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THE MICROWAVE SPECTRA OF THE ASTEROIDS PALLAS, VESTA, AND HYGIEA

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ABSTRACT

Microwave observations of Pallas, Vesta, and Hygiea at 2 and 6 cm wavelength yield brightness temperatures that are much lower than would be expected for a rapidly rotating blackbody. An analysis of the wavelength dependence of the observed brightness temperatures shows that, as was found for Ceres, these asteroids may be covered by a layer of material with the physical properties of finely divided dust. Models with layer depths of greater than 6 cm (Pallas), 6 cm (Vesta), and 8 cm (Hygiea) were found to represent well the variation in emissivity at radio wavelengths. The properties of the underlying layer are not well constrained by the microwave observations. It does appear that the real part of the dielectric vector for the substrate is similar to that of basaltic rock. Major compositional changes, if any, must take place at depths greater than about 10 cm. No evidence for water ice was found. Disk-resolved observations of the 2 cm emission of Vesta yield physical dimensions consistent with the recently published speckle-interferometry results.

I. INTRODUCTION

Observations of the centimeter wavelength emission of asteroids have mostly been limited to the asteroid Ceres, due to the intrinsic weakness of the emission. At 6 cm wavelength, the flux density of Ceres is, at most, 1 mJy, while the flux density of Vesta is at most 0.4 mJy. Prior to 1980, only antennas similar to the 100 m antenna of the Max Planck Institute for Radio Astronomy at Effelsberg, West Germany, had sufficient pointable collecting area to accomplish the detection of centimeter wavelength emission from asteroids smaller than Ceres.

By January of 1980, Ceres had been observed at 3.3 mm and 2 cm wavelength, Vesta at 3.3 mm, and Euphrosyne and Bamberga at 2 cm (Dickel 1979). In addition, some longer-wavelength observations of Ceres with modest signal-to-noise ratio were available (Briggs 1973; Andrew 1974). With the advent of the Very Large Array (VLA) of the National Radio Astronomy Observatory, it has become possible to observe the larger asteroids at wavelengths of several centimeters with sufficient signal-to-noise ratio to analyze the resulting continuum spectra for surface properties.

Previously (Webster *et al.* 1988), we have reported on the continuum spectrum of Ceres. In this paper, we discuss observations of Pallas, Vesta, and Hygiea. The continuum spectra are analyzed using the same techniques employed in our analysis of the Ceres spectrum, i.e., vector interpolation in a statistical universe of model microwave spectra and formal inversion of the spectra for physical properties. Although the data are much less extensive than for our analysis of Ceres, we have been able to derive models for the surface layers and establish some bounds on the depth of the surface layer and the dielectric properties of the material. In addition, we have obtained a well-resolved image of the 2 cm emission of Vesta which allows us to examine the uniformity of the emission.

II. OBSERVATIONS

The observations reported here were obtained with the VLA in either the A (maximum spacing 35 km) or B (maximum spacing 11.1 km) configurations at wavelengths of 6.14 or 2.0 cm between December 1981 and November 1986. All available antennas (usually 27) were used. The flux-density scale was established by assuming the flux density of 3C 286 to be 7.41 and 3.44 Jy at 6.14 and 2.0 cm, respectively (Baars *et al.* 1977). Before August 1983, the observing bandwidth was 50 MHz; after this time, 100 MHz was used.

The positions of the asteroids were calculated for epoch of date and tracked by phase shifting using standard VLA on-line software. In addition, the pointing of the individual antennas was updated at frequent intervals to avoid attenuation of the signals by the primary beam of the 25 m antennas. Two 5 min observations of the asteroids were followed by one 5 min observation of a compact extragalactic source positioned as close as possible on the sky (usually within 15°) to the asteroid. The observations of the extragalactic sources were used for phase and amplitude calibration of the array and to make first-order corrections for the effect of the atmosphere. This sequence of observations was continued for about 8 hr, except in the case of the July–August 1985, where 2 cm data of about 4 hr duration were obtained.

The calibrated amplitudes and phases were naturally weighted and Fourier transformed to produce images of the brightness distribution on the sky. The resulting maps were "cleaned" using the standard VLA clean algorithm. A minimum of three cells was spanned by the synthesized beam. Due to the intrinsic weakness of the signals, we could not employ the self-calibration procedures normally used with strong sources. Because of this and because we were forced to observe at declinations that were as low as $-30°$, local meteorological conditions are a significant factor in our signal-to-noise ratios. Also, although confusion by background sources is not a problem at 2 cm, scattered emission due to (nonmoving) background sources at 6 cm can decrease the signal-to-noise ratio substantially. Because we employ phase tracking to follow the moving asteroids, weak background sources will produce patches of emission extended in the direction of asteroid motion. Since the asteroid signals are typically 100–500 mJy, we carefully inspected the images for the effect of this emission on the weak asteroidal signals.

The observations are given in Table I. The normalized brightness temperatures are for a heliocentric distance corresponding to the semimajor axis of the asteroid's orbit. Flux densities were measured from the maps by summing the flux density in a box on the image which contained all the asteroidal signal. As a check, a Gaussian was also fit to the observed brightness distribution to determine a flux density. This consistency test allowed us to assess the effect of any low-level errors that might be present in the data.

III. RESULTS AND ANALYSIS

The calculation of the brightness temperatures is dependent on a knowledge of the asteroidal diameters. Since the span of wavelengths is not great enough to analyze the flux densities by themselves and since Webster and Johnston (1988) have shown that the apparent emissivity at radio wavelengths can be as much as 25% less than in the infrared, we are forced to analyze the brightness temperatures themselves. In the case of Pallas, we have adopted the occultation diameter of 538 km (Wasserman *et al.* 1979); for Vesta we have adopted 520 km from the speckle results (Drummond *et al.* 1988), while for Hygiea we have adopted 450 km. The Hygiea value results from adopting a radio emissivity of 0.8 at 2 cm and determining a photometric diameter from the 6 and 2 cm flux densities. Our adopted value is at the lower end of the range considered by Lebofsky *et al.* (1985). Were we to adopt a value corresponding to the most likely submillimeter diameter (520 km) found by Lebofsky *et al.* (1985), the resulting brightness temperatures would be of order 90 K. Since a rapidly rotating blackbody at Hygiea's distance has a brightness temperature of 163 K, the microwave results would require too low a radio emissivity for a diameter of 520 km.

A direct determination of the diameter of Pallas and Hygiea was not possible since these asteroids were only partially resolved. However, Vesta was sufficiently resolved at 2 cm that we have been able to check the speckle diameter. We have obtained an image of Vesta with a resolution of 0.1 arcsec.

a) Pallas

The well-determined occultation diameter of Pallas eliminates the uncertainty of the diameter as a contributor to the error budget of the brightness temperature. The difference between the blackbody temperature and the observed brightness temperature is diagnostic for a finely divided surface layer while the variation between 2 and 6 cm provides the basis for an estimate of the depth of the surface layer. The spectrum is given in Fig. 1(a).

If we adopt the dielectric properties of generic lunar dust and basalt (Dickel 1979), the inversion process yields a depth for the surface layer of at least 6 cm. This relatively thick dustlike layer is consistent with the radar results reported by Ostro *et al.* (1985). Their data show that Pallas is extremely smooth on a size scale of centimeters to meters, but is much rougher than the Moon on a scale of sizes larger than several meters. Our analysis suggests that very little of the topography detected by the radar observations is free of the dust cover.

Our measurements have very little sensitivity to the properties of the substrate. If we take the apparent slope of the observed brightness temperatures at face value, the dust layer could be as deep as 10 cm. Without longer-wavelength data, we can only assert with certainty that the layer depth is not less than the longest wavelength of observation (6 cm). We can, however, make a rough determination of the real part of the dielectric vector of the surface material. The result ($\epsilon = 7.2$ at 2 cm) eliminates ice and free metals as major constituents and agrees with the spectroscopic evidence that Ceres and Pallas have different bulk compositions. The results of the analysis are summarized in Table II.

b) Vesta

With the addition of a previously reported 3.3 mm measurement by Conklin *et al.* (1977), it is clear that the microwave spectrum of Vesta given in Fig. 1(b) has the same shape as the spectrum of Ceres (Webster *et al.* 1988). The inversion analysis yields a model with a 6 cm deep layer of dust with the dielectric properties of typical lunar basaltic dust and a dense substrate with the dielectric properties of lunar basalt. As in the case of Pallas, these results show that free metals and water ice are no more than very minor constituents. These results are in agreement with the infrared-spectroscopy results (Matson *et al.* 1976), which suggest that at least a portion of the surface of Vesta is covered by basalt. Because the rotation period is most likely to be 5^h 20^m (Taylor *et al.* 1985), the low flux densities at 2 and 6 cm do not allow us to map the surface distribution of dielectric properties. Our results thus pertain to the rotation-averaged properties and suggest that basalt-like materials make up most of the upper layers of Vesta.

It has been proposed that the surface mineralogical composition of Vesta determined from the infrared measurements is similar to that of basaltic achondrite meteorites and that, therefore, Vesta is a differentiated body (McCord *et al.* 1970) (see Matson *et al.* 1976 for a further discussion). It should be noted that microwave-continuum data by themselves cannot distinguish among the varieties of basaltic compositions (or even among many rock types) because, within the accuracy possible in the inversion process, the various varieties all have the same dielectric properties. Accordingly, we refer to the materials as generic basaltic dust and basalt. Our results are summarized in Table III.

Radar observations by Ostro *et al.* (1985) indicate substantial roughness on decimeter size scales. Although the apparent radar albedos of Ceres and Vesta are essentially the same, the observed circular polarization ratio (indicative of surface roughness) of Vesta is ten times that of Ceres. Clearly, the surface structure of Vesta must vary with location. Accordingly, although our results imply an average layer depth of more than 6 cm, there must be regions with substan-

TABLE I. Observational data

DATE	FREQUENCY MHz	WAVELENGTH M	INSTRUMENT	GEOCENTRIC DISTANCE AU	FLUX DENSITY (Jy)	BRIGHTNESS TEMPERATURE K	HELIOCENTRIC DISTANCE	NORMALIZED BRIGHTNESS TEMPERATURE K	PHASE ANGLE DEGREES	REFERENCE
PALLAS										
12/29/81	4.885	0.0614	VLA	2.162	0.000207±0.000027	131± 17	2.254	118± 15	26	THIS PAPER UNLESS
03/24/82	4.885	0.0614	VLA	1.476	0.000537±0.000033	158± 10	2.43	148± 9	9	OTHERWISE SPECIFIED
04/11/83	4.885	0.0614	VLA	3.112	0.000115±0.000016	151± 21	3.248	163± 23	18	
07/22/85	14.96	0.0201	VLA	2.841	0.001369±0.000007	159± 8	2.507	152± 8	-21	
09/01/85	14.96	0.0201	VLA	2.346	0.002241±0.000051	178± 4	2.409	166± 4	-24	
11/09/86	14.96	0.0201	VLA	3.289	0.001085±0.000036	169± 6	2.44	159± 5	10	
VESTA										
08/23/83	4.885	0.0614	VLA	2.682	0.000146±0.000016	152± 17	2.558	158± 16	22	
01/08/84	4.86	0.0617	VLA	1.68	0.000322±0.000054	133± 22	2.567	139± 22	12	
12/06/84	4.885	0.0614	VLA	2.602	0.000242±0.000049	237± 48	2.325	236± 44	22	
03/05/85	14.985	0.0200	VLA	1.486	0.0043±0.000054	146± 2	2.241	142± 2	20	
dec 75	90	0.0033	12M	2.25	0.08975±0.0121*	194± 26	2.4	195± 24		Conklin et al.
HYGIEA										
04/13/83	4.885	0.0614	VLA	1.821	0.000214±0.000044	137± 28	2.817	130± 29	3	
08/14/85	14.985	0.0200	VLA	2.9	0.000568±0.00005	98± 9	3.375	102± 10	16	
08/19/85	14.985	0.0200	VLA	2.838	0.000681±0.000059	113± 10	3.379	117± 11	16	
11/05/85	14.985	0.0200	VAL	3.16	0.000598±0.000059	123± 12	2.39	126± 13	7.7	
03/06/83		0.00077	UKIRT	2.079	1.33± 0.41	175± 54	2.845	166± 55	14.9	Lebofsky et al.
03/06/83		0.00037	UKIRT	2.079	6.8± 1.1	206± 33	2.845	197± 34	14.9	Lebofsky et al.

* obtained from the reported brightness temperature of Conklin et al., 1977

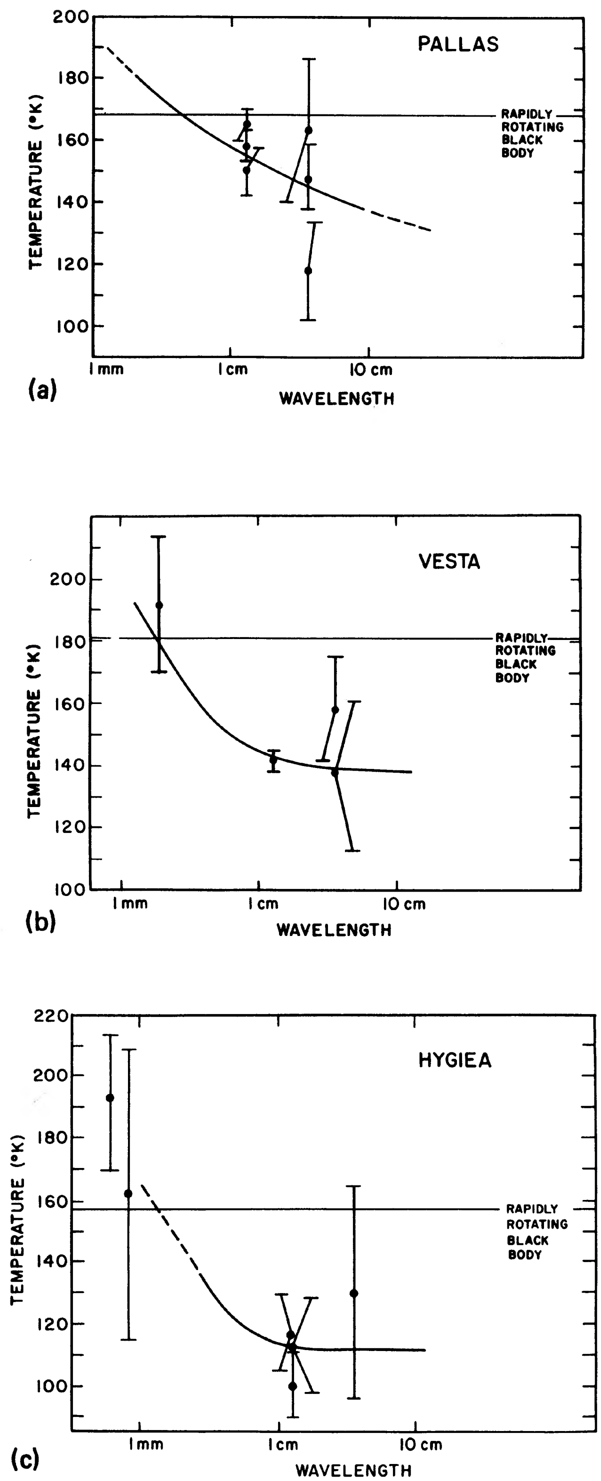

FIG 1. (a) Microwave spectrum of the Pallas. The brightness temperatures are normalized to a distance of 2.77 AU from the Sun and an assumed diameter of 538 km. The solid line is the fit to the spectrum by surface parameters in Table II. (b) Microwave spectrum of Vesta. Again, the brightness temperature has been normalized to a distance of 2.36 AU from the Sun and an assumed diameter of 520 km. The solid line is the fit to the spectrum given by the surface properties of Table III. (c) Microwave spectrum of Hygiea. The brightness temperatures are normalized to a distance of 3.14 AU from the Sun and an assummed diameter of 450 km. The solid line is the fit to the surface properties given in Table IV.

TABLE II. Model properties of Pallas.

Diameter: 538 km recommended mean occultation diameter
Upper Layer:
 Depth: greater than 6 cm 90% confidence
Composition: $\epsilon = 7.2$ 45% confidence
 4.0 15% confidence (dry clay)
 ice < 5% by volume
 free metals < 1% by volume
Lower Layer: Not detected
ϵ = real part of dielectric vector

tially deeper and shallower dust covers. Millimeter wavelength observations of sufficient signal-to-noise ratio to measure the rotational phase dependence of brightness temperature could be used to identify those areas that are essentially bare. Radio light curves could be obtained at 1 mm with the Pico Velata telescope or at 3 mm with the Kitt Peak telescope, provided that the receiver-noise performance is sufficient.

Our 2 cm observations were obtained with sufficient minimum fringe spacing to resolve well the disk of Vesta. Accordingly, we have a valuable check on the speckle results reported by Drummond *et al.* (1988). Although our data are averaged over rotational phase, the location of the subradio point on the disk (assuming the pole position reported by Drummond *et al.*) allows us to assess the latitudinal variations in radio brightness temperature on the disk of Vesta. The image of Vesta is given in Fig. 2. A simple restoration based on a uniform disk (Panagia and Walmsley 1978) yields a major axis of 665 km and a minor axis of 476 km. The uncertainty in these values is dependent on the pixel size and the shape of the unrestored brightness distribution (see Webster *et al.* 1988 for a discussion) and is conservatively estimated as 50 km in each direction. These results are in good agreement with the speckle results of $584 \times 531 \times 467$ km and yield the same brightness weighted mean of 520 km. We find no evidence for brightness variations greater than 15% across the radio disk of Vesta. This uniformity implies that the microwave surface properties do not vary much with latitude.

c) Hygiea

Lebofsky *et al.* (1985) have pointed out that the current state of thermophysical modeling does not allow the construction of a single model that simultaneously predicts the observed emission throughout the wavelength range from microns to centimeters. A comparison between the submillimeter observations and our centimeter observations could provide valuable clues to the appropriate physics that such a

TABLE III. Model properties of Vesta.

Diameter: 520 km speckle and direct resolution
Upper Layer:
 Depth: 6 cm (0.2 cm resolution) 85% confidence
Composition: $\epsilon = 2.9$, $\delta = 0.015$ 95% confidence 2 cm wavelength (over limit)
 Water ice < 5% (upper limit)
Lower Layer: Composition: $\epsilon = 7.2$, $\delta = 0.054$ 90% confidence
 2 cm wavelength (lunar basalt)
ϵ = real part of dielectric vector
δ = loss tangent

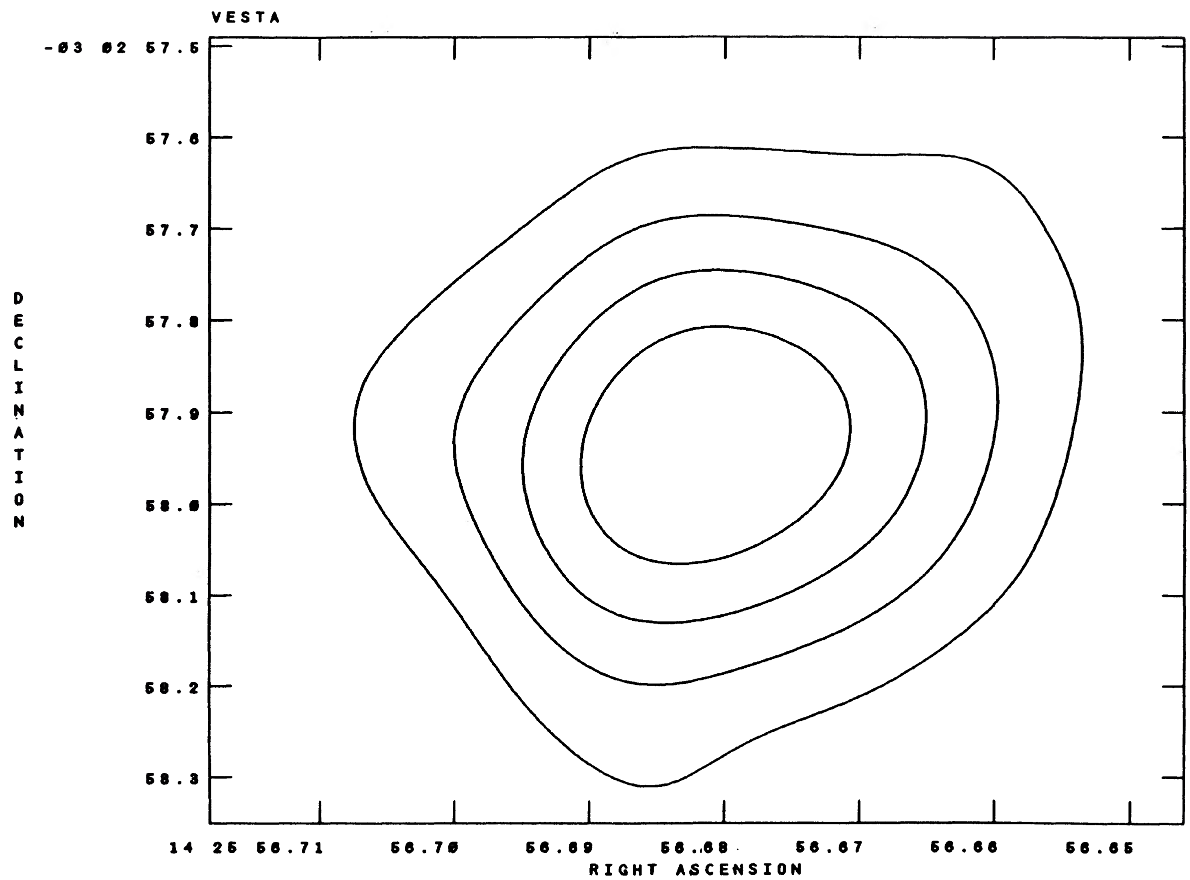

FIG. 2. Map of the image of Vesta obtained on 5 March 1985. The contour levels are 0.2, 0.4, 0.6, and 0.8 of the peak flux density, which is 2.076 mJy/beam. The restoring beam is 0.17×0.17 arcsec. The map was made with natural weighting and a taper of 750 000 wavelengths of the *uv* plane data and a cell size of 0.01 arcsec.

general model should include. In Fig. 1(c), we give our observed continuum spectrum of Hygiea. Note that we have also plotted the Lebofsky *et al.* (1985) observations in Fig. 1(c).

As in the case of Pallas, we have adopted the dielectric properties of generic lunar dust and lunar basalt for the inversion analysis. We also tried lower and higher values of the real part of the dielectric vector without an improvement in the results. The flattening of the spectrum in the centimeter values is indicative of a very deep dustlike layer. The inversion yields a depth of 9 cm with a confidence of 70% and a confidence level of 90% for the depth being greater than 8 cm. The presence of the dust layer is also evident in the observations of Lebofsky *et al.* (1985). Although we have assumed dielectric properties in the above analysis, we did fit the dielectric properties, assuming the thermal properties of the appropriate model derived by Lebofsky *et al.* (1985). This analysis yielded a real part of the dielectric vector essentially the same as basaltic dust and serves to show that free metals, "wet" and "dry" clay, and water ice are no more than minor constituents of the upper layers of Hygiea. The results are summarized in Table IV.

It should be noted that the dielectric properties of various candidate materials are known only poorly for frequencies above 1.4 GHz ($\lambda < 20$ cm). The most reliable published determinations at high frequencies are for clays, soils, and a very few varieties of rock, but even these are measured at frequencies no higher than 10 GHz ($\lambda = 2.8$ cm). From the published data, it is not possible to distinguish carbonaceous chondrite assemblages from generic basaltic dust and basalt on the basis of high-frequency dielectric properties. This conclusion also applies to the analysis of the Pallas spectrum. In the case of Vesta, the infrared-spectroscopy results

TABLE IV. Model properties of Hygiea.

Diameter: 450 km microwave photometric (see text)	
Upper Layer:	
Depth: 9 cm 70% confidence	
>8 cm 90% confidence	
Composition: $\epsilon = 7.2$, $\delta = 0.5$ assumed	
2 cm wavelength (lunar basalt)	
Water ice $<3\%$	
Lower Layer:	
Real Part of Dielectric Vector at 2 cm	
$\epsilon = 7.0$	50% confidence (basalt)
4.0	30% confidence
2.0	10% confidence

provide the means to assert that the material mineralogical composition is basalt-like.

IV. CONCLUSIONS

The analysis of the centimeter emission from the major asteroids shows that all four (Ceres, Pallas, Vesta, and Hygiea) display a brightness temperature lower than that expected from a rapidly rotating blackbody and are consistent with models that are covered by a surface layer that has the physical properties of dust. The dielectric properties of this dust vary from asteroid to asteroid, consistent with the compositional differences indicated by infrared spectroscopy. To the extent to which a determination of the substrate properties is possible, it appears that the substrate is chemically similar to the surface layer but more compacted. This result gives added support to the assumption that the infrared spectral analyses indicate the surface and subsurface composition of the asteroids and not only a possibly anomalous surface layer. It has been suggested, however, by Britt and Pieters (1988) and by Gaffey (1988) that this may not be so. In accounting for the discrepancy between the abundance of ordinary chondrites as terrestrial falls and the distribution of spectral types of the asteroids, they have proposed that surface processes may have altered the spectral signatures of the asteroids. This possibility must be pursued by further studies of both meteorites and additional asteroids, but our results indicate that there is no gross discrepancy between the surface-layer composition and the substrate composition for the asteroids studied here. Any major composition changes must take place at depths in excess of 10 cm.

The surface dust layer cannot be the entire asteroidal regolith. Several lines of evidence, summarized by Carr (1981), show that even bodies as small as Phobos and Deimos have regoliths at least several meters thick. The much larger asteroids considered here must have comparably thick regoliths. Accordingly, the substrate we detect cannot be undisturbed solid rock and must have been extensively gardened by impacts. Since the microwave spectral analysis process will detect porosities greater than about 15% and since the substrate has the signature of solid rock, the lower layer must be compacted impact-gardened rubble.

There is no reason to expect that these results should not apply to all asteroids larger than, perhaps, 200 km. In the two cases (Eunomia and Interamnia) (Webster *et al.* 1987) where sufficient data are available to do at least a crude form of analysis, a dustlike layer over a much more compact substrate is found. It thus appears that conventional remote-sensing techniques will not yield a determination of the total regolith depth unless radar or radio observations at wavelengths longer than 75 cm become possible.

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