larger (Suppe, 1985, p. 155). Thus, although 2002 AA29 is rotating too rapidly to be a zero-tensile-strength gravitational aggregate (e.g., Richardson et al., 2002), it could be held together by very meager bonds. A similar conclusion was reached for the similar-sized object 1998 KY26 (Ostro et al., 1999).

The total number of near-Earth asteroids with $H_V \geqslant 25$ is thought to be of order 10^6 (Morrison et al., 2002), of which about a hundred have been discovered. Other than 2002 AA29 and 1998 KY26, five have been detected with radar and are under analysis [see Table 5 in Ostro et al. (2002), updated by Benner (2003)], so prospects for characterizing very small asteroids are promising. However, with H_V near 25, 2002 AA29's optical brightness stays dimmer than apparent magnitude 21 through January 2004 and then stays dimmer than apparent magnitude 23 until 2095; the horseshoe orbit precludes Earth-based observations at low solar phase angles. The next 2002 AA29 radar opportunity as favorable as the 2003 approach is in 2097.

Acknowledgments

We thank Antonio Crespo, Victor Negrón, and the technical staff of the Arecibo Observatory for help with the observations. We thank Alan Harris (SSI), Petr Pravec, Gareth Williams, Peter Birtwhistle, Grant Stokes, and Richard Frederick for discussions of photometric techniques. We thank Carl Sauer for his analysis of the accessibility of 2002 AA29 to spacecraft missions. We thank Robert Jedicke and an anonymous reviewer for their critiques. Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation and with support from NASA.

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