N78-29015

INFRARED OBSERVATIONS OF ASTEROIDS FROM EARTH AND SPACE

DENNIS L. MATSON and GLENN J. VEEDER

Space Sciences Division
Jet Propulsion Laboratory, Pasadena, California 91103

and

LARRY A. LEBOFSKY

Lunar and Planetary Laboratory
University of Arizona, Tucson, Arizona 85721

Infrared observations of asteroids have made possible key steps in our understanding of asteroids. The list of accomplishments includes: diameters, albedos, surface morphology and surface composition. Current topics of interest include the presence of water of hydration on Ceres, the presence of mixtures of silicate and metallic phases, and the state of development of asteroidal regoliths which range from rocky (1580 Betulia) to lunar-like (*e.g.*, Ceres, Vesta). We review these accomplishments critically and assess the advantages which can be obtained by performing infrared observations from Earth orbit and from interplanetary spacecraft.

REFLECTED RADIATION

Introduction

The measurement of reflectances at wavelengths between 1 and 4 μm yields important information about asteroid surface composition and the processes by which these surfaces may have been modified. Further, it more than doubles the wavelength range over which asteroids may be compared with available reflectivity data for meteorites and other laboratory samples. As a result, it is possible to classify asteroids better and to devise more precise tests for hypotheses about their surface compositions.

The need for asteroid photometry at wavelengths longer than 1 μm was first recognized as a result of laboratory investigations into the bulk reflectance properties of meteorite samples (Johnson and Fanale, 1973; Chapman and Salisbury, 1973; Gaffey, 1974, 1976). These works showed that meteorites as a group exhibited a large range in infrared reflectance. This should also be true for asteroids with meteorite-type compositions. Furthermore, it was argued that high spectral resolution would not be essential because for many meteorites the infrared reflectances (particularly those for the carbonaceous chondrites and the irons) do not vary sharply with wavelength in the 1 to 3 μm interval. But, even when bands (arising from solid state transitions in minerals) were present, the features were observed to be typically 0.5 μm or more in width. Therefore, existing astronomical infrared bandpasses and, more important, existing systems of standard stars are suitable for asteroid photometry.

The first asteroid study with this technique was carried out by Johnson *et al.* (1975) who observed Ceres, Pallas and Vesta. They were able to use published V bandpass photometry for these asteroids to derive the asteroidal reflectances at 1.25, 1.65 and 2.2 µm. However, they noted that simultaneous visual wavelength photometry would be necessary for any other asteroids observed by this technique because of the large uncertainties in the instantaneous apparent visual magnitude due to (1) lightcurve, (2) aspect, and (3) phase effects. Chapman and Morrison (1976) and Leake *et al.* (1978) have reported J, H, and K photometry for 433 Eros and about a dozen other asteroids. Veeder *et al.* (1976, 1977, 1978) have observed 30 asteroids at 0.56, 1.6 and 2.2 µm and derived the relative infrared reflectances for these objects. Lebofsky (1977) has extended this technique to 3.45 µm for Ceres.

Photometry and spectroscopy are complementary techniques. For example, over the last several years the sensitivity of infrared astronomical interferometers has increased dramatically. Such an instrument has been applied to the asteroids and high resolution spectra of 4 Vesta, 433 Eros, and 1 Ceres are now available (Larson and Fink, 1975; Larson *et al.*, 1976; Feierberg *et al.*, 1977). These spectra allow precise band centers to be determined and as such are very important for compositional identifications. Based on the statistics of asteroid types (Chapman *et al.*, 1975; Zellner and Bowell, 1977), we estimate that more than 80% of the asteroids will exhibit infrared spectral reflectances which are essentially linear. In these cases the main task is to determine the slope of the spectrum by photometry. The remaining asteroids, especially if they have apparent bands or peculiarities in their photometry or spectrophotometry, become prime candidates for high resolution infrared spectral investigations.

The purpose of this section of this paper is to assess the state of asteroid infrared reflectance measurements and the advantages offered by Earth orbit and spacecraft observations. The second section deals with thermal radiation emitted by the asteroids and the third section discusses future observations of asteroids from space.

Infrared Photometry

The available infrared reflectance data for asteroids have been drawn together in Tables 1 and 2. The only published reflectances at 1.25 µm are those of Johnson *et al.* (1975). However, magnitudes published by Chapman and Morrison (1976), Leake *et al.* (1978), and Lebofsky (1978) are used here together with the observations of the same asteroids by Veeder *et al.* (1976, 1977, 1978) and solar data from Johnson *et al.* (1975) to compute 1.25 µm reflectances. The method by which this was done is described in footnote 3 of Table 1.

Figure 1 shows the infrared results for three asteroids and the 0.3-1.1 µm spectrophotometry published by Chapman *et al.* (1973). Vesta has a relatively high infrared reflectance, while the infrared reflectances of Ceres and Pallas are distinctly flat or low. A high infrared reflectance compared with that at 0.55 µm is typical of many silicate minerals and rocks (Hunt and Salisbury, 1970) and most meteoritic materials (Chapman and Salisbury, 1973; Gaffey, 1974, 1976). On the other hand, flat infrared curves such as those of Ceres and Pallas are unusual for ordinary terrestrial rocks, but are apparently common in the asteroid belt. Johnson and Fanale (1973) found that some carbonaceous chondrites and laboratory mixtures of carbon black and silicates have flat spectral reflectances as well as low albedos. The scaled reflectance plot (Figure 1) allows direct comparison with spectral features of meteorites without confusion from slight overall albedo differences due to laboratory methods, grain size, or sample packing characteristics. Care must be taken, of course, to compare materials with generally similar albedos; for example, pure enstatite and carbon black have similar visual reflectance spectra but greatly different albedos.

Table 1. Infrared Reflectances

Asteroid	R_λ			Type[6,7]	Footnote
	1.25 μm	1.6 μm	2.2 μm		
1 Ceres	0.98 ± 0.09	0.99 ± 0.09	1.08 ± 0.09	C	1
		0.94 ± 0.13	1.03 ± 0.10		4
2 Pallas	1.05 ± 0.09	0.97 ± 0.09	1.05 ± 0.09	C	1
		0.79 ± 0.08	0.83 ± 0.08		4
3 Juno		1.19 ± 0.10	1.30 ± 0.10	S	4
4 Vesta		1.18 ± 0.1[illegible]	1.29 ± 0.14		1,8
		1.10 ± [illegible]	1.16 ± 0.07		4
5 Astraea	1.15 ± 0.16	1.25 ± 0.10	1.30 ± 0.15	S	3,4
6 Hebe	1.15 ± 0.15	1.21 ± 0.09	1.30 ± 0.12	S	3,4
7 Iris	1.16 ± 0.10	1.31 ± 0.09	1.44 ± 0.09	S	3,4
8 Flora	1.25 ± 0.12	1.42 ± 0.10	1.55 ± 0.11	S	4,10
9 Metis		1.27 ± 0.09	1.45 ± 0.10	S	4
10 Hygiea		0.96 ± 0.07	1.06 ± 0.10	C	4
12 Victoria		1.51 ± 0.12	1.72 ± 0.13	S	4
14 Irene		1.39 ± 0.08	1.52 ± 0.10	S	4
15 Eunomia	1.21 ± 0.09	1.24 ± 0.08	1.38 ± 0.08	S	4,10
16 Psyche		1.14 ± 0.09	1.37 ± 0.10	M	4
19 Fortuna		0.97 ± 0.11	1.10 ± 0.11	C	4
20 Massalia		1.28 ± 0.09	1.39 ± 0.10	S	4
22 Kalliope		1.14 ± 0.12	1.46 ± 0.14	M	4
27 Euterpe		1.26 ± 0.11	1.37 ± 0.10	S	4
39 Laetitia		1.38 ± 0.08	1.49 ± 0.08	S	4
40 Harmonia		1.38 ± 0.11	1.46 ± 0.11	S	4
43 Ariadne		1.44 ± 0.12	1.47 ± 0.19	S	4
44 Nysa		1.03 ± 0.12	1.15 ± 0.11	E	4
51 Nemausa		1.24 ± 0.13	1.28 ± 0.10	C	4
63 Ausonia		1.50 ± 0.10	1.70 ± 0.12	S	4
129 Antigone	1.02 ± 0.10	1.28 ± 0.07	1.45 ± 0.08	M?	3,4
192 Nausikaa		1.47 ± 0.07	1.62 ± 0.10	S	4
230 Athamantis		1.33 ± 0.15	1.55 ± 0.14	S	4
349 Dembowska		1.38 ± 0.10	1.57 ± 0.14	-	4,9
354 Eleonora		1.48 ± 0.14	1.69 ± 0.16	S	4
433 Eros	1.3 ± 0.14	1.5 ± 0.1	1.7 ± 0.1	S	2,3
511 Davida	0.85 ± 0.11	1.03 ± 0.08	1.19 ± 0.08	C	3,4
1976AA			1.5 ± 0.3	-	5

[1] Johnson *et al.* (1975).

[2] Veeder *et al.* (1976)

[3] These values of $R_\lambda(1.25\ \mu m)$ have been computed from the published J-K magnitudes of Chapman and Morrison (1976) using the formula:

$$R_\lambda(1.25\ \mu m) = R_\lambda(2.2\ \mu m)\mathrm{dex}\{-0.4[(J-K)_{asteroid} - (J-K)_{Sun}]\}$$

The values of $R_\lambda(2.2\ \mu m)$ are those in the above table and $(J-K)_{Sun}$ is 0.36 from Johnson *et al.* (1975). The tabulated errors are estimates only, having been computed upon the assumption that the errors in $(J-K)_{asteroid}$ and $R_\lambda(2.2\ \mu m)$ are random.

[4] Veeder *et al.* (1978).

[5] Veeder *et al.* (1977).

[6] Type C and S classifications are defined by Chapman *et al.* (1975)

[7] Types M and E have been discussed by Zellner *et al.* (1975), Zellner and Gradie (1976), Chapman (1976), Morrison (1977a,b,c), Zellner *et al.* (1977a,b,c,d), Matson *et al.* (1977a), Zellner and Bowell (1977), Veeder *et al.* (1977), Morrison (1978), Zellner (1978), *cf.*, Gaffey and McCord (1977), McCord (1978)

[8] Basaltic achondritic.

[9] Olivine plus metal; *cf.*, Gaffey and McCord (1977) and Veeder *et al.* (1978).

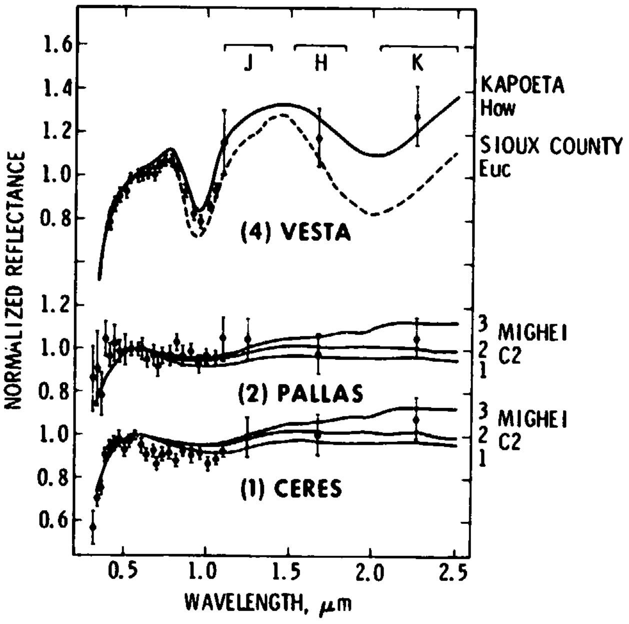
[10] These values of $R_\lambda(1.25\ \mu m)$ have been computed from the published J-K magnitudes of Leake *et al.* (1978) as in Footnote 3.

Table 2. Observations of Ceres by Lebofsky (1978)

Wavelength	Magnitudes		Reflectance R_λ			
					Model Limits[2]	
	m_λ	$\sigma_{\overline{X}}$	Nominal[1]	$\sigma_{\overline{X}}$	Upper	Lower
1.25 (J)	6.41	0.02	0.98	0.02	0.98	0.98
2.22 (K)	5.89	0.01	1.07	0.01	1.07	1.07
3.03	6.23	0.05	0.75	0.04	0.75	0.74
3.12	6.19	0.02	0.77	0.02	0.76	0.75
3.43	5.77	0.02	1.12	0.02	1.06	0.97
3.45 (L')	5.74	0.01	1.16	0.01	1.08	0.98

[1] Scaled to 1.0 at V (Johnson *et al.*, 1975). Before thermal flux removed.
[2] Thermal flux removed. The upper and lower limits are due to the uncertainty in the removal of the thermal flux.

Fig. 1. Normalized spectral reflectances for 1 Ceres, 2 Pallas, and 4 Vesta, compared with laboratory data for several meteorites. The 0.03-1.1 μm asteroid data are those of Chapman *et al.* (1973). Meteorite curves are from Johnson and Fanale (1973), Chapman and Salisbury (1973), and Gaffey (1974, 1976). The bars near the top indicate the full width at half-minimum of the infrared bandpasses.



ORIGINAL PAGE IS
OF POOR QUALITY

Infrared reflectance data are quite useful for asteroid classification; *cf.*, Matson *et al.* (1977a). This can be shown in one way by plotting the visual geometric albedo versus $R_\lambda(2.2\ \mu m)$ as in Figure 2. On this plot the C asteroids are clearly separated from the others. The cluster of points to the right contains not only S but also the M asteroids 16 Psyche and 22 Kalliope. Several peculiar asteroids stand out on this plot. 4 Vesta is the best understood in that it is known to have a basaltic surface. E asteroid 44 Nysa has a very high albedo, perhaps in excess of 0.3 or 0.4 (Zellner, 1975; Morrison, 1977a,c), but has an $R_\lambda(2.2\ \mu m)$ otherwise characteristic of C asteroids. Zellner (1975) and Zellner *et al.* (1977c) have suggested that Nysa is of an enstatite-achondrite-like composition. 2 Pallas and 51 Nemausa represent the extremes of low albedo asteroids observed in the infrared. The data of Figure 2 suggest that we are seeing either a surface compositional or a surface morphological sequence within both the C and S classes.

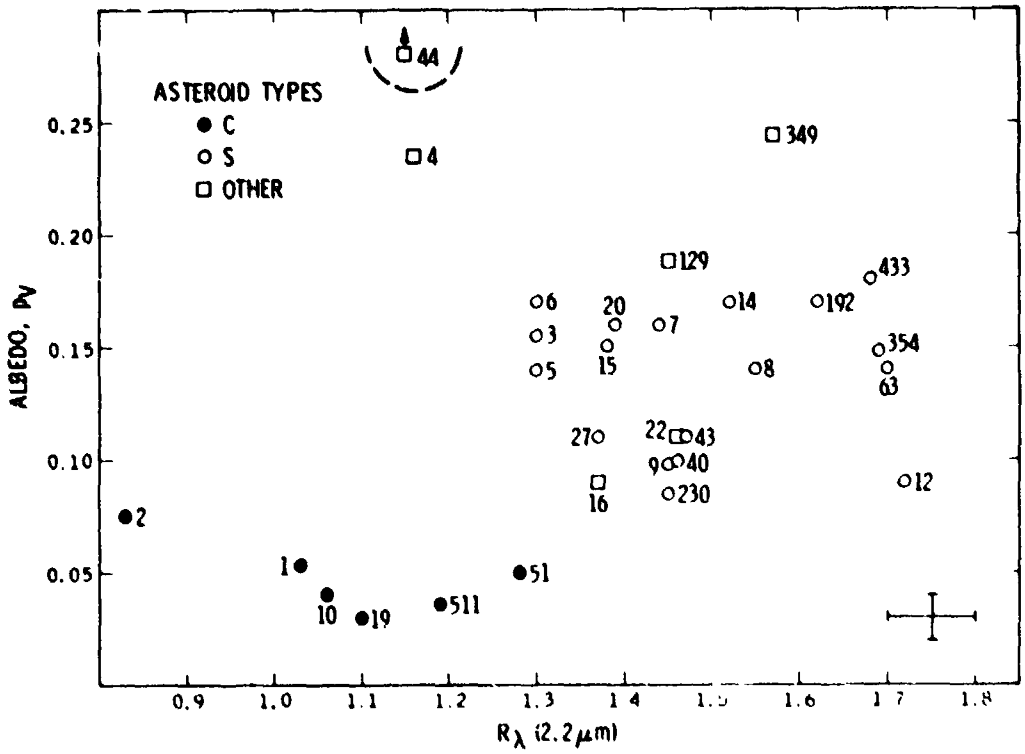


Fig. 2. Geometric albedo vs. relative reflectance at 2.2 μm. The albedos were determined by the radiometric method and are from Morrison (1974, 1977a), and Morrison and Chapman (1976). Typical error bars (estimated relative error) are indicated. The asteroid types are defined by Chapman *et al.* (1975). Use of radiometric albedos from Hansen (1976a, 1977) or polarimetric albedos from Zellner and Gradie (1976) would also result in a similar diagram.

From an inspection of Table 1 it is obvious that asteroids that have large values of $R_\lambda(1.6\ \mu m)$ also have high values of $R_\lambda(2.2\ \mu m)$. This is illustrated by plotting the two reflectances in Figure 3. Once again the C and S objects are separated. The meteorites, which are natural samples from space, provide a logical set of objects for comparison with the telescopically observed asteroids. Using the laboratory data of Gaffey (1974, 1976) we plot the relative infrared reflectances of meteorite samples in Figure 3.

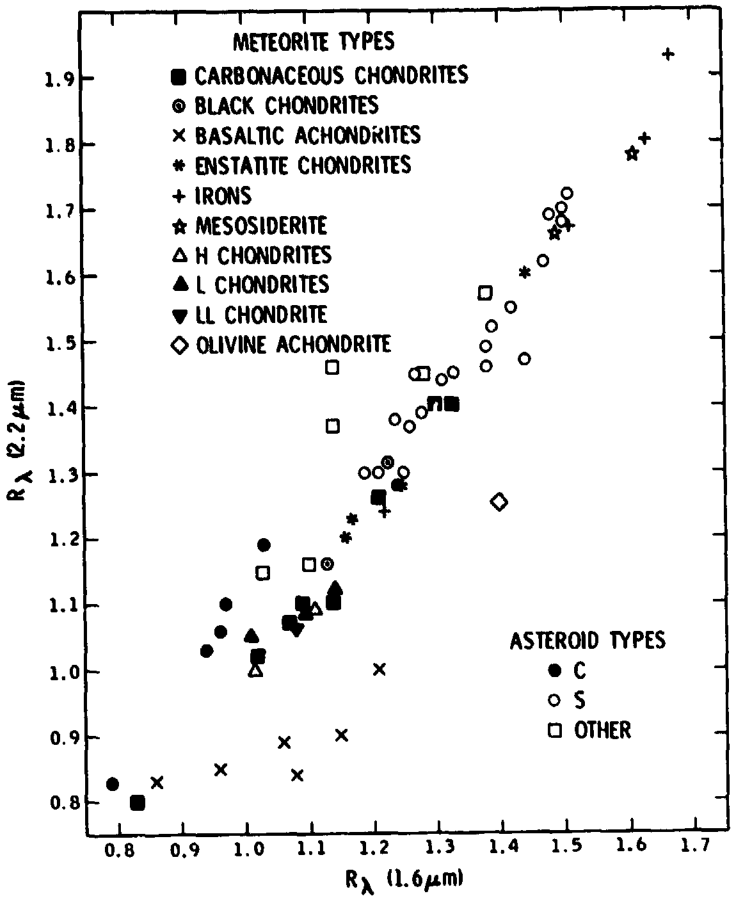


Fig. 3. Comparison of asteroid and meteorite data on a color plot: $R_\lambda(2.2\ \mu m)$ versus $R_\lambda(1.6\ \mu m)$. The asteroid data are from Veeder *et al.* (1978). The meteorite data are from Gaffey (1974, 1976). While the meteorites plotted here are unlikely to be fragments from any of the asteroids shown, they do provide a set of natural compositional hypotheses. For example, the reddest asteroids fall among the data for iron and mesosiderite meteorites. It now appears that the known space weathering processes do not operate significantly to redden asteroids. Thus, the presence of a metallic phase is strongly suggested (Matson *et al.*, 1977b). As one can see in the above plot, several compositional hypotheses appear able to explain the 1.6 and 2.2 µm infrared reflectance data. Further optical tests will help to distinguish between them, or perhaps will point to a closely related composition not currently represented in the meteorite sample. This has already proved to be the case for Vesta.

The meteorite data more than span the range of the asteroid data. There are carbonaceous chondrites which are as low in infrared reflectance as 2 Pallas and there are irons and mesosiderites which exceed the redness of the reddest known asteroids. Note that all of the meteorites which are as red as the reddest asteroids have a significant metallic phase. However, when Figure 3 is considered in detail it remains obvious that there are asteroids which do not correspond to any of the meteorites thus far measured. On the other hand, there are clear examples of types of meteorite materials which have not yet been observed telescopically. The olivine achondrites provide a case in point.

It may be significant that the carbonaceous chondrites do not exactly coincide with the C asteroids. The C asteroids tend to be redder, having a higher reflectance at 2.2 μm relative to their 1.6 μm reflectance than the corresponding meteorites. This effect cannot be easily explained by reddening the reflectance curve due to particle or grain size effects. Johnson and Fanale (1973) measured meteorite reflectances as a function of grain size. Examination of their data for the C2 meteorite Mighei, for example, shows that this type of reddening would move the plotted meteorite data along the trend of the meteorite data already plotted in Figure 3 and not perpendicular to it. There is also the possibility that the meteorite spectra have been affected somewhat by Earth weathering (Gaffey, 1976). Of course, the sample of meteorite data is not complete. Furthermore, there are cases of samples of the same meteorite being considerably different. The C1 meteorite Orgueil provides such an example. The effect of phase on $R_\lambda(1.6\ \mu m)$ and $R_\lambda(2.2\ \mu m)$ has been investigated by Veeder *et al.* (1978). They find no significant variation. This led them to the conclusion that the 1.6 and 2.2 μm phase coefficients are similar in magnitude to that in the visual. Color dependent photometry calibration, or the H-K solar color, might be in error by 0.1 magnitude and cause the C asteroids not to coincide with the carbonaceous chondrites, but we do not think that this is a very likely possibility. Zellner *et al.* (1975) have also noticed a similar effect in the UBV data. Thus, we are not yet able to detail the nature of the differences in terms of either composition or morphology, although the general agreement in albedo and shape of the reflectance spectrum between C asteroids and carbonaceous meteorites remains evidence that they are compositionally similar.

Space weathering or the alteration of surface optical properties on a planetary object as a result of exposure to the space environment has been a source of concern ever since it was realized that the lunar soils are different from the optical properties of rocks or rock powders. The effect of maturation on the optical properties of lunar soils is a systematic darkening and "reddening," or steepening of the reflectance spectrum continuum. At the optically "young" stage are the fresh crystalline rocks and powders, as seen in the laboratory and in the rims of fresh, young craters on the Moon. These rocks exhibit high albedos and reflectance spectra which are typically flat and have one or more electronic absorption bands (see Adams and McCord, 1971). At the optically "mature" end of the scale are the mare soils having low albedos and very red reflectance spectra without strong bands.

The optical maturation of asteroid regoliths has been studied by Matson *et al.* (1977b) and compared with the lunar example. They found: (1) that space weathering has not significantly altered asteroid optical properties; (2) that the most probable reasons for this fact relate to the lack of optically mature impact regoliths on low gravity objects; and (3) that within this context comparisons of asteroid spectra with powdered (but "unweathered") meteorite and other rock samples are valid.

Recently a search for absorption bands due to H_2O on asteroid surfaces has been initiated by Lebofsky (1977, 1978). In the 3-4 μm wavelength region of Ceres' spectrum he found evidence for the presence of water of hydration (see Table 2 and Figure 4). This spectral feature was confirmed subsequently by Feierberg *et al.* (1977). In Figure 4 the results have been rescaled to $R_{1.25} = 0.98$ ($R_{0.56} = 1.0$) and plotted along with the shorter wavelength data on Ceres (Chapman *et al.*, 1973; Johnson *et al.*, 1975). The normalized reflectances of three different meteorites have also been plotted for comparison. An absorption feature can clearly be seen in the Ceres spectrum and appears to be centered around 3 μm. Also, the general shape and depth of the curves in the 3-4 μm region are fairly similar to that of the Type II carbonaceous chondrite Murchison and differ significantly from the other carbonaceous chondrites. Comparison with other laboratory spectra of meteorites confirms the similarity to the spectra of Type II carbonaceous chondrites. Analogy with C2 composition suggests the presence of about 10-15% water in the form of water of hydration on the surface of Ceres. This is the first evidence of water in the surface material of an asteroid.

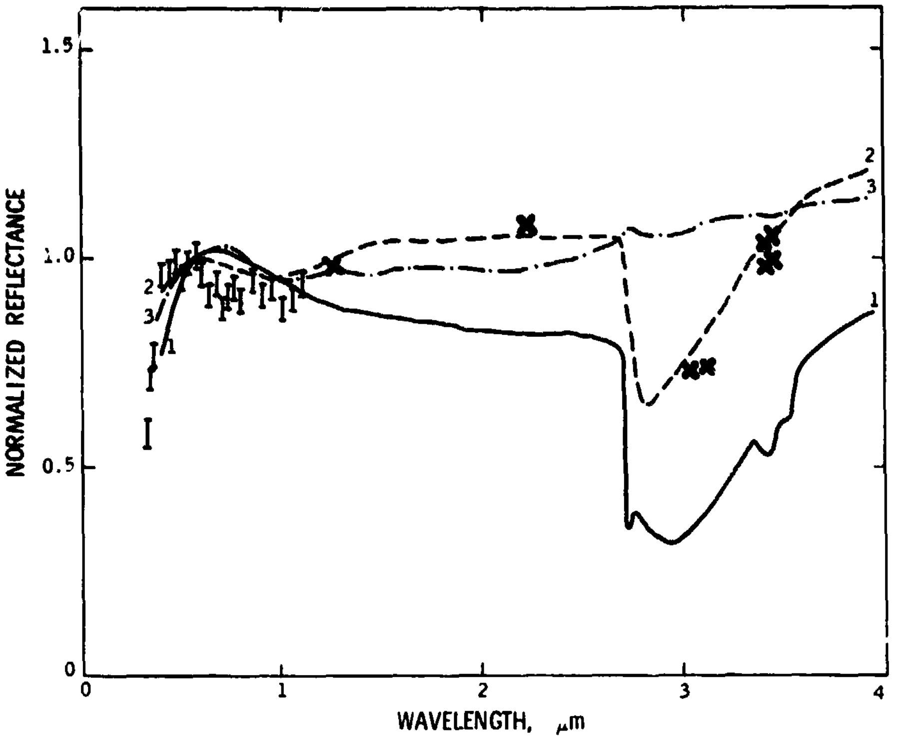


Fig. 4. Comparison of the spectrum of Ceres with three laboratory spectra of carbonaceous chondrites, scaled to 1.0 at V. The 2.5-4.0 μm spectra are unpublished data from Salisbury: (1) Orgueil, C1. 0.3-2.5 μm, Johnson and Fanale (1973); (2) Murchison, C2. 0.3-2.5 μm, Johnson and Fanale (1973); (3) Karoonda, C4. 0.3-2.5 μm, Gaffey (1974). Ceres data from 0.3-1.1 μm are from Chapman *et al.* (1973). Infrared data for Ceres are from Lebofsky (1978). The two sets of points at 3.43 and 3.45 μm give upper and lower limits after removal of thermal flux.

Infrared Spectroscopy

Advances in infrared detector technology and availability of large astronomical telescopes have made it possible to apply the techniques of Fourier transform spectroscopy to asteroids. So far, Vesta (Larson and Fink, 1975), Eros (Larson *et al.*, 1976) and Ceres (Feierberg *et al.*, 1977) have been observed. In the next few years a spectral resolution of 50 cm^{-1} will become available for many asteroids brighter than about eleventh visual magnitude.

The infrared is a key spectral region for absorption bands and the determination of band centers and shapes is essential to precise mineralogical identifications. Partly for historical reasons, the contribution thus far of infrared spectroscopy has been confined to performing detailed checks on compositional hypotheses formulated on the basis of other types of data. In the future the importance of this technique will grow as scientific interest demands ever more precise identifications of surface compositions.

THERMAL EMISSION

Introduction

The study of thermal emission radiation from asteroids has yielded a way to determine their sizes and albedos. Results are now in hand for some 200 objects. Asteroids as a whole are found to be larger and darker than was previously supposed. The typical Bond albedo of an asteroid is a few percent. Objects this dark absorb almost all of the sunlight that reaches their surface. The absorbed power heats the surface and eventually leaves the asteroid as thermal radiation concentrated in the infrared spectral region. Thus asteroids are relatively easy to detect at wavelengths of 10-20 μm.

To a first approximation, the thermal emission from an asteroid surface has a blackbody wavelength distribution (Gillett and Merrill, 1975; Hansen, 1976b). However, for the purpose of size determination, the range of available phase angles is not adequate to determine the angular distribution of infrared radiation, and thus photometric-thermal models must be constructed in order to account for thermal emission in the directions which cannot be observed from the Earth. The size and albedo of the asteroid are derived by using such models to equate the solar insolation with the sum of the total thermal emission power and the power of the scattered sunlight. For a spherical asteroid the balance between incoming and outgoing radiation may be represented by:

$$\pi R^2(1 - A)S_0 = \beta \varepsilon \sigma R^2 \int_0^{2\pi} \int_0^{\pi} T^4(\theta,\phi) \sin \phi \, d\phi \, d\theta \qquad (1)$$

where R is the radius of the asteroid, A is the bolometric Bond albedo, S_0 is the solar constant, β is a normalization constant (of order unity) whose value is determined by the angular distribution of the thermal emission, ε is the emissivity, σ is the Boltzmann constant, $T(\theta,\phi)$ is the temperature at a point on the surface at longitude θ and latitude ϕ. The Earth and Sun are both in the equatorial plane of the coordinate system at $\theta=0$, $\phi=0$.

Photometry of thermal emission from asteroids has been obtained by Low (1965, 1970), Allen (1970, 1971a), Matson (1971a,b), Cruikshank and Morrison (1973), Morrison (1973, 1974, 1976, 1977a), Morrison and Chapman (1976), Morrison *et al.* (1976), Hansen (1976a), Cruikshank (1977), Cruikshank and Jones (1977), and Lebofsky *et al.* (1978). Quantitative descriptions of the methods of deriving albedo and diameter from thermal infrared observations have been given principally by Allen (1970, 1971a), Matson (1971b), Morrison (1973, 1977c), Jones and Morrison (1974), Hansen (1977), and Lebofsky *et al.* (1978). The albedos of asteroids determined by the radiometric method compare well with those found by the polarimetric method. (The polarimetric method is an empirical relation between geometric albedo and the slope of the linear polarization at visual wavelengths as a function of phase angle (Zellner and Gradie, 1976).) Earlier differences between many of the radiometric and the polarimetric diameters (*cf.*, Chapman *et al.*, 1975; Hansen, 1977) have been resolved by the recent recalibration of the polarimetric albedo-slope relationship (*cf.*, Zellner *et al.*, 1977b, as well as Morrison, 1977c). Approximately 50 asteroids have been well observed by both techniques (*cf.*, review by Morrison, 1977c). A few diameters obtained from analyses of speckle interferometry, radar, radio, lunar occultation and stellar occultation data agree (within their estimated uncertainties) with the radiometric diameters. The use of radar is a promising new technique in asteroid studies. Diameters have been derived for 433 Eros and 1580 Betulia. The radar and visual polarimetric observations of Betulia are interesting because they do not result in a diameter in agreement with that obtained by the radiometric method. The resolution of this problem is the subject of a section of this paper.

In the following sections, three photometric-radiometric models used for interpreting radiometric data are discussed (see Table 3).

Radiometric Model 1: Lunar-Type Surface

The cratered surfaces of Mercury, the Moon and Mars as well as Phobos and Deimos are evidence of an intensive bombardment history. There is every reason to expect that the asteroids have also been bombarded and that their surfaces are heavily cratered. This type of history was also experienced by some of the meteorite parent bodies as pieces of their surface regoliths have reached the Earth as gas-rich, brecciated meteorites (*cf.*, Wilkening, 1976; Rajan *et al.*, 1974, 1975).

The larger asteroids are expected to possess well-developed regoliths. Once gravity differences are taken into account, these regoliths should resemble in many ways that of the Moon. For example, the asteroid Vesta (~550 km in diameter) has sufficient gravity that more than 95% of the ejecta from impact craters falls back to the surface. There, as on the Moon, material may be reworked by subsequent impacts (Chapman, 1971, 1976, 1978, Matson, 1971b; Gaffey, 1974, 1976). Although asteroids are small, the above statements can be made with considerable certainty because mass determinations are available for Ceres, Pallas and Vesta (Schubart, 1974, 1975; Hertz, 1968) and because laboratory data on impacts into basalt (Gault *et al.*, 1963) can be used to provide a worst case analysis leading to the same conclusions. This reasoning is consistent with the negative polarization branch of the light reflected from asteroids at small phase angles which indicates that their surfaces are covered with dust. Thus, it is reasonable to assume that the surfaces of the larger asteroids are porous or particulate.

The lunar-type model was pioneered by Allen (1970, 1971a) and Matson (1971a,b) and was the first model used to obtain asteroid sizes and albedos from infrared photometry. Further development and extensive application of this model has been done by Morrison (1973, 1976, 1977b,c), Jones and Morrison (1974), Hansen (1976b, 1977) and Chapman *et al.* (1975).

Model 1, whose parameters are tabulated in Table 3, uses the photometric and thermal properties of the lunar mare to define a model for asteroid surfaces. This model corresponds to a slowly rotating body of relatively low thermal inertia. The following assumptions are made: (1) isotropic emission from each surface element, (2) negligible emission from the non-illuminated side, (3) emissivity constant with wavelength, and (4) no conduction of heat to depth. A closely related variant allows for the possibility of nonisotropic emission from surface elements on the asteroid, *i.e.*, emission peaking toward zero phase as has been observed for the Moon by Saari and Shorthill (1972). This can be approximated by setting β = 0.8-0.9 and leaving $T(\theta,\phi)$ unchanged (however, the subsolar temperature increases); *cf.*, Jones and Morrison (1974). A recent remodel due to Hansen (1977) also accounts for some backside emission. The result of such corrections for nonisotropic emission is on the order of 5-10% reduction in the derived diameter of the asteroid.

Table 3. Model Parameters

Parameter	Model 1	Model 2	Model 3
Analogy	Lunar Surface	Rock	Iron Meteorite
Thermal Response	Low Thermal Inertia	High Thermal Inertia	High Thermal Inertia
Rotation	Slow	Rapid	Rapid
β	1.0	π	π
Emissivity, ϵ	1.0	1.0	0.1
$T(\theta,\phi)$, $\lvert\theta\rvert \leq 90^\circ$	$T_{max} \cos^{1/4}\theta \cos^{1/4}\phi$	$T_{max} \cos^{1/4}\phi$	$T_{max} \cos^{1/4}\phi$
$\lvert\theta\rvert > 90^\circ$	0	$T_{max} \cos^{1/4}\phi$	$T_{max} \cos^{1/4}\phi$

The lunar-type model has been used to interpret the photometry of thermal emission from about 200 asteroids. A recent review of this effort has been written by Morrison (1977c). A table of diameters appears in this volume (Morrison, 1978). Diameters of Vesta have been determined by three other methods. The results are compared in Table 4.

Table 4. Vesta's Diameter by Different Methods

Method	Diameter (km)	Reference
Radiometry*	538 ± 54**	Morrison (1977a) Hansen (1977)
Polarimetry	536 ± 54	Computed from data in Zellner *et al.* (1977c)
Radio	597 ± 41	Computed from data and model of Conklin *et al.* (1977)
Speckle Interferometer	513 ± 51	Worden *et al.* (1978)

*Model 1
**Estimated error

Radiometric Model 2: Rock Surface

While the possibility of the failure of some of the assumptions used in the infrared method has been considered previously (Matson, 1971b, 1975), the data recently obtained for 1580 Betulia by Lebofsky *et al.* (1978) provide the first concrete example where Model 1 does not give results consistent with those obtained by other methods. Based on a comparison with the diameters determined from visual polarimetric (Tedesco *et al.*, 1978) and radar data (Pettengill, personal communication), it would appear that Model 2 as described in Table 3 better represents the actual temperature distribution on the surface of Betulia. This model would imply that the surface thermal properties are dominated by material of high thermal inertia (*e.g.*, rock). While at first this would appear to be in disagreement with the polarimetric results which indicate a dusty surface, any discrepancy would be resolved, if, for example, the rock is covered with a very thin layer of dust.

Clearly, it is possible that the surface of such a small asteroid could consist only of bedrock. However, it is more likely that some regolith is present. Blocks as large as the thermal wavelength (∿20 cm) or larger can be present on the surface without significantly reducing the thermal inertia. The effect of such boulder fields has been considered previously in studies of lunar eclipse and lunation cooling data, where they provide an effective means to retain heat into the lunar night (Fudali, 1966; Allen, 1971b; Mendell and Low, 1975). If the polarimetric diameter of Betulia is assumed to be correct, it is then possible to use the requirement of high thermal inertia to place a limit on the amount of fine grain material present. The limit on the areal coverage (using a linear combination of Models 1 and 2) of this material is $\lesssim 40\%$ (Lebofsky *et al.*, 1978).

Parameters for Model 2 are indicated in Table 3 and the results are shown in Figure 5 for representative objects in the main belt (*i.e.*, P = 2.7 AU). The main differences of these spectra from those of Model 1 are that a significant amount of thermal emission is shifted to large phase angles (in particular to the night hemisphere) so that the apparent infrared flux observed at the Earth is reduced relative to Model 1. In addition, the effective temperature is lowered so that the radiation peak is shifted to slightly longer wavelengths.

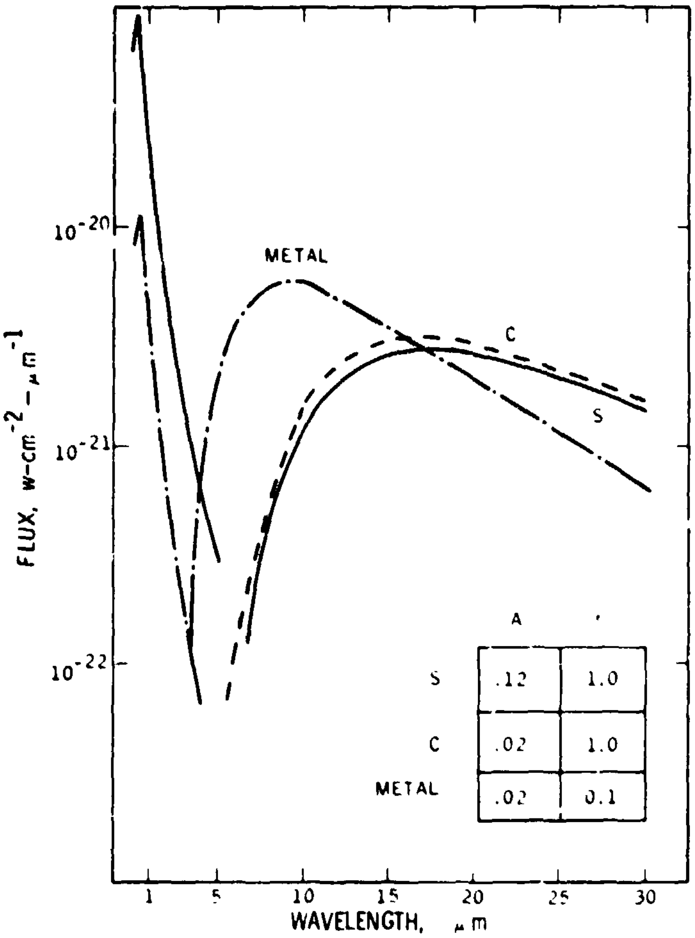


Fig. 5. A comparison of the spectra for C and S asteroids (Model 2) and a metallic asteroid (Model 3) with radii of 1 km at a solar distance of 2.7 AU representative of the main belt Relatively rapid rotation with high thermal inertia results in a significant amount of thermal emission from the night side and a decrease in infrared flux observed at the Earth. Rapid rotation also lowers the effective temperature relative to Model 1 and shifts the peak of the thermal emission to longer wavelengths. The low emissivity characteristic of metallic surfaces increases the effective temperature and shifts the peak of the thermal emission to shorter wavelengths.

Radiometric Model 3: Iron Surface

With modern advances in infrared technology the limiting magnitude to which astronomical objects can be observed has become much fainter. In the future advanced instruments such as the Infrared Astronomical Satellite, Space Telescope and other spacecraft will lead to other significant advances. A few years from now, it will be possible to observe main belt asteroids with diameters as small as tens to hundreds of meters. In this size range it is likely that a number of metal asteroids, analogous to the iron meteorites, will be discovered. In fact, some larger metal-rich objects have already been suggested on the basis of reflection spectroscopy (McCord and Gaffey, 1974; Gaffey and McCord, 1977; Matson *et al.*, 1977a; Veeder *et al.*, 1978).

With these considerations in mind we have started an investigation of Model 3. This model corresponds to a homogeneous metal sphere. As such, it has low emissivity and very high thermal inertia, as indicated in Table 3 and shown in Figure 5. As in Model 2 a significant amount of infrared flux is emitted at large phase angles. The low emissivity raises the effective temperature of the model surface and shifts the radiation peak to shorter wavelengths. The assumption of a low albedo for such an object is as yet only a guess. The chief result of this exercise is to determine the gross characteristics of the thermal spectrum and to develop criteria for recognizing metal-rich asteroids.

DIRECTIONS FOR FUTURE INFRARED RESEARCH

There are a number of problems toward which work can be directed profitably:

a. It is important to determine if the degree of redness (*e.g.*, $R_\lambda(2.2\ \mu m)$ can be correlated quantitatively with the metal content (*cf.*, McCord and Gaffey, 1974; Gaffey and McCord, 1977).

b. The presence of significant amounts of metal has implications which need to be studied for the radiometric and the polarimetric methods of asteroid size determination.

c. It is important to extend the size of the sample of observed asteroids and meteorites. For example, the Trojan asteroids are known to be significantly different from other asteroids, as well as unlike *any* laboratory sample (McCord and Chapman, 1975).

d. Theoretical studies should be conducted on the origin and evolution of the asteroids using the asteroid reflectance data as well as the meteorite data as boundary conditions.

These and other ground-based efforts will: (1) identify interesting asteroids as potential targets for spacecraft missions, and (2) characterize the asteroids as a whole so that detailed observations from spacecraft visits to a few can be placed in proper context and be used to further understand the origin and evolution of the solar system.

Asteroid observers in Earth-orbit will immediately have the entire thermal emission spectrum available to them as well as all the diagnostic bands in the infrared reflection spectrum. In addition, observations from space have some engineering advantages. It is possible to suppress thermal emission from the telescope and other instrument surfaces by cooling them. Atmospheric emission background no longer floods the detectors, and the limit in performance is lowered to the level of the zodiacal light and of the detectors themselves. The general levels of accuracy and precision are increased because corrections for atmospheric extinction are not needed. The science return from these advances is expected to be great. Observations of the entire thermal emission and reflection spectra will immediately result in improved thermal models and hence more accurate albedos and sizes, and in better interpretations of surface composition. It will be possible to search for compositional information not only via the model emissivity but also directly by measuring any Reststrahling and Christiansen bands present. These bands are related to the Si:O ratio (*i.e.*, the degree of polymerization of the SiO_4 tetrahedron) and the index of refraction, respectively.

Flyby and rendezvous observations will give spatial resolution across the asteroid's surface. This will allow the mapping of geologic units based upon their reflection and thermal properties. Chief goals for spacecraft measurements of the reflected infrared radiation (1-5 μm) are: (1) to map the compositional units on asteroid surfaces at a resolution of better than 1 km for large asteroids (such as Ceres and Vesta) and at better than 1 m for small asteroids (1-10 km diameter), (2) to establish the variety of chemical species present including discrete classes and mixtures of, for example, ices, silicates, oxides, and metals, (3) to study the variation of the degree of hydration within individual units and from one asteroid to another, (4) to map the angular distribution of the scattered infrared radiation and to use this information to infer surface texture and morphological and other properties which are otherwise not directly observable. Emitted thermal data obtained at large phase angles and across the terminator will yield maps of the thermal inertia. Strong constraints on regolith grain size will result. In addition, the amount of bare rock or boulders exposed will be immediately apparent. The detailed study of several asteroids by these methods will give the necessary absolute calibration for future remote infrared observations from the ground or Earth-orbit.

In addition to the foregoing there is an experiment, conceptual in nature, that requires study and development before its implementation can be assessed properly. A small scanning spacecraft at one of the Lagrange points of the Earth-Sun system can be used to search for Apollo asteroids. These objects are relatively bright in the infrared and can be distinguished readily from the celestial background by using their relative motion and spectral signatures. Such an experiment would scan a great circle on the celestial sphere, thus defining a plane. Any object crossing this surface would be discovered, permitting intensive study by all available techniques. A more sophisticated experiment might include the main belt asteroids. The scientific return from this experiment would include a determination of the number density of asteroids as well as identifications according to compositional types.

For the near future, the most important advances from space are likely to come from the IRAS (Infrared Astronomical Satellite) observatory scheduled for launch in 1982. This satellite will be capable of carrying out a total sky survey in a number of infrared bandpasses reaching to a 10 μm N magnitude of about 7 (Aumann and Walker, 1977). If appropriate data processing can be carried out to retrieve the asteroid observations, it may be possible to obtain radiometric diameters of essentially all of the asteroids with known orbits, thus increasing our catalog of diameters by more than an order of magnitude.

ACKNOWLEDGMENT

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS7-100, sponsored by the National Aeronautics and Space Administration.

REFERENCES

Adams, J. B., and McCord, T. B. (1971). Optical properties of mineral separates, glass and anorthositic fragments from Apollo mare samples. *Proc. 2nd Lunar Sci. Conf.*, 2183-2195.

Allen, D. A. (1970). The infrared diameter of Vesta. *Nature* 227, 158-159.

Allen, D. A. (1971a). Infrared diameters of asteroids. In *Physical Studies of Minor Planets* (T. Gehrels, ed.), pp. 41-44. NASA SP-267.

Allen, D. A. (1971b). Infrared studies of the lunar terrain - II: Thermal anomalies. *The Moon* 2, 435-462.

Aumann, H. H., and Walker, R. G. (1977). Infrared astronomical satellite. *Optical Engineering*. In press.

Chapman, C. R. (1971). Surface properties of asteroids. Ph.D. Thesis, Massachusetts Institute of Technology.

Chapman, C. R. (1976). Asteroids as meteorite parent-bodies: The astronomical perspective. *Geochim. Cosmochim. Acta* 40, 701-719.

Chapman, C. R. (1978). Asteroid collisions, craters, regoliths, and lifetimes. In this volume.

Chapman, C. R., and Salisbury, J. W. (1973). Comparisons of meteorite and asteroid spectral reflectivities. *Icarus* 19, 507-522.

Chapman, C. R., and Morrison, D. (1976). J, H, K photometry of 433 Eros and other asteroids. *Icarus* 28, 91-94.

Chapman, C. R., McCord, T. B., and Johnson, T. V. (1973). Asteroid spectral reflectivities. *Astron. J.* 78, 126-140.

Chapman, C. R., Morrison, D., and Zellner, B. (1975). Surface properties of asteroids: A synthesis of polarimetry, radiometry, and spectrophotometry. *Icarus* 25, 104-130.

Conklin, E. K., Ulich, B. L., Dickel, J. R., and Ther, D. T. (1977). Microwave brightnesses of 1 Ceres and 4 Vesta. In *Comets, Asteroids, Meteorites* (A. H. Delsemme, ed.), pp. 257-261. University of Toledo.

Cruikshank, D. P. (1977). Radii and albedos of four Trojan asteroids and Jovian satellites 6 and 7. *Icarus* 30, 224-230.

Cruikshank, D. P., and Morrison, D. (1973). Radii and albedos of asteroids 1, 2, 3, 4, 6, 15, 51, 433 and 511. *Icarus* 20, 477-481.

Cruikshank, D. P., and Jones, T. J. (1977). Diameter and albedo of asteroid 1976AA. *Icarus* 31, 427-429.

Feierberg, M., Larson, H., and Fink, U. (1977). Remote spectroscopic identification of carbonaceous chondrite mineralogies: Applications to Ceres and Pallas (abstract). *Bull. Amer. Astron. Soc.* 9, 503.

Fudali, R. F. (1966). Implications of the nonuniform cooling behavior of the eclipsed Moon. *Icarus* 5, 536-544.

Gaffey, M. J. (1974). Spectral reflectivity characteristics of the meteorite classes. Ph.D. Thesis, Massachusetts Institute of Technology.

Gaffey, M. J. (1976). Spectral reflectance characteristics of the meteorite classes. *J. Geophys. Res.* 81, 905-920.

Gaffey, M. J., and McCord, T. B. (1977). Asteroid surface materials: Mineralogical characterizations and cosmological implications. *Proc. 8th Lunar Sci. Conf.*, 113-143.

Gault, D. E., Shoemaker, E. M., and Moore, H. J. (1963). Spray ejected from the lunar surface by meteoroid impact. NASA TN D-1767.

Gillett, F. C., and Merrill, K. M. (1975). 7.5-13.5 micron spectra of Ceres and Vesta. *Icarus* 26, 358-360.

Hansen, O. L. (1976a). Radii and albedos of 84 asteroids from visual and infrared photometry. *Astron. J.* 81, 74-84.

Hansen, O. L. (1976b). Thermal emission spectra of 24 asteroids and the Galilean satellites. *Icarus* 27, 463-471.

Hansen, O. L. (1977). An explication of the radiometric method for size and albedo determination. *Icarus* 31, 456-482.

Hertz, H. G. (1968). Mass of Vesta. *Science* 160, 299-300.

Hunt, G. R., and Salisbury, J. W. (1970). Visible and near-infrared spectra of minerals and rocks: 1. Silicate minerals. In *Modern Geology*, pp. 283-300.

Johnson, T. V., and Fanale, F. P. (1973). Optical properties of carbonaceous chondrites and their relationship to asteroids. *J. Geophys. Res.* 78, 8507-8518.

Johnson, . V., Matson, D. L., Veeder, G. J., and Loer, S. J. (1975). Asteroids: Infrared photometry at 1.25, 1.65, and 2.2 μm. *Astrophys. J.* 197, 527-531.

Jones, T. J., and Morrison, D. (1974). A recalibration of the radiometric/photometric method of determining asteroid sizes. *Astron. J.* 79, 892-895.

Larson, H. P., and Fink, U. (1975). Infrared spectral observations of asteroid 4 Vesta. *Icarus* 26, 420-427.

Larson, H. P., Fink, U., Treffers, R. R., and Gautier III, T. N. (1976). The infrared spectrum of asteroid 433 Eros. *Icarus* 28, 95-103.

Leake, M., Gradie, J. C., and Morrison, D. (1978). Infrared (JHK) photometry of meteorites and asteroids. *Meteoritics*. In press.

Lebofsky, L. A. (1977). 1 to 4 micron studies of asteroids and satellites (abstract). *Bull. Amer. Astron. Soc.* 9, 905.

Lebofsky, L. A. (1978). Asteroid 1 Ceres: Evidence for water of hydration. *Monthly Not. Royal Astron. Soc.* In press.

Lebofsky, L. A., Veeder, G. J., Lebofsky, M. J., and Matson, D. L. (1978). Visual and radiometric photometry of 1580 Betulia. *Icarus*. In press.

Low, F. J. (1965). Planetary radiation at infrared and millimeter wavelengths. *Lowell Obs. Bull.* 6, 184-187.

Low, F. J. (1970). Sky survey, semi-annual technical report. AF Cambridge Research Laboratories. AFCRL-70-0179.

McCord, T. B. (1978). Asteroid surface mineralogy: Evidence from Earth-based telescope observations. In this volume.

McCord, T. B., and Gaffey, M. J. (1974). Asteroids: Surface composition from reflection spectroscopy. *Science* 186, 352-355.

McCord, T. B., and Chapman, C. R. (1975). Asteroids: Spectral reflectance and color characteristics. II. *Astrophys. J.* 197, 781-790.

Matson, D. L. (1971a). Infrared observations of asteroids. In *Physical Studies of Minor Planets* (T. Gehrels, ed.), pp. 45-50. NASA SP-267.

Matson, D. L. (1971b). I. Astronomical photometry at wavelengths of 8.5, 10.5 and 11.6 μm. II. Infrared emission from asteroids at wavelengths of 8.5, 10.5 and 11.6 μm. Ph.D. Thesis, California Institute of Technology.

Matson, D. L. (1975). Asteroids: Complications for the interpretation of radiometry (abstract). *Bull. Amer. Astron. Soc.* 7, 377.

Matson, D. L., Johnson, T. V., and Veeder, G. J. (1977a). Asteroid infrared reflectances and compositional implications. In *Comets, Asteroids, Meteorites* (A. H. Delsemme, ed.), pp. 229-241. University of Toledo.

Matson, D. L., Johnson, T. V., and Veeder, G. J. (1977b). Soil maturity and planetary regoliths: The Moon, Mercury, and the asteroids. *Proc. 8th Lunar Sci. Conf.*, 1001-1011.

Mendell, W. W., and Low, F. J. (1975). Infrared orbital mapping of lunar features. *Proc. 6th Lunar Sci. Conf.*, 2711-2719.

Morrison, D. (1973). Determination of radii of satellites and asteroids from radiometry and photometry. *Icarus* 19, 1-14.

Morrison, D. (1974). Radiometric diameters and albedos of 40 asteroids. *Astrophys. J.* 194, 203-212.

Morrison, D. (1976). The diameter and thermal inertia of 433 Eros. *Icarus* 28, 125-132.

Morrison, D. (1977a). Radiometric diameters of 84 asteroids from observations in 1974-76. *Astrophys. J.* 214, 667-677.

Morrison, D. (1977b). Sizes and albedos of the larger asteroids. In *Comets, Asteroids, Meteorites* (A. H. Delsemme, ed.), pp. 177-184. University of Toledo.

Morrison, D. (1977c). Asteroid sizes and albedos. *Icarus* 31, 185-220.

Morrison, D. (1978). Physical observations and taxonomy of asteroids. In this volume.

Morrison, D., and Chapman, C. R. (1976). Radiometric diameters for an additional 22 asteroids. *Astrophys. J.* 204, 934-939.

Morrison, D., Gradie, J. C., and Rieke, G. H. (1976). Radiometric diameter and albedo of the remarkable asteroid 1976AA. *Nature* 260, 691.

Rajan, R. S., Brownlee, D. E., Heiken, G. A., and McKay, D. S. (1974). Glassy agglutinate-like objects in the Bununu howardite. *Meteoritics* 9, 394-395.

Rajan, R. S., Haneke, J. C., Smith, S. P., and Wasserburg, G. J. (1975). ^{40}Ar-^{39}Ar chronology of isolated phases from Bununu and Malvern howardites. *Earth Planet. Sci. Lett.* 27, 181-190.

Saari, J. M., and Shorthill, R. W. (1972). The sunlit lunar surface. I. Albedo studies and full Moon temperature distribution. *The Moon* 5, 161-178.

Schubart, J. (1974). The masses of the first two asteroids. *Astron. Astrophys.* 30, 289-292.

Schubart, J. (1975). The mass of Pallas. *Astron. Astrophys.* 39, 147-148.

Tedesco, E. F., Drummond III, J. D., Candy, B., Birch, P., Nikoloff, I., and Zellner, B. (1978). The Amor asteroid 1580 Betulia: An unusual asteroid with an extraordinary lightcurve. *Icarus*. In press.

Veeder, G. J., Matson, D. L., Bergstralh, J. T., and Johnson, T. V. (1976). Photometry of 433 Eros from 0.65 to 2.2 μm. *Icarus* 28, 79-85.

Veeder, G. J., Matson, D. L., and Hansen, O. L. (1977). Photometry of the asteroid 1976AA. *Icarus* 31, 424-426.

Veeder, G. J., Matson, D. L., and Smith, J. C. (1978). Visual and infrared photometry of asteroids. *Astron. J.* In press.

Wilkening, L. L. (1976). Carbonaceous chondrite xenoliths and planetary-type noble gases in gas-rich meteorites. *Proc. 7th Lunar Sci. Conf.*, 3549-3559.

Worden, S. P., Stein, M. K., Schmidt, G. D., and Angel, J.R.P. (1978). The angular diameter of Vesta from speckle interferometry. *Icarus* 32, 450-457.

Zellner, B. (1975). 44 Nysa: An iron-depleted asteroid. *Astrophys. J.* 198, L45-L47.

Zellner, B. (1978). Geography of the asteroid belt. In this volume.

Zellner, B., and Gradie, J. (1976). Minor planets and related objects. XX. Polarimetric evidence for the albedos and compositions of 94 asteroids. *Astron. J.* 81, 262-280.

Zellner, B., and Bowell, E. (1977). Asteroid composition types and their distributions. In *Comets, Asteroids, Meteorites* (A. H. Delsemme, ed.), pp. 185-197. University of Toledo.

Zellner, B., Wisniewski, W. Z., Andersson, L., and Bowell, E. (1975). Minor planets and related objects. XVIII. UBV photometry and surface composition. *Astron. J.* 80, 986-995.

Zellner, B., Andersson, L., and Gradie, J. (1977a). UBV photometry of small and distant asteroids. *Icarus* 31, 447-455.

Zellner, B., Lebartre, T., and Day, K. (1977b). The asteroid albedo scale - II. Laboratory polarimetry of dark carbon-bearing silicates. *Proc. 8th Lunar Sci. Conf.*, 1111-1117.

Zellner, B., Leake, M., Lebartre, T., Duseaux, M., and Dollfus, A. (1977c). The asteroid albedo scale - I. Laboratory polarimetry of meteorites. *Proc. 8th Lunar Sci. Conf.*, 1091-1110.

Zellner, B., Leake, M., Morrison, D., and Williams, J. G. (1977d). The E asteroids and the origin of the enstatite achondrites. *Geochim. Cosmochim. Acta* 41, 1759-1767.

DISCUSSION

McCORD: Can you say whether the H_2O bands observed on Ceres indicate water, or water of hydration? It is a problem not only on the asteroid, but on the satellites as well.

MATSON: Clearly in the laboratory the spectrum of Murchison is due to water of hydration; whether it is water of hydration on Ceres, I don't know.

MORRISON: I would like to make a skeptical comment concerning the use of thermal measurements to obtain compositional data. Although some information on composition is surely present, the fact is that no demonstration of the utility of thermal spectra has been made, largely due to masking of compositional effects in real objects with regolith surfaces. I expect asteroid thermal spectra will turn out to be nearly featureless blackbodies.

VEVERKA: In your thermal models do you allow for nonspherical objects? Couldn't you match Betulia's thermal spectrum by changing the shape?

MATSON: These models assume spherical shapes. Betulia was observed for a long time over several nights, and the infrared lightcurve indicates that shape is not important. The nice thing about these lunar type models, if they work, is that the thermal conductivity is so low that each element is virtually in instantaneous equilibrium with sunlight. If you put shape into the models, there might be only a 10 or 20% difference.

McCORD: Are you sure there is not an error in the flux measurement itself?

MATSON: That was my first reaction but the observations were so closely linked with standard stars that there is no way to question them. So we had to consider another model based upon the fact that Betulia is a small object and at some size one should start to see rocks instead of regolith.

ARNOLD: Let me ask how thick a dust layer you are assuming in your Model 2?

MATSON: It is too thick if it becomes a thermal impediment and reduces the thermal inertia. So it has to be thick enough, at least a few microns, to get the polarization data but it can't be much more than a millimeter. If you had centimeters of dust, it would be thermally insulating and the lunar type model probably would work.

ARNOLD: As I will say in my paper, if you are doing gamma-ray studies, the scale length which determines whether you are looking at the underlying rock soil or the dust is tens of centimeters. And if you are doing X-ray studies, the scale length is comparable to that for optical measurements.

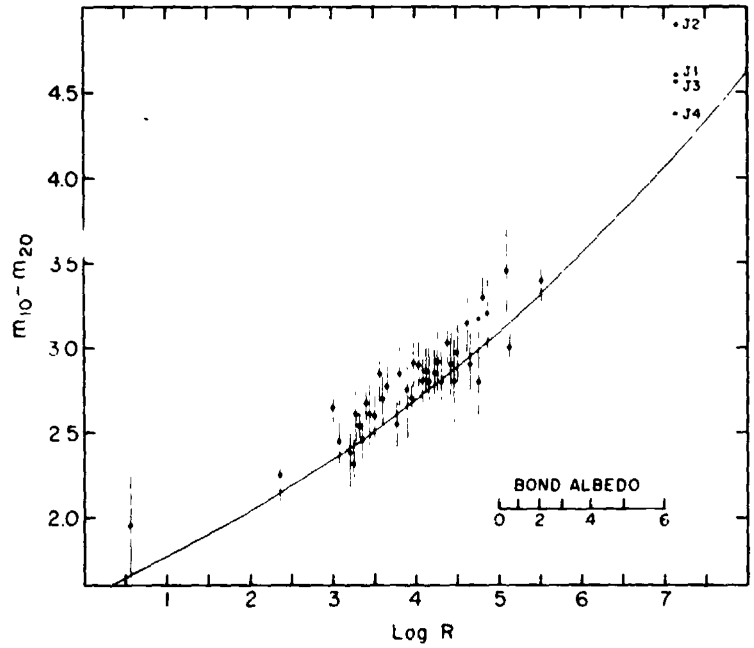
SHOEMAKER: You couldn't distinguish a surface that was broken blocks whose dimensions are typically tens of centimeters from a solid. You can have a regolith of very coarse blocks.

MATSON: We see that on the Moon. A boulder field is seen as a thermal anomaly after dark. It is essentially like bare rock.

CHAPMAN: Isn't it the case that the 10 and 20 μm data, which we have or can obtain, can really distinguish between your Models 1 and 2 and the metal model?

MATSON: Yes. However, you could gain a lot if you could go above the atmosphere or into space and get data at about 7 μm and at 30 or 50 μm. Using 10 and 20 μm data is harder because the effect isn't as large compared to the errors in the data.

MORRISON: I published a graph showing 10 to 20 μm color indices for about 35 asteroids in 1974. There were no anomalies. And since then I have looked at a much larger sample amounting to almost 100 observations and have seen no anomalies of the magnitude that you have calculated for a pure metal model. Clearly smaller anomalies get lost. But it is still interesting that there is a fairly substantial set of data which do not show this effect. (Figure from Morrison (1974) follows.)



MATSON: When you start mixing metals and silicates it gets extremely complicated. But clearly if there is an asteroid with a great deal of metal on or very near the surface, it will be recognized by thermal radiometry.