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Radar Detection of Vesta

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Asteroid 4 Vesta was detected on 1979 November 6 with the Arecibo Observatory's S-band (12.6-cm-wavelength) radar. The echo power spectrum, received in the circular polarization opposite to that transmitted, yields a radar cross section of $(0.2 \pm 0.1)\pi a^2$, for $a = 272$ km. The data are too noisy to permit derivation of Vesta's rotation period.

Vesta may be the only intact differentiated minor planet. Its photometric and polarimetric properties are unique among the asteroids (Bowell *et al.*, 1978), and its visible–infrared reflection spectrum is strikingly similar to those of certain basaltic achondritic meteorites (McCord *et al.*, 1970; Chapman *et al.*, 1975; Drake, 1979). Here we report 12.6-cm-wavelength radar observations of Vesta made at the Arecibo Observatory.

Vesta was observed on 1979 November 3, 4, and 6. Experimental procedures were similar to those followed by Ostro *et al.* (1980), except that the receiver polarization was maintained in the circular sense opposite to that transmitted. Reception in this "OC" sense was intended to maximize echo strength. For each night, subtraction of the noise background yielded a spectral baseline whose slope and intercept deviate insignificantly from zero. Measured values of the standard deviation of the noise fluctuations are within 3% of the predicted values. In order to improve the signal-to-noise ratio, the spectra were convolved with a smoothing filter whose bandwidth was one-third of the maximum a priori bandwidth of Vesta's echo (see discussion below).

Although the observations on the first two dates did not yield detectable echoes, a weak echo from Vesta is evident in the power spectrum obtained on 1979 November 6 and shown in Fig. 1. The reliability of this detection is supported by agreement of a priori and a posteriori estimates of the noise statistics, and by agreement of the Doppler shift of the central peak in Fig. 1 with the predicted value.

Integration of the received spectral power yields a value for Vesta's normalized radar cross section: $\hat{\sigma}_{OC} = (0.2 \pm 0.1)\ \pi a^2$. Here a is Vesta's radius, 272 km (Schubart and Matson, 1979), and the stated uncertainty corresponds to the rms noise fluctua-

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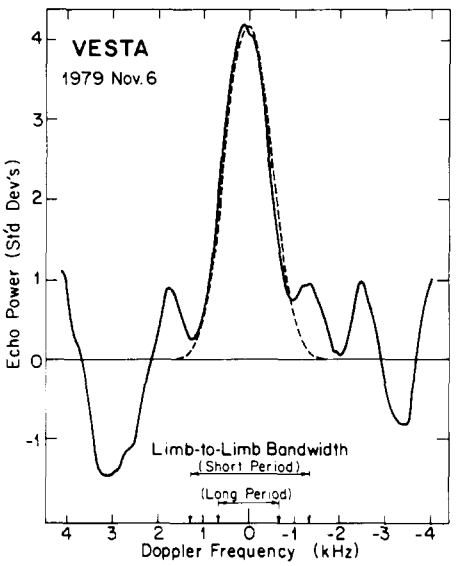

FIG. 1. The echo power spectrum (solid curve) obtained for Vesta on 1979 November 6. Received power is in units of standard deviations of the associated receiver noise. The Doppler shift resulting from the (well-known) motion of Vesta relative to the radar has been removed. Limb-to-limb bandwidths corresponding to short (5.34-hr) and long (10.68-hr) rotation periods are indicated. The dashed curve is derived from a scattering model which assumes the short rotation period. Both curves have been smoothed to a resolution equal to one third of the short-period limb-to-limb bandwidth (see text).

tion within the maximum a priori bandwidth of Vesta's echo (see discussion below).

Calculation of the relative rotational phases of Vesta at the midpoints of data reception on November 3, 4, and 6 requires knowledge of Vesta's rotation period, P, a quantity which is not firmly established. Vesta's optical lightcurve has been interpreted as having double maxima per 10.68-hr rotation period (e.g., Cuffey, 1953) or as having a single maximum per 5.34-hr rotation period (e.g., Gehrels, 1967). Recent polarimetric results (Degewij *et al.*, 1977; Gradie *et al.*, 1978) support the short-period interpretation, but the question should not be considered closed. [See Degewij *et al.* (1979) for references and a detailed discussion.]

Defining the rotational phase for our November 6 observation as 0°, corresponding phases for November 3/4 are 212°/5° if the short period is valid, or 106°/182° if the long period is valid. If, as the polarimetric data suggest, the short period is correct, then we observed virtually the same side of Vesta on November 4 and 6. The failure to detect Vesta on November 4, inexplicable in terms of *known* night-to-night differences in system sensitivity (Table I), is therefore especially disconcerting. Although we are unaware of significant errors in antenna tracking or transmitter power calibration, the possibility that such problems indeed existed cannot be excluded.

The limb-to-limb spectral bandwidth for the echo from a rotating spherical target is $(8\pi a \sin\delta)/(\lambda P)$, where λ is the wavelength and δ is the aspect angle, measured between the radar line of sight and the target's rotation pole. Pole positions can be estimated from astrometric analysis of epochs of primary photometric maxima (Taylor, 1979). Taylor (1980, private communication) has determined that for our observations of Vesta, $\delta = 69°$ if the short period is assumed or $\delta \approx 78°$ if the long period is assumed. The corresponding values of the limb-to-limb bandwidth are 2630 or 1380 Hz, respectively, as indicated in Fig. 1. Although the wider bandwidth (and hence

TABLE I

SYSTEM CHARACTERISTICS AND OBSERVATIONAL PARAMETERS[a]

	Date (1980)		
	Nov. 3	Nov. 4	Nov. 6
One-way antenna gain	69.8 dB	70.1 dB	69.9 dB
Transmitter CW power	355 kW	325 kW	390 kW
Receiving system temperature	69°K	53°K	62°K
Round-trip echo delay	25^m45^s	25^m46^s	25^m48^s
Duration of observation	31.5 m	25.5 m	20.9 m
Midpoint of data reception (UT)	$05^h01^m45^s$	$04^h40^m10^s$	$04^h39^m43^s$

[a] Reception was in the "OC" polarization, defined as the rotational sense of circular polarization opposite to that transmitted.

the 5.34-hr period) appears consistent with the width of the echo spectrum, the data are far too noisy to rule out the 10.68-hr period.

Using weighted-least-squares techniques described by Campbell *et al.* (1978), and assuming that Vesta's period is 5.34 hr, we have estimated the exponent in a scattering law of the form $\cos^n\theta$, where θ is the angle of incidence to the surface. Our best fit to the (unsmoothed) data yields $n = 7.5 \pm 5.0$, corresponding to the (smoothed) dashed curve in Fig. 1. This result is comparable to the value ($n = 7 \pm 3$) derived by Ostro *et al.* (1979) from observations of Ceres at the same wavelength and in the same polarization. Hence, if the short period is valid, Vesta's 12.6-cm-wavelength roughness seems similar to that of Ceres. On the other hand, Vesta's normalized cross section ($\hat{\sigma}_{OC} = 0.2 \pm 0.1$) seems to be significantly larger than the corresponding value for Ceres ($\hat{\sigma}_{OC} = 0.04 \pm 0.01$). This result might be due to known differences in composition (Gaffey and McCord, 1979) and/or density (Schubart and Matson, 1979) between these two asteroids.

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