Reports

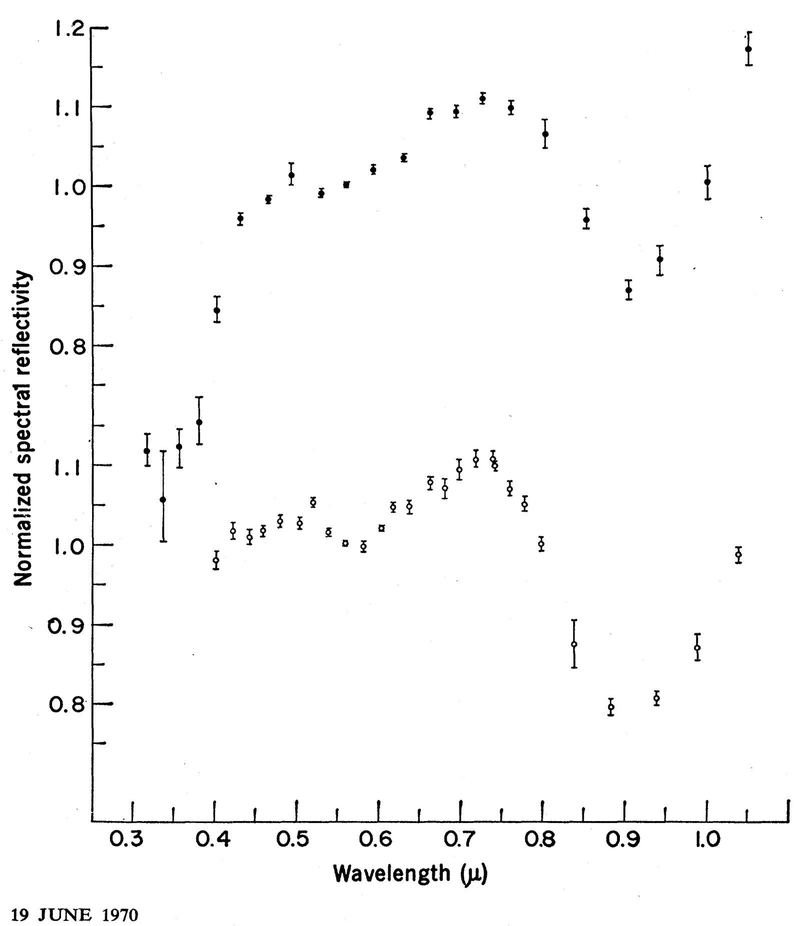
Asteroid Vesta: Spectral Reflectivity and Compositional Implications

Abstract. *The spectral reflectivity (0.30 to 1.10 microns) of several asteroids has been measured for the first time. The reflection spectrum for Vesta contains a strong absorption band centered near 0.9 micron and a weaker absorption feature between 0.5 and 0.6 micron. The reflectivity decreases strongly in the ultraviolet. The reflection spectrum for the asteroid Pallas and probably for Ceres does not contain the 0.9-micron band. Vesta shows the strongest and best-defined absorption bands yet seen in the reflection spectrum for the solid surface of an object in the solar system. The strong 0.9-micron band arises from electronic absorptions in ferrous iron on the* M2 *site of a magnesian pyroxene. Comparison with laboratory measurements on meteorites and Apollo 11 samples indicates that the surface of Vesta has a composition very similar to that of certain basaltic achondrites.*

We are carrying out a program to measure the spectral reflectivity of many asteroids. The spectral reflectivity is useful in determining the mineralogy and composition of the surface of objects in the solar system (*1*). Here we discuss some important results concerning the bright asteroid Vesta.

The 60-inch (152-cm) telescope of the Cerro Tololo Inter-American Observatory and the 60-inch and 100-inch (254-cm) telescopes of the Mount Wilson Observatory were used with a double-beam photometer (*2*) to observe asteroids. A set of narrow-band interference filters was used to scan the spectrum between 0.3 and 1.1 μ. The reflectivity was obtained by observing the asteroid and a standard star, each many times through all filters during each night of observation. The results are a ratio of the flux of the asteroid to that of the star for each filter with the effects of atmospheric transmission and instrument response removed. This quantity is multiplied by the ratio of the flux of the star to that of the sun to yield the ratio of the flux of the asteroid to that of the sun, which is proportional to the reflectivity of the asteroid. All runs are scaled to unity at 0.564 μ for ease in the comparison of curve shapes. The standard star fluxes are those of Oke (*3*), modified by Oke and Schild (*4*). The solar fluxes are from Labs and Neckel (*5*). The standard star α Leo was used in 1969. In 1968 η Psc was used and was calibrated against the standard star ξ^2 Cet.

Some results for Vesta and Pallas are shown in Figs. 1 and 2; values for the points plotted are given in Table 1. An absorption band centered near 0.9 μ is the most striking feature in the curve



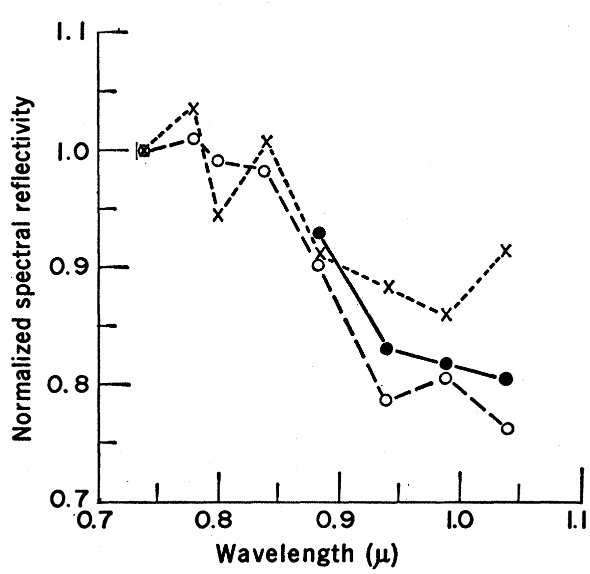


Fig. 1 (left). Normalized spectral reflectivity of Vesta as a function of wavelength for each of two independent observation sessions approximately 1 year apart. (Solid circles) Observations at Cerro Tololo, Chile, December 1969; (open circles) observations at Mount Wilson, October 1968. Each point represents an average of measurements through one interference filter. The standard deviation for each average value is shown as an error bar. Fig. 2 (above). Normalized spectral reflectivity of Pallas for a more limited spectral region than that shown in Fig. 1. (Solid circles) One run, 16 May 1967; (open circles) one run, 17 May 1967; (X's) two runs, 18 May 1967.

for Vesta. This is the strongest and best-defined absorption band we have seen in the reflection spectrum for the solid surface of an object in the solar system. Weaker absorption features also appear between about 0.4 and 0.7 μ. There is a sharp decrease in Vesta's reflectivity toward the ultraviolet with a shoulder at 0.43 μ. The spectrum of Pallas (Fig. 2) lacks the strong 0.9-μ absorption band, although an absorption feature centered beyond 1 μ is suggested. Data for Ceres (not shown here) also suggest the absence of the 0.9-μ band. Vesta therefore has a distinct spectrum with absorption bands which is quite different from the spectrum for several other asteroids.

The small differences between the two curves shown in Fig. 1 for Vesta, mainly a simple red to blue tilt of one curve with respect to the other, may be due to errors in our calibration between the star η Psc used for the 1968 Vesta observations and the standard star ξ^2 Cet against which η Psc was calibrated. Changes in the spectrum of this asteroid due to aspect and reflection geometry, particularly solar phase angle, are more likely. However, we have found no large changes in the reflection spectrum with spin phase.

The spectrum of Vesta is shaped by the composition and mineralogy of the surface material. We have interpreted the absorption bands in the spectrum in terms of surface mineralogy by using an understanding of the physics of absorption-band formation for solids and by comparing Vesta's spectrum with spectra for terrestrial and meteoritic materials.

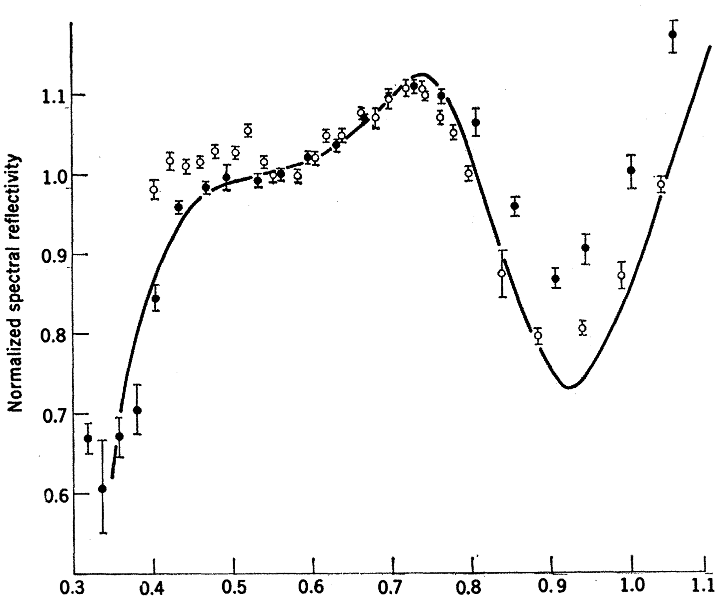
The main features of the Vesta reflectivity curve are (i) a pronounced absorption band near 0.90 μ, (ii) a sharp decrease in reflectivity in the blue and ultraviolet region, and (iii) a shallow band between 0.5 and 0.6 μ. All bands can be interpreted in terms of electronic absorptions in common rock-forming silicate minerals (*1*). No band coincides with known reflection properties of CO_2 or H_2O ices (*6*) or with gas absorption features.

A band near 0.90 μ is a well-known feature of Mg-rich orthopyroxene or pigeonite, where it is produced by Fe^{2+} in sixfold coordination (*7*). To our knowledge no other common minerals exhibit the 0.9-μ band. In Mg-rich orthopyroxenes the absorption band minimum in diffuse reflected light occurs at 0.90 μ. As the Fe or Ca content of the orthopyroxenes increases, the band position shifts to longer wavelengths (*8*). For all compositions the band shape is nearly symmetric.

By imposing the requirement of band symmetry on the points in Fig. 1, we conclude that the band minimum for Vesta occurs at 0.915 ± 0.005 μ. If we disregard symmetry, the extreme minimum positions are at 0.895 and 0.925 μ. If pyroxene is the only mineral contributing to the band, the implied compositional range is limited to less than 15 percent $CaSiO_3$ and less than 60 percent $FeSiO_3$. A better compositional estimate could be made if the shape of the Vesta curve were known in the range from 1.8 to 2.0 μ. A

Table 1. Normalized spectral reflectivity of Vesta as a function of wavelength for two independent observation sessions, one at Mount Wilson in 1968 and the other at Cerro Tololo in 1969.

Wavelength (μ)	Measurements (1968)	Wavelength (μ)	Measurements (1969)
0.4032	0.9816	0.319	0.669
.4224	1.0187	.338	.607
.4422	1.0091	.358	.674
.4612	1.0180	.383	.701
.4800	1.0308	.402	.842
.5040	1.0282	.433	.959
.5210	1.0537	.467	.982
.5403	1.0147	.498	.998
.5600	1.0000	.532	.990
.5782	0.9978	.564	1.000
.6030	1.0202	.598	1.020
.6180	1.0473	.637	1.033
.6380	1.0476	.665	1.070
.6637	1.0787	.699	1.091
.6814	1.0695	.730	1.1097
.6976	1.0952	.765	1.097
.7204	1.1079	.809	1.064
.7413	1.1061	.855	0.959
.7440	1.0982	.906	.869
.7610	1.0612	.948	.906
.7790	1.0514	1.002	1.008
.7990	1.0004	1.053	1.171
.8400	0.8753		
.8850	.7959		
.9400	.8067		
.9900	.8697		
1.0400	.9861		
1.0800	.9871		



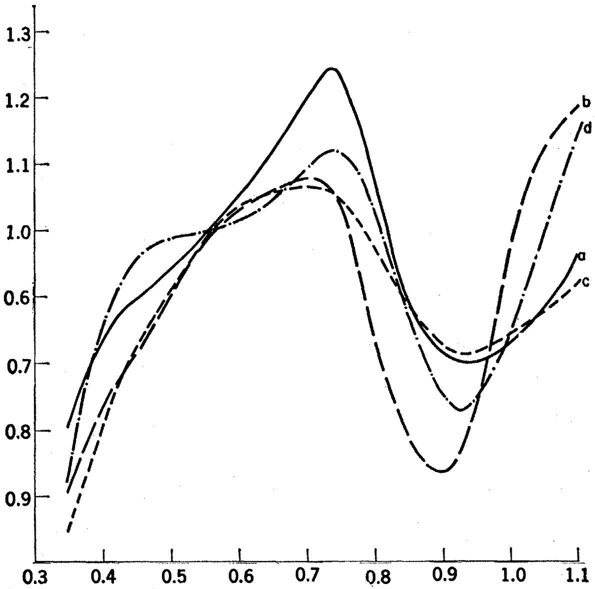


Fig. 3 (left). Laboratory measurements of the spectral reflectivity of the Nuevo Laredo meteorite shown with the telescope data points from Vesta replotted from Fig. 1. (Solid line) Nuevo Laredo basaltic achondrite; (open and solid circles) Vesta. Fig. 4 (right). Laboratory measurements of the spectral reflectivity of several meteorite samples and of an Apollo 11 sample. (a) Apollo 11 sample 10003; (b) bronzite from Sylva, North Carolina [orthopyroxene (En_{80})]; (c) Holbrook chondrite (hypersthene-olivine); (d) Nuevo Laredo basaltic achondrite. The curve for the Nuevo Laredo sample (Fig. 3) is shown for comparison to illustrate the uniqueness of the match between laboratory sample data and telescope data.

second principal pyroxene band in this wavelength region is particularly sensitive to changes in the Ca and Fe content.

It is possible, however, that the Vesta band at 0.9 μ may result from two minerals. For example, enstatite (0.90 μ) combined with a few percent olivine (1.04 μ) could yield a combination band at 0.915 μ. However, this possibility seems to be ruled out by the shape of the reflectivity curve of Vesta in the visible spectral region, as we discuss below.

We interpret the sharp decrease in reflectivity below 0.4 μ to be a charge-transfer band. Only the long-wavelength side of this band is shown. The band is typical of pyroxenes and of other iron-bearing minerals. Unfortunately, the band does not allow further insight into the pyroxene composition.

The structure of the Vesta curve between 0.4 and 0.7 μ is somewhat ambiguous because of the differences between the data from Chile and Mount Wilson. The general flattening of the curve in this region is clear, and there is a band center somewhere between 0.5 and 0.6 μ. A broad, weak absorption between 0.5 and 0.6 μ is characteristic of pigeonites but not of the orthopyroxenes or orthopyroxene-olivine mixtures, which, in addition, also have steeper curves. The most probable band assignment is Ti^{3+} which gives a broad band near 0.5 μ. Other bands in this spectral region arise from Fe^{2+} and Fe^{3+} on octahedral sites. However, these bands are usually too weak to be resolved in diffuse reflected light.

If we consider the Vesta curve as a whole, the best comparison is with a magnesian pigeonite that contains minor amounts of titanium. Orthopyroxene plus a small amount of olivine or calcic clinopyroxene could account for the 0.915-μ band, but the spectrum of this mixture is in poor agreement with the Vesta curve between 0.5 and 0.6 μ and drops too abruptly toward the ultraviolet.

The strength of the 0.9-μ absorption band ($\sim$30 percent) is in itself important. Studies of the Apollo 11 lunar samples have suggested that the abundance of opaque materials on the lunar surface has depressed the absorption band strength for lunar surface material as viewed through telescopes from the earth (*8, 9*). Thus it appears that Vesta's surface is relatively free of such opaque materials. A silicate surface of this sort should have a visible albedo considerably higher than that of the lunar surface, perhaps in the range of 30 to 40 percent.

We have compared the Vesta curves with laboratory curves for Apollo 11 samples, chondrites, and basaltic achondrites (Figs. 3 and 4). The curves for chondrites do not flatten between 0.5 and 0.6 μ, because of the dominance of orthopyroxene structure, and therefore do not compare well with the curve for Vesta. The lunar samples and the basaltic achondrites with calcic pyroxenes have the major band at 0.93 μ or longer wavelength. However, the basaltic achondrites with predominant pigeonite have the main band as low as 0.925 μ and show an excellent agreement with the other features of the Vesta curves (Fig. 3). The discrepancy of 0.01 μ in the position of the main band is just within the error range when one compares the telescope and laboratory data. Although the visible region of the reflectivity curve very quickly drops below an acceptable level as the content of orthopyroxene is increased, the band could be slightly shifted to shorter wavelengths if a slightly more orthopyroxene-rich specimen were selected.

We conclude that the surface of Vesta is similar in composition to certain basaltic achondrites. Furthermore, the mineralogy of this asteroid appears to be distinctly different from that of other meteorite types and from samples of the lunar surface at the Apollo 11 landing site. Determination of Vesta's spectrum from 1.1 to 2.5 μ would help to confirm our conclusions; a band should exist centered near 2.0 μ. Also, additional spectral reflectivity measurements of other asteroids would yield further information on the heterogeneity of the asteroids and on their relationship to meteorites.

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References and Notes

1. J. B. Adams, *Science* **159**, 1453 (1968).
2. T. B. McCord, *Appl. Opt.* **7**, 475 (1968).
3. J. B. Oke, *Astrophys. J.* **140**, 689 (1964).
4. ——— and R. Schild, *ibid.*, in press.
5. D. Labs and H. Neckel, *Z. Astrophys.* **69**, 1 (1968).
6. H. H. Kieffer, thesis, California Inst. of Technology (1968); *J. Geophys. Res.* **75**, 501 (1970).
7. G. M. Bancroft and R. G. Burns, *Amer. Mineral.* **52**, 1278 (1967); W. B. White and K. L. Keester, *ibid.*, p. 1508.
8. J. B. Adams and R. L. Jones, *Science* **167**, 737 (1970).
9. J. B. Adams and T. B. McCord, *Geochim. Cosmochim. Acta*, in press.
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Chlorophyll Derivatives in Middle Eocene Sediments

Abstract. *Chloroform extracts of middle Eocene brown coal were made; the chlorophyll derivatives obtained were separated chromatographically. The visible light spectrum, chromatographic behavior, HCl number, infrared spectrum, and mass spectrum of one of the pigments extracted is indicative of methyl pheophorbide a. This is the oldest occurrence of fossil phorbins reported.*

Green-colored angiosperm leaves were reported in 1931 by Weigelt and Noack (*1*) from middle Eocene brown coals of the Geisel valley near Halle, East Germany. Weigelt and Noack identified several chlorophyll derivatives from crude extracts of these green fossil leaves and their associated brown coals. A reinvestigation of this material by modern techniques of chromatography and spectrophotometry has made possible a more precise separation and identification of the green pigmentation of this material.

The material examined in this study was collected from the Neumark-Süd open pit brown coal mine in the Geisel valley near Halle, East Germany. Only a small number of the angiosperm leaf impressions in the Geisel valley brown coal are green; they are most often dark brown to black with a few scattered light-brown to white-colored leaf impressions present. The color of the green