DRA

February 1984

CORNELL UNIVERSITY

Center for Radiophysics and Space Research

(NASA-CR-175348) RADAR INVESTIGATIONS OF ASTEROIDS (Cornell Univ.) 28 p HC A03/MF A01 CSCL 03B

N84-17100

Unclas

G3/91 18242

CA, N.Y.

[redacted]

A RESEARCH PROPOSAL
SUBMITTED TO THE
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

for

Renewed Support of NASA Grant NAGW-116

RADAR INVESTIGATION OF ASTEROIDS

July 1, 1984 - June 30, 1985

Principal Investigator: Prof. Steven J. Ostro

[redacted]

CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY
ITHACA, NEW YORK 14853

RESEARCH PROPOSAL
for
Renewed Support of NASA Grant NAGW-116

"Radar Investigations of Asteroids"

Date:	February, 1984
Submitted to:	National Aeronautics and Space Administration
Submitted by:	Cornell University Ithaca, New York 14853
Principal Investigator:	Dr. Steven J. Ostro Assistant Professor, Center for Radiophysics and Space Research SSN: [redacted] Tel: (607) 256-3508
Requested Period of Support:	July 1, 1984 through June 30, 1985
Total Funds Requested:	$35,000

Endorsements:

Principal Investigator — Steven J. Ostro

Director, Center for Radiophysics and Space Research — E. E. Salpeter

Assistant Director, Office of Sponsored Programs (607) 256-5014 — Peter A. Curtiss

TABLE OF CONTENTS

ABSTRACT

This is a proposal for renewal of NASA Grant NAGW-116 in support of radar investigations of asteroids, including observations during 1984-1985 of at least 8 potential targets and continued analyses of radar data obtained during 1980-1984 for 30 other asteroids. The proposed research involves small (~ 1 km), Earth-approaching objects (e.g., 2101 Adonis, 1862 Apollo, and 1983 TB) as well as much larger (~ 100 km) mainbelt minor planets (e.g., 747 Winchester, 7 Iris, 12 Victoria, 16 Psyche, 80 Sappho, and 554 Peraga). The primary scientific objectives include estimation of echo strength, polarization, spectral shape, spectral bandwidth, and Doppler shift. These measurements yield estimates of target size, shape, and spin vector; place constraints on topography, morphology, density, and composition (e.g., metal content) of the planetary surface; yield refined estimates of target orbital parameters; and can reveal the presence of asteroidal satellites.

INTRODUCTION AND SUMMARY OF CURRENT RESEARCH

Asteroid science possesses the potential for critical contributions to our understanding of the origin and evolution of the solar system. The distributions of asteroidal spin rates and physical dimensions measured for ~ 10% of the ~ 3000 catalogued minor planets span several orders of magnitude. Asteroidal compositions are expected to be at least as diverse as our current meteorite sample, and existing groundbased VIS/IR data support this view. Broadband VIS/IR parameters (e.g., color indices and geometric albedo) measured for asteroids have been sorted into nine taxonomic types (C, S, M, etc.; see Gradie and Tedesco, 1982, and Zellner, 1979), and high-resolution (24-color) VIS/IR reflectance spectroscopy, which is more directly diagnostic of surface mineralogy (Gaffey and McCord, 1978, 1979), has revealed ~ 80 spectral types among 277 observed asteroids (Chapman and Gaffey, 1979). Certainly each asteroid is a unique planetary body deserving intensive individual study. However, with very few exceptions, fundamental physical properties (sizes, shapes, sidereal rotation periods, pole directions, and compositions) are not well known.

Radar observations achieve spatial resolution of a planetary target in a manner that is independent of the target's apparent angular size and hence provide a powerful ground-based tool for investigating asteroids, which generally remain unresolved by optical telescopes. Furthermore, by virtue of the wavelengths employed, radar can furnish unique information about (i) surface structure at scales (~ 10^{-2} to ~ 10 meters) much larger than the scales probed by optical polarimetry, but much smaller than typical asteroid dimensions; and (ii) compositional parameters (e.g., volume fractions of metal, rock, and vacuum) that are only weakly constrained by VIS/IR methods.

Asteroid radar detections

Efforts by the principal investigator to apply the Arecibo Observatory's powerful S-band (2380-MHz, 13-cm-wavelength) radar system to the study of asteroids have met with considerable success. Since 1980, observations supported by NASA Grant NAGW-116 have resulted in the detection of strong echoes from 20 asteroids. (Additionally, useful upper limits have been set on the radar reflectivities of nine other minor planets). In contrast with these results, only six minor planets had been detected with radar during 1968-79. As shown in Table I, asteroids comprise 24 of the 37 radar-detected planetary objects.

RADAR-DETECTED PLANETARY TARGETS*

Year of first detection	Asteroids (Main-Belt)	Ref.	Asteroids (Earth-Approaching)	Ref.	Other Objects
1946					Moon
1961-1963					Venus, Mercury, Mars
1968-1979	1 Ceres	5	1566 Icarus	1	Saturn's Rings
	4 Vesta	6	1685 Toro	2	Ganymede
			433 Eros	3	Callisto
			1580 Betulia	4	Europa
					Io
1980	7 Iris	9	1862 Apollo	9	Comet Encke
	16 Psyche	9			
1981	97 Klotho	9	1915 Quetzalcoatl	9	
	8 Flora	9	2100 Ra-Shalom	8	
1982	2 Pallas	9			Comet Grigg-Skjellerup
	12 Victoria	9			
	19 Fortuna	9			
	46 Hestia	9			
1983	5 Astraea	9	1620 Geographos	9	Comet Iras-Araki-Alcock
	139 Juewa	9	2201 Oljato	9	Comet Sugano-Saigusa-Fujikawa
	356 Liguria	9			
	80 Sappho	9			
	694 Ekard	9			

TOTALS: 24 Asteroids (15 M-B, 9 E-A)
4 Comets
4 Galilean Satellites
4 Terrestrial objects
1 Ring system

37 Planetary targets

* Dual-polarization observations of Vesta[9] and Toro[7] were first carried out in 1980-81. In addition to the above detections, the 1980-83 observations yield upper limits[9] on the radar cross sections of asteroids 11 Kalliope, 75 Eurydike, 132 Aethra, 216 Kleopatra, 219 Thusnelda, 471 Papagena, 699 Hela, 1865 Cerberus, and 2340 Hathor.

1. Goldstein (1969), Icarus 10, 430; Pettengill et al. (1969), Icarus 10, 432.
2. Goldstein et al. (1973), Astron. J. 78, 508.
3. Jurgens and Goldstein (1976), Icarus 28, 1; Campbell et al. (1976), Icarus 28, 17.
4. Pettengill et al. (1979), Icarus 40, 350.
5. Ostro et al. (1979), Icarus 40, 355.
6. Ostro et al. (1980), Icarus 43, 169.
7. Ostro et al. (1983), Astron. J. 88, 565.
8. Ostro et al. (1984), Icarus, submitted.
9. Ostro et al., in preparation.

The following recent results of research supported under this grant illustrate the various types of contributions that radar investigations can make to asteroid science:

Orbital parameters

Radar detecton of an asteroid always provides an estimate of the echo Doppler shift and/or time delay. Either quantity can be used to refine existing values for orbital parameters. Errors in predicted orbits occasionally are severe: Radar observations of the Earth-approaching asteroid 1862 Apollo revealed the predicted distance to be wrong by 3230 km. Similar circumstances are anticipated for 2101 Adonis and 1983 TB.

Spin vectors

If a nearly monochromatic (CW) signal is transmitted toward a rotating asteroid, the echo will be Doppler broadened to a bandwidth, $B = (4\pi D/\lambda P) \cos \delta$, where P is the synodic rotation period, δ is the astrocentric declination of the radar, and D is the breadth in the direction of Earth of the asteroid's polar silhouette. For a sphere, D would be the diameter. Asteroidal shapes are poorly known, but they are probably not spherical and may often be quite irregular. As discussed by Ostro et al. (1983b), the proper interpretation of D depends on a priori knowledge of both the spin vector and the rotational phase coverage provided by the echo spectrum used to estimate the bandwidth, B. Given B, one can estimate one of the variables, D, P, or δ if the remaining two have been estimated independently.

Prior to the radar observations of Astraea, estimates of this mainbelt asteroid's diameter and rotation period yielded an expression, $B = (190 \pm 8) \cos \delta$, for the echo bandwidth (Hertz). Taylor's (1978) estimate for the pole direction predicted that $\delta = 77° \pm 4°$ and $B = 43 \pm 15$ Hz. However, Astraea's radar spectrum (Fig. 1) yields $B = 220 \pm 50$ Hz, corresponding to $\delta = 0° \pm 27°$. In other words, the radar view of Astraea must have been nearly equatorial, contrary to the prediction (based on Taylor's analysis of optical lightcurves) that the view would be nearly pole-on.

Sizes and shapes

Variations in spectral bandwidth as a function of rotational phase (Φ) can provide constraints on the convex hull of an asteroid's polar silhouette (Ostro and Connelly, 1984). For example, Fig. 2 illustrates the several-fold variation in the bandwidth of Geographos' echo spectrum, supporting inferences from optical lightcurves that this is an unusually distended object. Figure 3 graphically demonstrates constraints on the size, shape, and orientation of 2100 Ra-Shalom derived by combining radar, photoelectric, and infrared radiometric data (Ostro et al., 1984).

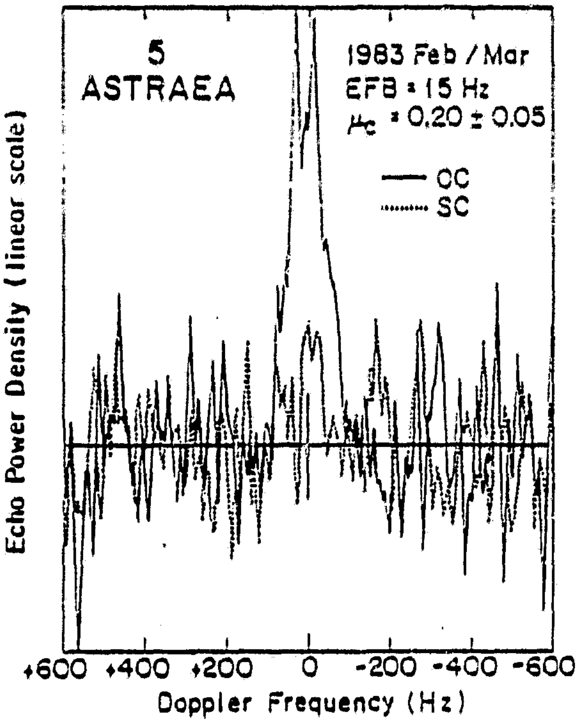


FIGURE 1

Average OC and SC echo power spectra for 5 Astraea, smoothed to a resolution (i.e., effective filter bandwidth, EFB) of 15 Hz. Echo power density is plotted vs. Doppler frequency. Zero Doppler corresponds to the a priori shift of the target center of mass.

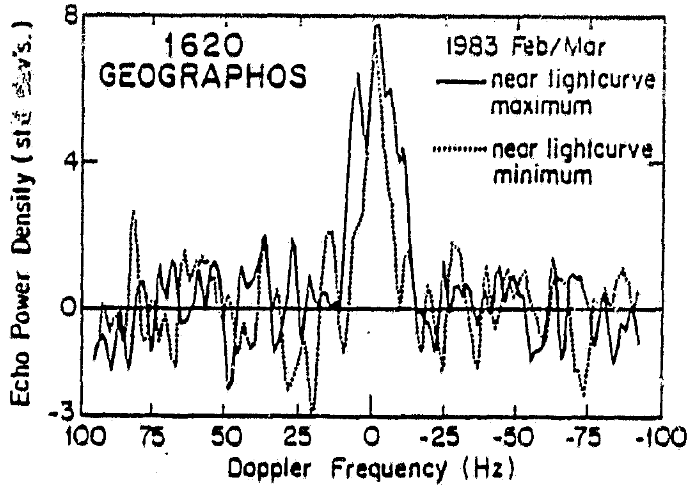


FIGURE 2

OC echo power spectra for 1620 Geographos, obtained at rotation phases within about 30° of extremes of optical brightness.

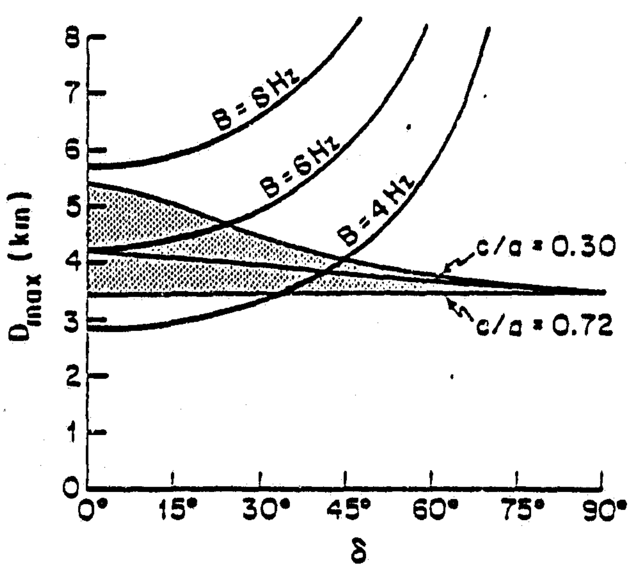


FIGURE 3

Constraints on the size, shape, and pole direction of 2100 Ra-Shalom. D_{max} is the maximum breadth of the asteroid's polar silhouette and δ is the absolute value of the mean subradar latitude in Aug 1981. The heavy curves plot D_{max} vs. δ for three values of the echo bandwidth, B, assuming a synodic rotation period of 19.79 h. Modelling Ra-Shalom as an ellipsoid with semiaxis lengths $c \leq b \leq a = D_{max}/2$, we calculate D_{max} as a function of δ for three values of c/a, assuming b/a = 0.72.

Asteroidal satellites?

Several authors have argued that certain lightcurves, stellar-occultaton profiles, and speckle-interferometric results indicate the existence of asteroidal satellites (e.g., Van Flandern et al., 1979). Theoretical considerations do not preclude the existence of multiple asteroids, and even suggest that collisional processes may have bestowed companions on ~ 10% of the mainbelt minor planets (Hartmann, 1979; Chapman et al., 1980). Nevertheless, whereas the binary-asteroid hypothesis provides an interesting, credible explanation for various peculiar observational results, this hypothesis has not been proved for any asteroid.

The possiblility that 2 Pallas might be accomanied by a large satellite (diameter, d ~ D/6 to D/3, D = 538 km = Pallas' diameter) was suggested by Hege et al. (1980; see also Kerr, 1981) on the basis of speckle interferometry. Echoes from such a large satellite with a specified orbit should be detectable in the Pallas radar data. However, no evidence has been found for echoes from a satellite in a (tidally evolved) synchronous equatorial orbit about Pallas (Showalter et al., 1982; Showalter and Ostro, 1984). The radar data establish a five-standard-deviation upper limit on the radar cross section of such an object, corresponding under reasonable assumptions about its radar scattering behavior to an upper limit $d \leq 130$ km $< D/4$, on the satellite's diameter.

Surface structure

The delay and/or Doppler dispersion of a radar echo depends on the target asteroid's gross shape and its surface structure (which determines its angular scattering law, i.e., the degree of limb darkening). Although the tight coupling between these two factors precludes precise statements about the angular scattering law of radar-detected asteroids, it is apparent that asteroid radar echoes lack the sharply peaked spectral signature of the "quasispecular" radar targets (the Moon, Mercury, Venus, and Mars). This result requires that asteroidal surfaces be rough at some scales(s) at least as large as several centimeters.

The scale of this roughness can be elucidated by an estimate of the circular polarization ratio μ_C, of echo power received in the same sense of circular polarization as transmitted (i.e., the SC sense) to that received in the opposite (OC) sense. This ratio would be zero for single-reflection, coherent backscattering from smooth surface elements, but would increase toward unity with increasing multiple scattering and/or surface roughness. (For the Moon, $\mu_C \approx 0.1$.) Estimation of μ_C is largely immune to systematic (e.g., antenna calibration) errors and is independent of the target's size, shape, and orientation.

So far, the NASA-supported radar observations have generated estimates of the circular polarization ratio for 18 minor planets. The results (Fig. 4) suggest that μ_C depends on target size and taxonomic type. Weighted mean values of μ_C span the ranges 0.14-0.33, 0.08-0.20, and 0.00-0.13 for small Earth-approaching

ORIGINAL PAGE IS
OF POOR QUALITY

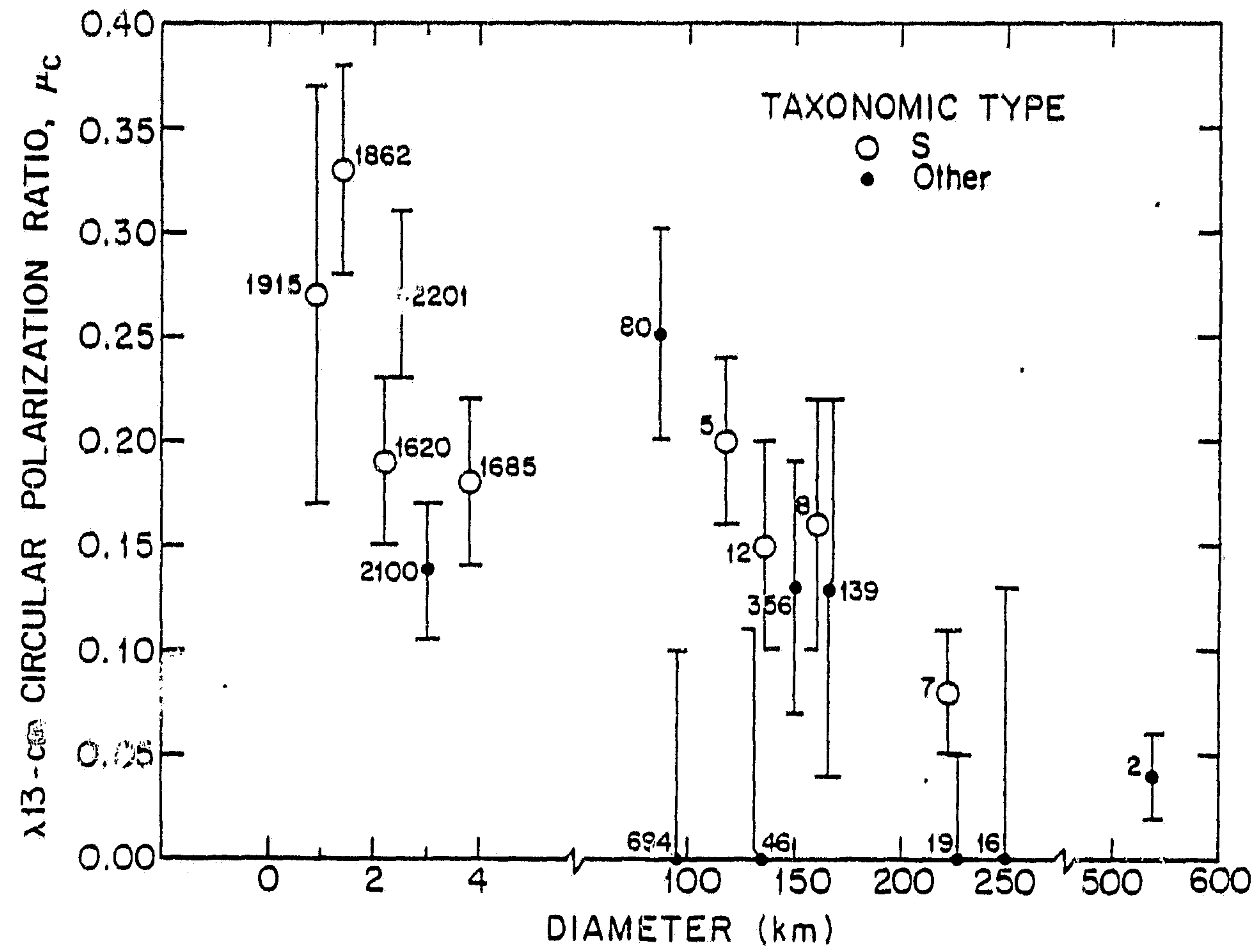


FIGURE 4

The circular polarization ratio μ_c, of echo power received in the same sense of circular polarization as transmitted (i.e., the SC sense) to that received in the opposite (OC) sense, is plotted vs. diameter for radar-detected asteroids. The error bars represent plus and minus one standard deviation of the uncertainty in the ratio estimates. Except for 2201, 80 and 2, the non-S-type objects are all type C.

ORIGINAL PAGE IS
OF POOR QUALITY

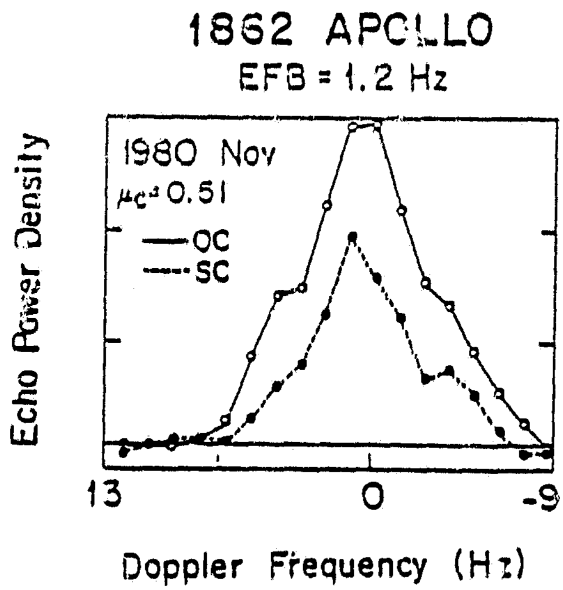
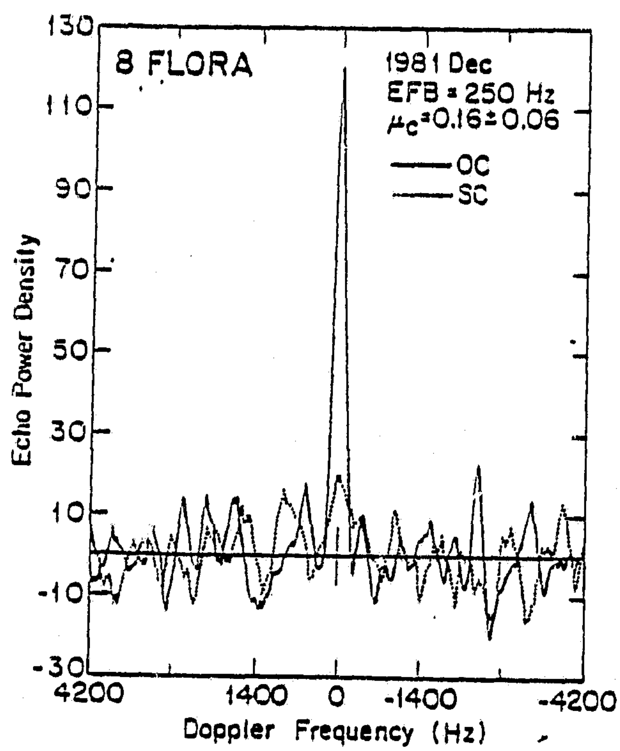
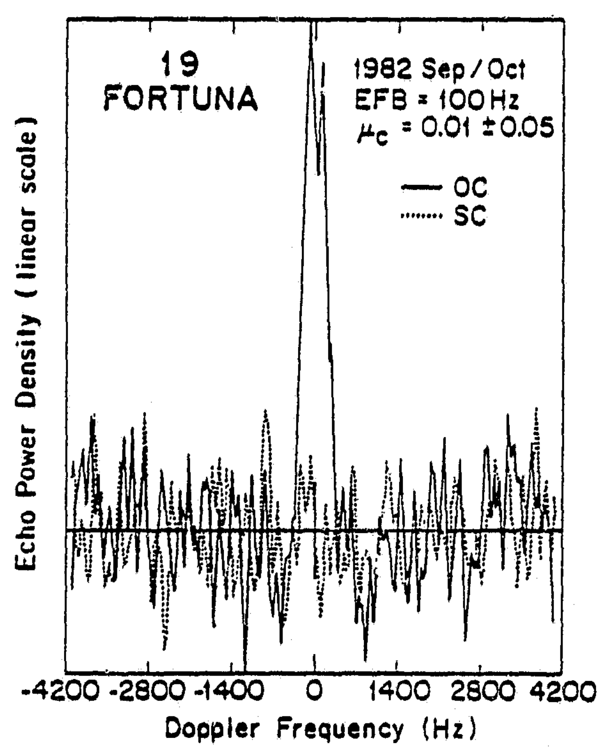


FIGURE 5

OC and SC echo power spectra for the small, Earth-approaching asteroid Apollo; the S-type mainbelt asteroid Flora, and the C-type mainbelt asteroid Fortuna. These objects' circular polarization ratios, , decrease in the stated order, indicating decreasing degrees of near-surface, decimeter-scale roughness. The Apollo spectrum samples about 15° of rotational phase, whereas the mainbelt-asteroid spectra represent more global averages.





objects, S-type mainbelt objects, and C-type mainbelt objects respectively. Figure 5 shows echo spectra of representatives of these three groups. Values of μ_C near zero require that the echo be due to single reflections from surfaces that are smooth at centimeter-to-meter scales, whereas values $\gtrsim$ 0.2 suggest substantial multiple scattering and/or near-surface roughness. If the trend in the existing data is representative of the asteroid population, then it demonstrates that asteroids differ widely in degree of near-surface, decimeter-scale structure. This situation could arise from gravitational or compositional control of regolith formation, but could also reflect the collisional evolution of major dynamical classes of asteroids.

Surface composition and porosity

Given sufficient information about target size and shape, measurements of radar cross section, spectral shape, and μ_C can be used to approximate R, the normal-incidence Fresnel power refleciton coefficient (Ostro et al., 1983b). R is a function of the radar-frequency electrical properties of the surface material, and depends on both composition and porosity.

For example, the VIS/IR reflectance spectrum of 1685 Toro suggests a mineralogy similar to L-chondritic meteorites (Chapman et al., 1973). Since the electrical properties of several L chondrites have been determined, the radar data (Ostro et al., 1983b) provide an estimate of the porosity (~ 50%) of Toro's regolith.

Optical and infrared reflectance spectra show that M-type asteroids such as Psyche have free Fe/Ni metal on their surfaces. If these objects are made entirely of metal, they are probably remnants of the cores of much larger objects which differentiated and cooled before they were fragmented in collisions. However, optical and infrared observations are insensitive to subsurface composition, and cannot distinguish free metal from a mixture of free metal and neutral silicates. Psyche's radar albedo is the highest measured for any asteroid, but is much lower than that expected for a pure metallic object.

The electrical properties of metal-plus-silicate particulate mixtures at the Arecibo radar frequency are needed to deduce meaningful constraints on the composition of asteroids whose regoliths contain free metal. As these data do not exist in the literature, the principal investigator has undertaken the necessary measurements. Pilot experiments involving various weight fractions of metal were conducted during 1982-1983. The results indicate that R depends on both density and metal fraction, at least for the particle-size distributions investigated ($\lesssim$ 40 μm). If Psyche's regolith is characterized by a similar distribution, then the combination of the radar and laboratory experimental results favor an enstatite chondritic (rather than metallic) surface mineralogy, unless the near-surface density is less than 1 g cm^{-3}.

DESCRIPTION OF THE PROPOSED RESEARCH

Observations

The radar characteristics of asteroids might well be as variegated as their VIS/IR properties. The success of the recent radar observations argues for application of similar techniques to additional minor planets to establish a statistical base for taxonomic classification, to permit correlation with results from other techniques, and to strengthen physical interpretation of the experimental results.

Support is requested to conduct radar observations of asteroids 6 Hebe, 7 Iris, 111 Ate, 144 Vibilia, 554 Peraga, 747 Winchester, 2101 Adonis, and 1983 TB. Each potential target is expected to be detectable at or above the five-standard-deviation level in a single night (< 3 hours), and rarely reaches apparitions as favorable as that in 1984-85. With the sole exception of Iris, none of these objects has previously been observed with radar.

The mainbelt objects include three C-types (144, 554, 747) and three S-types (6, 7, 111). The two Earth-approaching asteroids (2101, 1983 TB) have yet to be classified.

High-resolution reflection spectra (Gaffey and McCord, 1979) show Peraga to be VIS/IR spectral type TA, possibly indicating a mineralogy analogous to that of the most primitive carbonaceous chondritic meteorites. Vibilia's spectrum is unique among the 277 obtained by Chapman and Gaffey (1979).

Both Hebe and Euterpe are spectral types RA-2, possibly indicative of metal grains with relatively large (> cm) dimensions (Gaffey, 1983). Hebe is "located" close to the ν_6 secular resonance, which can interact with planetary encounters to perturb collision fragments into Earth-crossing orbits (Wetherill, 1977). Hence, Hebe is a prime candidate for a parent body of metal-rich meteorites.

1983 TB, discovered by the Infrared Astronomy Satellite (IRAS) last October, has the same orbit at the Geminids (Waldrop and Kerr, 1983) and probably is the (now extinct) cometary progenitor of those meteors.

The proposed observations will attempt to achieve the following experimental objectives for each asteroid:

1. Detection of the target; measurement of absolute Doppler shift, OC and SC radar cross sections and circular polarization ratio.
2. Measurement of the full spectral bandwidth, B, and characterization of the spectral shape of the echo.
3. Exploration of the dependence of the asteroid's radar signature on rotational phase.

These objectives will be pursued using a simple CW waveform. If echo strength is sufficiently high (as is expected for at least Adonis and Iris), phase-coded CW observations will be carried out to resolve the echoes in delay, permitting determination of target distance and direct measurement of target radius. An accurate estimate of radius, whether from radar observations or independent methods, is necessary for reliable estimation of intrinsic reflectivity (i.e., geometric albedo).

Data analyses

Support is requested for continued analysis and interpretation of the asteroid radar data obtained since 1980.

Although echo power spectra and average, disc-integrated quantities (e.g., radar cross section, circular polarization ratio, geometric albedo, echo bandwidth, Doppler center frequency) obtained for most of the asteroids detected since 1980 will have been reported in the literature by mid-1984, more extensive studies of variations of radar properties with rotational phase are warranted for those targets yielding strong echoes. Each of the radar-observed asteroids poses a distinctly individual array of interpretive problems corresponding to the particular prior constraints on its physical properties that are available from VIS/IR observations. Partially due to efforts by the principal investigator, optical lightcurves have now been obtained in tandem with radar observations of most post-1981 targets.

For targets yielding echoes with high signal-to-noise ratios (especially Apollo, Pallas, Iris, Victoria, and Sappho), the radar data sets are enormous, and interpretation of data becomes an iterative, bootstrapping operation. At the other extreme, data yielding marginal detections or non-detections (e.g., Kalliope, Eurydike, and Kleopatra) must be analyzed exhaustively to ensure assignment of accurate, useful, upper limits on radar cross section.

Objectives of the proposed analyses include:

1. Definition and statistical classification of the radar properties (geometric albedo, circular polarization ratio, and spectral shape) of detected asteroids.
2. Combination of rotation-phase-resolved radar data with optical lightcurves and IR fluxes to constrain target dimensions and to assess the heterogeneity of surface properties.
3. Complete reduction of ranging data obtained for Apollo, Iris, Geographos, and Oljato.
4. Prediction of all favorable opportunities for Arecibo radar detection of asteroids (including newly discovered Earth-approaching objects) through the end of this century.

Laboratory measurements

Support is requested for laboratory measurements of the electrical properties (dielctric permittivity and loss tangent) of metal-plus-silicate powdered mixtures. The proposed experiments are designed to examine the possible dependence of these properties on particle-size distribution, and will further elucidate coupling between density and metal weight fraction. When coupled with radar albedo estimates, these data will provide unique constraints on (i) modern theories of asteroid regolith evolution and (ii) mineralogical interpretations of VIS/IR reflection spectra. The proposed measurements will be performed by W. Westphal at MIT on a fee-for-service basis.

PAGES 18 and 19 REMOVED BY DOCUMENT EVALUATOR
BECAUSE OF FUNDING INFORMATION

REFERENCES

Chapman, C. R., and M. J. Gaffey (1979). Reflectance spectra for 277 asteroids. In Asteroids (T. Gehrels, ed.), Univ. of Arizona Press, Tucson.

Chapman, C. R., D. R. Davis, and S. J. Weidenschilling (1980). Creation and destruction of multiple asteroids. Bull. Amer. Astron. Soc. 12, 662.

Chapman, C. R., T. B. McCord, and C. Pieters (1973). Minor planets and related objects. X. Spectrophotometric study of the composition of (1685) Toro. Astron. J. 78, 502.

Gaffey, M. J. (1983). Private communication.

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

Gaffey, M. J., and T. B. McCord (1979). Mineralogical and petrological characterizations of asteroid surface material. In Asteroids (T. Gehrels, ed.), Univ. of Arizona Press, Tucson.

Gradie, J., and E. Tedesco (1982). Compositional structure of the asteroid belt. Science 216, 1405.

Hartmann, W. K. (1979). Diverse puzzling asteroids and a possible unified explanation. In Asteroids (T. Gehrels, ed.), Univ of Arizona Press, Tucson.

Hege, E. K., W. J. Cooke, and E. N. Hubbard (1980). Possible secondaries of asteroids found by speckle interferometry. Bull. Amer. Astron. Soc. 12, 662.

Kerr, R. A. (1981). Satellites of asteroids coming into vogue. Science 211, 1333.

Ostro, S. J., and R. Connelly (1984). Convex profiles from asteroid lightcurves. Icarus 55, in press.

Ostro, S. J., A. W. Harris, D. B. Campbell, I. I. Shapiro, and J. W. Young (1984b). Radar and photoelectric observations of asteroid 2100 Ra-Shalom. Submitted to Icarus.

Ostro, S. J., D. B. Campbell, and I. I. Shapiro (1983a). Radar detection of Astraea, Victoria, Fortuna, Hestia, Juewa, Geographos, and Oljato. Bull. Amer. Astron. Soc., 15, 823.

Ostro, S. J., D. B. Campbell, and I. I. Shapiro (1983b). Radar observations of asteroid 1685 Toro. Astron. J., 88, 565-576.

Ostro, S. J., D. B. Campbell, and I. I. Shapiro (1981). Radar detection of Apollo, Iris, Klotho, Psyche, and Quetzalcoatl. Bull. Amer. Astron. Soc. 13, 716.

Ostro, S. J., D. B. Campbell, G. H. Pettengill, and I. I. Shapiro. (1980). Radar detection of Vesta. Icarus 43, 169.

Ostro, S. J., D. B. Campbell, I. I. Shapiro and G. R. Olhoeft (1983). Asteroid surface properties. Bull. Amer. Astron. Soc. 15, 823.

Ostro, S. J., D. B. Campbell, I. I. Shapiro, and M. R. Showalter (1982). Radar detection of 2 Pallas, 8 Flora, and 2100 Ra-Shalom. Bull. Amer. Astron. Soc. 14, 725.

Ostro, S. J., G. H. Pettengill, I. I. Shapiro, D. B. Campbell, and R. R. Green (1979). Radar observations of asteroid 1 Ceres. Icarus 40, 355-358.

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

Showalter, M. R., and S. J. Ostro (1984). Radar detectability of asteroidal satellites. In preparation.

Showalter, M. R., S. J. Ostro, I. I. Shapiro, and D. B. Campbell (1982). Upper limit on the radar cross section of a Pallas satellite. Bull. Amer. Astron. Soc. 14, 725.Taylor, R. C. (1978). Minor planets and related objects. XXIV. Photometric observations for (5) Astraea. Astron. J. 83, 201-204.

Van Flandern, T. C., E. F. Tedesco, and R. P. Binzel (1979). Satellites of asteroids. In Asteroids (T. Gehrels, ed.), Univ. of Arizona Press, Tucson.

Waldrop, M. M., and R. A. Kerr (1983). IRAS Science Briefing, Science 222, 916-917.

Wetherill, G. W. (1977). Fragmentation of asteroids and delivery of fragments to Earth. In Comets, Asteroids, Meteorites (A. H. Delsemme, ed.), Univ. of Toledo Press, Toledo, Ohio, pp. 283-291.

Zellner, B. (1979). Asteroid taxonomy and the distribution of the compositional types. In Asteroids (T. Gehrels, ed.), Univ. of Arizona Press, Tucson.

VITA

Steven J. Ostro

CURRENT POSITION:	Assistant Professor of Astronomy, Cornell University
ADDRESS:	Space Sciences Building Cornell University Ithaca, New York 14853 Telephone: (607) 256-3508
DATE AND PLACE OF BIRTH:	[redacted]
ACADEMIC DEGREES:	B.S. Ceramic Science, Rutgers University, 1969 A.B. Liberal Arts, Rutgers University, 1969 M. Eng'g. Engineering Physics, Cornell University, 1974 Ph.D. Planetary Sciences, Massachusetts Institute of Technology, 1978
EMPLOYMENT:	Assistant Professor of Astronomy, Cornell, 1979 to present Postdoctoral Research Associate, MIT, 1978-1979 Research Ceramist, Corning Glass Works, 1970-1971
PROFESSIONAL SOCIETIES:	Division for Planetary Sciences of the American Astronomical Society American Geophysical Union Meteoritical Society American Association for the Advancement of Science

BIBLIOGRAPHY
Steven J. Ostro

1. The Structure of Saturn's Rings and the Surfaces of the Galilean Satellites as Inferred from Radar Observations. S. J. Ostro. MIT, Ph.D. Dissertation (1978).

2. Galilean Satellites: 1976 Radar Results. D. B. Campbell, J. F. Chandler, S. J. Ostro, G. H. Pettengill, and I. I. Shapiro. Icarus 34, 254 (1978).

3. Icy Craters on the Galilean Satellites? S. J. Ostro and G. H. Pettengill. Icarus 34, 268 (1978).

4. Radar Observations of Asteroid 1580 Betulia. G. H. Pettengill, S. J. Ostro, I. I. Shapiro, B. G. Marsden, and D. B. Campbell, Icarus 40, 350 (1979).

5. Radar Observations of Asteroid 1 Ceres. S. J. Ostro, G. H. Pettengill, I. I. Shapiro, D. B. Campbell, and R. R. Green. Icarus 40, 355 (1979).

6. Radar Observations of Saturn's Rings at Intermediate Tilt Angles. S. J. Ostro, G. H. Pettengill, and D. B. Campbell. Icarus 41, 381 (1980).

7. Radar Detection of Vesta. S. J. Ostro, D. B. Campbell, G. H. Pettengill, and I. I. Shapiro. Icarus 43, 169 (1980).

8. Radar Observations of the Icy Galilean Satellites. S. J. Ostro, D. B. Campbell, G. H. Pettengill, and I. I. Shapiro. Icarus 44, 431 (1980).

9. Delay-Doppler Radar Observations of Saturn's Rings. S. J. Ostro, G. H. Pettengill, D. B. Campbell, and R. M. Goldstein. Icarus 49, 367 (1982).

10. Comet Encke: Radar Detection of Nucleus. P. G. Kamoun, D. B. Campbell, S. J. Ostro, G. H. Pettengill, and I. I. Shapiro. Science 216, 293 (1982).

11. Radar Properties of Europa, Ganymede, and Callisto. S. J. Ostro. In Satellites of Jupiter, edited by D. Morrison, Univ. of Arizona Press, p. 213 (1982).

12. Dual-Polarization Radar Observations of Mars: Tharsis and Environs. J. K. Harmon, D. B. Campbell, and S. J. Ostro. Icarus 52, 171 (1982).

13. Planetary Radar Astronomy. S. J. Ostro. Rev. Geophys. Space Phys. 21, 186 (1983).

14. Radar Observations of Asteroid 1685 Toro. S. J. Ostro, D. B. Campbell, and I. I. Shapiro. Astron. J. 88, 565 (1983).

15. Asteroid Radar Astronomy. S. J. Ostro. Minor Planet. Bull. 10, 10 (1983).

16. Review of Formation of Planetary Systems (A. Brahic, Ed.), S. J. Ostro, Icarus 55, 498 (1983).

17. Glass on the Surfaces of Io and Amalthea. J. Gradie, S. J. Ostro, P. C. Thomas, and J. Veverka. In Glass in Planetary and Geological Phenomena (L. D. Pye, Ed.), North Holland, in press (1984).

18. A Review of Radar Observations of Saturn's Rings. S. J. Ostro and G. H. Pettengill. In Planetary Rings, edited by A. Brahic, Centre National d'Etudes Spatiales, Toulouse, France, in press (1984).

19. Convex Profiles from Asteroid Lightcurves. S. J. Ostro and R. Connelly. Icarus 57, in press (1984).

20. Radar and Photoelectric Observations of Asteroid 2100 Ra-Shalom. S. J. Ostro, A. W. Harris, D. B. Campbell, I. I. Shapiro, and J. W. Young. Submitted to Icarus (1984).

21. Ellipsoids and Lightcurves. R. Connelly and S. J. Ostro. In preparation for submission to Geometriae Dedicata (1984).

22. Dual-Polarization Radar Observations of Mars: 1982 Opposition. J. K. Harmon and S. J. Ostro. In preparation for submission to Icarus (1984).

23. Radar Detectability of Asteroidal Satellites. M. R. Showalter and S. J. Ostro. In preparation for submission to Icarus (1984).

24. Radar Observations of Main-Belt Asteroids. S. J. Ostro, D. B. Campbell, and I. I. Shapiro. In preparation for submission to Science (1984).

25. Radar-Frequency Electrical Properties of Metal-Plus-Silicate Particulate Mixtures. S. J. Ostro. In preparation for submission to Meteoritics (1984).