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Radar Observations of Asteroid 1 Ceres

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Radar observations of asteroid 1 Ceres were made at a 12.6-cm wavelength from the Arecibo Observatory in March/April 1977. The measurements, made with a received circular polarization orthogonal to that transmitted, yield a radar cross section of $(0.04 \pm 0.01)\pi R^2$, for $R = 510$ km. The corresponding radar reflectivity is less than that measured for any other celestial body. Within the accuracy of measurement, no significant variation of cross section with rotational phase is apparent. The shape of the power spectrum suggests that Ceres is rougher at the scale of the observing wavelength than the Moon and inner planets, but smoother than the outer three Galilean satellites.

INTRODUCTION

Opportunities for the radar investigation of asteroids have been severely limited by the small sizes and great distances from Earth of these bodies. In fact, prior to 1977 only four asteroids approached Earth closely enough to be detected by radar [1566 Icarus, 1685 Toro, 433 Eros, and 1580 Betulia: see companion paper by Pettengill *et al.* (1979)]. None of these are "main belt" asteroids, however, and the authors welcomed the chance to observe 1 Ceres using the 12.6-cm-wavelength radar of the Arecibo Observatory at a favorable opposition in March/April 1977.

Ceres, by far the largest and most massive of the minor planets, was also the first to be discovered (by the Sicilian astronomer Giuseppe Piazzi on 1 January 1801). Although its 0.3- to 1.1-μm reflection spectrum resembles that of carbonaceous chondritic meteorites, Ceres should not be considered a prototype of C-class asteroids because of its atypically high visual geometric albedo (0.054 vs 0.03–0.04 for typical C-class objects), as emphasized by Bowell *et al.* (1978). Gaffey and McCord (1978) conclude that the surface of Ceres "is most probably a well-developed assemblage of olivine and magnetite, but that an opaque-rich, iron-poor clay . . . cannot be ruled out." In any event, radar echoes may shed light on the surface properties at longer wavelengths and may be helpful in illuminating some characteristics of the surface at a larger scale.

OBSERVATIONS AND RESULTS

Ceres was observed at Arecibo on 25, 28, 29, and 31 March and 1 April 1977. Each evening's observations comprised two runs,

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each consisting of a frequency-switched, continuous-wave, circularly polarized transmission lasting about 25 min (slightly less than the average round-trip echo delay of 26 min 49 sec) followed by a reception of the Doppler-shifted echo for an equal time. Our experimental approach was identical to that described by Campbell *et al.* (1978) except that the polarization sensed by the receiver was not switched, but rather was maintained in the circular sense orthogonal (OC) to that transmitted. Reception in this polarization sense was intended to maximize echo strength, since coherent reflection reverses the circular handedness. At the time of observation, Ceres passed within 4° of the zenith at transit, permitting about 2 hr of useful observing time per night. Since system performance at Arecibo is greatest for low antenna zenith angles, the echo strength was optimized by placing the two runs possible each night immediately adjacent to each other and symmetrically around transit. Average characteristics of the radar system used are given in Table I.

The total of 10 runs yielded nine apparently valid echo power spectra, each corresponding to integration of the received signal for about 25 min. The individual spectra have been combined in an appropriately weighted average to enhance the signal-to-noise ratio; the results are shown in Fig. 1. The arrows in the figure locate the Doppler shifts corresponding to echoes from the limbs of Ceres, for a rotation period of

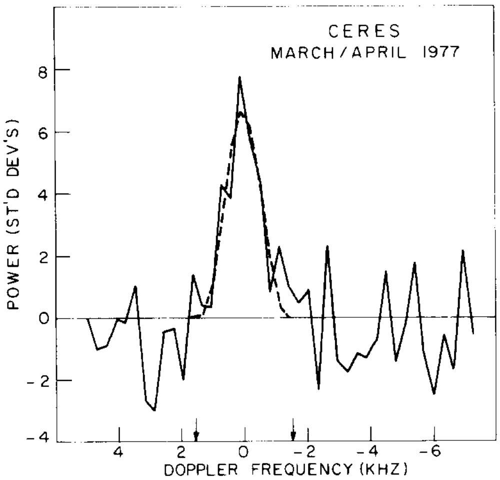

FIG. 1. The echo power spectrum for Ceres, summed over all 5 nights of observation. Doppler shifts resulting from the (well-known) motion of Ceres relative to the radar have been removed. Arrows show the calculated limb positions, under the assumptions that (i) the rotation vector is normal to the line of sight; (ii) the period is $9^{h}05^{m}$; and (iii) the radius os 510 km. Frequency resolution is ~310 Hz, or about 10% of the calculated limb-to-limb bandwidth. The ordinate is given in units of standard deviations of the associated receiver noise fluctuations. The dashed curve is the spectrum derived from the scattering model (see text).

$9^{h}05^{m}$ (Allen, 1973, p. 152), a pole position normal to the line of sight, and a radius R of 510 km (Bowell *et al.*, 1978). Despite the coarse spectral resolution (~310 Hz, or about 10% of the expected limb-to-limb bandwidth, f_{LL}) and the nearly 4-hr total integration time, the results shown in Fig. 1 exhibit a relatively low signal-to-noise ratio. Nevertheless, the echo is clearly significant.

The ephemeris used to point the telescope and to predict the Doppler shift for the echoes from the subradar point on Ceres was based on an orbital fit to photographic and meridian-circle observations; tests of the ephemeris against optical observations obtained only a few months prior to the radar experiment yielded residuals generally under 1 arcsec, a result more than adequate for pointing the Arecibo telescope, whose antenna beamwidth at S-band is about 2 arcmin. The predictions of Doppler shift were estimated to be in error by no

TABLE I

CHARACTERISTICS OF THE ARECIBO S-BAND RADAR SYSTEM[a]

One-way antenna gain	70.6 db
Transmitter cw power	350 kW
Operating frequency	2380 MHz
Transmitted polarization	Right-hand circular
Received polarization	Left-hand circular
Receiving system temperature	41°K

[a] All quantities are averaged over the five nights of observation.

more than a few hertz; thus, no attempt was made to estimate ephemeris corrections from the spectral data.

Ceres' radar cross section σ_{OC} was determined for each run from simple integration of the power spectrum. Except possibly for the data of 29 March, there is no significant variation in cross section over the approximately 200° of apparent rotational phase spanned by the nine runs (see Table II). The lower value seen on 29 March may be caused by variations in planetary albedo, but we note that it differs from other values by less than three standard deviations of the associated errors. The weighted mean of σ_{OC} for the entire set of observations is $(3.2 \pm 0.8) \times 10^4$ km^2, where the uncertainty corresponds to the estimated absolute (primarily systematic) error. The small amplitude (~0.05 mag) of Ceres' visual lightcurve suggests a nearly spherical shape (Taylor *et al.*, 1976); Ceres' *normalized* radar cross section: $\hat{\sigma}_{OC} = \sigma_{OC}/\pi R^2$ is, therefore, 0.04 ± 0.01.

Weighted-least-squares estimation of the exponent in a scattering law of the form $\cos^n\theta$, with θ the angle of incidence to the surface, yields $n = 7 \pm 3$ for a radius fixed at 510 km (see Campbell *et al.*, 1978). The calculated value of n is fairly sensitive to the value of R assumed in the estimation, since $(\partial n/\partial R) \approx 0.03$ km^{-1}.

TABLE II

RADAR CROSS SECTION σ_{OC} DETERMINED ON EACH OF 5 NIGHTS IN SPRING, 1977[a]

Date (1977)	Mean time of reception (UT) h m	Duration of observation (min)	Φ (deg)	σ_{OC} (10^4km^2)
25 March	01 04	49	0	3.7 ± 0.7
28 March	00 53	51	326	3.5 ± 0.7
29 March	00 49	51	195	1.6 ± 0.7
31 March	00 10	23	271	3.5 ± 1.1
1 April	00 34	53	159	3.8 ± 0.7

[a] Ceres' geometric cross section is 81.7×10^4 km^2 for a radius of 510 km. The errors given for measured values of σ_{OC} correspond to the rms fluctuation in the associated noise, the dominant source of relative error. Systematic effects place a floor of about 25% on the fractional uncertainty in stated values of the cross sections. Also listed for each date are the relative rotational phase Φ at the mean time of echo reception, and the duration of each night's observation.

DISCUSSION

The value of $\hat{\sigma}_{OC}$ for Ceres is significantly lower than corresponding values for S-band observations of Mercury ($\hat{\sigma}_{OC} = 0.055 \pm 0.02$; Goldstein, 1971), Venus ($\hat{\sigma}_{OC} = 0.11 \pm 0.03$; Carpenter, 1966), Mars ($0.04 \le \hat{\sigma}_{OC} \le 0.13$; Goldstein, 1965), the Moon ($\hat{\sigma}_{OC} = 0.07 \pm 0.02$; Hagfors and Evans, 1968, p. 228), and the asteroid 433 Eros ($\hat{\sigma}_{OC} = 0.16 \pm 0.03$; Jurgens and Goldstein, 1976). Because of uncertainties in the size and shape of Icarus, Toro, and Betulia, only upper limits on $\hat{\sigma}_{OC}$ could be estimated for these bodies. These limits are at least twice as large as the value measured for Ceres. Despite these uncertainties and the fact that only one polarization component was measured, our data suggest that Ceres has the lowest normalized radar cross section, at a wavelength of 12.6 cm, of any celestial object observed by radar.

The relatively low reflectivity of Ceres may result from a very loosely packed regolith layer on its surface. The surface gravitational acceleration on Ceres is only about one-sixth as strong as that on the Moon; thus, a layer of granular material on Ceres might be considerably more loosely packed than even the lunar regolith. As discussed by Hagfors and Evans (1968, p. 267), reduction in the bulk density of a dielectric material by loose packing is accompanied by a nearly proportional decrease in the bulk dielectric constant which, of course, lowers the radar reflectivity.

Expressed as a fraction of the full limb-to-limb bandwidth f_{LL}, the bandwith at half power of the spectrum of the radar echoes from Ceres is given by $B_{HP} \simeq 0.4$. [For a target whose angular scattering law varies as $\cos^n\theta$, $B_{HP} = (1 - 2^{-2/n})^{1/2}$.] The spectral distribution of power in the 12.6-cm "OC" radar echo from Ceres is broad compared to corresponding results for the inner planets

($0.02 \lesssim B_{HP} \lesssim 0.14$; Goldstein and Morris, 1975), but narrow compared to results for the outer three Galilean satellites ($B_{HP} \approx 0.8$; Ostro, 1978) as well as for the Apollo-Amor asteroids Eros ($B_{HP} \approx 0.8$; Jurgens and Goldstein, 1976) and Betulia ($B_{HP} \approx 0.9$; Pettengill *et al.*, 1979). The spectral shape of Ceres suggests that this object is probably rougher (at a scale *at least as large* as the observing wavelength) than the Moon and inner planets, but smoother than Europa, Ganymede, Callisto, Eros, and Betulia. Unfortunately, our ignorance of Ceres' radar polarization properties precludes an assessment of the detailed reflection mechanism involved.

CONCLUSION

The significant radar properties of Ceres are (1) an extremely low normalized radar cross section, and (2) a scattering law which is intermediate between those applying to the inner planets and those seen for the outer three (icy) Galilean satellites and for small, irregular asteroids. Echo polarization properties, which have been critical for a complete description of the radar scattering from the inner planets and the Galilean satellites, have yet to be measured for Ceres. Echo strength in the *same* sense of circular polarization as transmitted is at least 50% less than in the "OC" sense for all non-icy planets and satellites so far studied with radar. For this reason, about 2 weeks of nightly observations at Arecibo would likely be required to estimate the circular polarization ratio for radio waves reflected from Ceres. Although Ceres will be visible from Arecibo during oppositions in early 1981 and late 1984, the next observing opportunity that is highly favorable in both distance and declination occurs in March 1986. By then, the number of minor planets studied by radar will probably have increased severalfold. Within the next decade, the gross radar scattering behavior of a mineralogically diverse group of asteroids, including several of the largest main-belt asteroids, should be revealed.

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REFERENCES

Allen, C. W. (1973). *Astrophysical Quantities.* Athlone Press, University of London.

Bowell, E., Chapman, C. R., Gradie, J. C., Morrison, D., and Zellner, B. (1978). Taxonomy of asteroids. *Icarus* **35**, 313–335.

Campbell, D. B., Chandler, J. F., Ostro, S. J., Pettengill, G. H., and Shapiro, I. I. (1978). Galilean satellites: 1976 radar results. *Icarus* **34**, 254–267.

Carpenter, R. L. (1966). Study of Venus by CW radar—1964 results. *Astron. J.* **71**, 142–152.

Gaffey, M. J., and McCord, T. B. (1978). Asteroid surface materials: Mineralogical characterizations from reflectance spectra. *Space Sci. Rev.* **21**, 555–628.

Goldstein, R. M. (1965). Preliminary Mars radar results. *J. Res. Nat. Bur. Stand. D* **69**, 1625–1627.

Goldstein, R. M. (1971). Radar observations of Mercury. *Astron. J.* **76**, 1152–1154.

Goldstein, R. M., and Morris, G. A. (1975). Ganymede: Observations by radar. *Science* **188**, 1211–1212.

Hagfors, T., and Evans, J. H. (1968). Radar studies of the Moon. In *Radar Astronomy* (J. V. Evans and T. Hagfors, Eds.). McGraw–Hill, New York.

Jurgens, R. F., and Goldstein, R. M. (1976). Radar observations at 3.5 and 12.6-cm wavelength of asteroid 433 Eros. *Icarus* **28**, 1–15.

Ostro, S. J. (1978). The structure of Saturn's rings and the surfaces of the Galilean satellites as inferred from radar observations. Ph.D. thesis, Massachusetts Institute of Technology, Cambridge.

Pettengill, G. H. (1978). Physical properties of the planets and satellites from radar observations. *Ann. Rev. Astron. Astrophys.* **16**, 265–292.

Pettengill, G. H., Ostro, S. J., Shapiro, I. I., Campbell, D. B., and Marsden, B. G. (1979). Radar observations of asteroid 1580 Betulia. *Icarus* **40**, 350–354.

Taylor, R. C., Gehrels, T., and Capen, R. C. (1976). Minor planets and related objects. XXI. Photometry of eight asteroids. *Astron. J.* **81**, 778–785.