5

ASTEROID INFRARED REFLECTANCES AND COMPOSITIONAL IMPLICATIONS

D. L. MATSON, T. V. JOHNSON and G. J. VEEDER

This paper assesses the state of asteroid infrared reflectance measurements and discusses what they have contributed to our understanding of asteroidal surfaces. The data suggest that space weathering has not significantly affected the optical properties of the asteroids. Thus comparisons of asteroid reflectance spectra with unweathered meteorite and rock data is a valid procedure. The high 1.6 and 2.2 μm reflectances of a number of asteroids strongly suggest the presence of a metallic phase.

INTRODUCTION

The measurement of reflectances at wavelengths of 1.25, 1.6 and 2.2 μm yields important information about asteroid surface composition and the processes by which these surfaces have been modified. Further, it more than doubles the wavelength range over which asteroids may be compared with reflectivity data available for meteorites and other laboratory samples. As a result, it is now possible to classify asteroids better and to devise more precise tests for hypotheses about their surface compositions.

The need for asteroid photometry at these wavelengths 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, 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 half a micron or more in width. Therefore, existing astronomical infrared bandpasses and more important, existing system 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 several infrared wavelengths. 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) light curve, (2) aspect, and (3)

https://doi.org/10.1017/S0252921100070123 Published online by Cambridge University Press

phase effects. Chapman and Morrison (1976) have reported J, H, and K photometry for 433 Eros and 8 other asteroids. Veeder *et al.* (1976a,b, 1977) have observed 30 asteroids at 0.56, 1.6 and 2.2 μm and derived the infrared relative reflectances for these objects.

Photometry and spectroscopy are highly 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 and 433 Eros are now available (Larson and Fink 1975; Larson *et al.* 1976). These spectra allow precise band centers to be determined and as such are very important for compositional identifications. It is indeed lamentable that there is not an abundance of asteroids with observable infrared bands. Based on the statistics of asteroid types (Chapman *et al.* 1975; Zellner and Bowell 1977) we estimate that some eighty to ninety percent of the asteroids will exhibit 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 spectral investigations.

The purpose of the remainder of this paper is to assess the state of asteroid infrared reflectance measurements (in the 1 to 3 μm wavelength range) and to set forth what they have contributed to our understanding of asteroidal surfaces.

OBSERVATIONAL DATA

The available infrared reflectance data for asteroids has been drawn together in Table I. The only published reflectances at 1.25 μm are those of Johnson *et al.* (1975). However, magnitudes published by Chapman and Morrison (1976) are used here together with the observations of the same asteroids by Veeder *et al.* (1977) 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 I.

On the whole, there is reasonable agreement between the reflectances reported for the same asteroids by different papers (based on data from different epochs). However, there are some notable exceptions. The largest difference between Johnson *et al.* (1975) and Veeder *et al.* (1977) is for 2 Pallas. Although their error bars do overlap at 1.6 μm and almost so at 2.2 μm tending to indicate that the discrepancy is not very serious, we are inclined to accept the values reported by Veeder et al. (1977) as being the most reliable. This is because the latter work carefully measured *both* visual and infrared magnitudes. On the other hand, Johnson *et al.* (1975) used data drawn from the literature to calculate the visual magnitude at the epoch of the infrared observations. Though they correctly recognized uncertainty due to the light curve, and used the correct phase coefficient (0.037 magnitude per degree found by Müller in 1897 and recently confirmed photoelectrically by Schroll and Haupt 1976) a discrepancy of about 0.2 magnitude still remains. We now believe that this is due to the change in viewing aspect between the epochs of the visual and infrared photometry.

The magnitudes obtained by Veeder *et al.* (1977) can be compared with those of Chapman and Morrison (1976). This is done by means of a color-color plot of Fig. 1. The agreement is reasonable except for 129 Antigone for which the disagreement is greater than 0.1 magnitude in the *color*. Here, we prefer the data of Veeder *et al.* (1977) because they observed Antigone on 6 different nights distributed over 2 different oppositions.

The problems of light curve and phase effect induced variations in R_λ have been considered by all observers. They have designed their photometry programs so as to minimize any variations in R_λ due to light curves. However, there is

https://doi.org/10.1017/S0252921100070123 Published online by Cambridge University Press

TABLE I

INFRARED REFLECTANCES

Asteroid	R_λ 1.25 μm	R_λ 1.6 μm	R_λ 2.2 μm	Type[6,7]	Footnote
1 Ceres	0.98 ± 0.09	0.99 ± 0.09	1.08 ± 0.09	C	1
		0.97 ± 0.13	1.06 ± 0.11		4
2 Pallas	1.05 ± 0.09	0.97 ± 0.09	1.05 ± 0.09	C	1
		0.81 ± 0.09	0.85 ± 0.08		4
3 Juno		1.23 ± 0.10	1.28 ± 0.09	S	4
4 Vesta		1.18 ± 0.14	1.29 ± 0.14	-	1
		1.13 ± 0.07	1.18 ± 0.07		4
5 Astraea	1.18 ± 0.16	1.29 ± 0.11	1.33 ± 0.14	S	4,3
6 Hebe	1.18 ± 0.15	1.25 ± 0.09	1.33 ± 0.13	S	4,3
7 Iris	1.20 ± 0.10	1.39 ± 0.07	1.48 ± 0.08	S	4,3
8 Flora		1.46 ± 0.09	1.59 ± 0.11	S	4
9 Metis		1.34 ± 0.13	1.50 ± 0.11	S	4
10 Hygiea		0.99 ± 0.07	1.09 ± 0.10	C	4
12 Victoria		1.55 ± 0.12	1.77 ± 0.13	S	4
14 Irene		1.42 ± 0.08	1.56 ± 0.10	S	4
16 Psyche		1.17 ± 0.09	1.41 ± 0.11	M?	4
19 Fortuna		1.00 ± 0.11	1.13 ± 0.11	C	4
20 Massalia		1.32 ± 0.09	1.42 ± 0.10	S	4
22 Kalliope		1.20 ± 0.17	1.45 ± 0.11	M?	4
27 Euterpe		1.30 ± 0.11	1.41 ± 0.11	S	4
29 Amphitrite			1.31 ± 0.08	S	4
39 Laetitia		1.42 ± 0.08	1.54 ± 0.08	S	4
43 Ariadne		1.48 ± 0.12	1.51 ± 0.19	S	4
44 Nysa		1.06 ± 0.10	1.18 ± 0.11		4
51 Nemausa		1.31 ± 0.13	1.31 ± 0.10	C	4
63 Ausonia		1.55 ± 0.10	1.75 ± 0.12	C	4
129 Antigone	1.04 ± 0.10	1.30 ± 0.07	1.47 ± 0.07	-	4,3
230 Athamantis		1.37 ± 0.15	1.49 ± 0.15	S	4
349 Dembowska		1.47 ± 0.14	1.61 ± 0.19	-	4
354 Eleanora		1.52 ± 0.14	1.74 ± 0.16	S	4
433 Eros	1.3 ± 0.14	1.5 ± 0.1	1.7 ± 0.1	S	2,3
511 Davida	0.88 ± 0.11	1.06 ± 0.08	1.22 ± 0.08	C	4,3
1976 AA			1.5 ± 0.3	-	5

1. *Johnson* et al. *1975.*
2. *Veeder* et al. *1976.*
3. *These values of R_λ (1.25 μm) have been computed from the published J-K magnitudes of Chapman and Morrison (1976) using the formula:* R_λ *(1.25 μm)* $= R_\lambda$ *(2.2 μm) dex* $\{-0.4[(J-K)_{asteroid} - (J-K)_{sun}]\}$. *The values of R_λ (2.2 μm) are those in the above table and $(J-K)_{sun}$ is 0.25 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_λ (2.2 μm) are random.*
4. *Veeder* et al. *1977.*
5. *Veeder, Matson and Hansen 1977.*
6. *These classifications are given by Chapman, Morrison and Zellner (1975).*
7. *Type "M" asteroids have been discussed by Zellner* et al. *(1976), Morrison (1977), Veeder* et al. *(1977).*

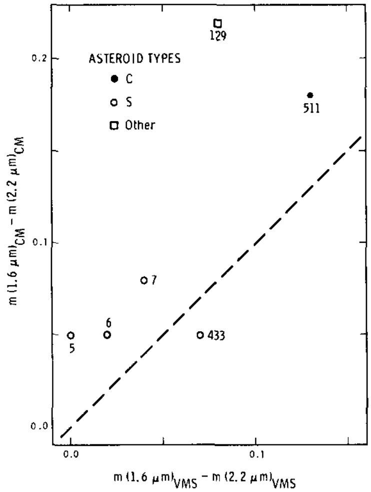

Figure 1. Color comparison plot. The ordinate is the m(1.6 μm) - m(2.2 μm) color of Chapman and Morrison (1976). The abcissa is the data of Veeder et al. *(1977). This plot provides a test of the consistency of the two sets of observations. The dashed line is the locus of perfect agreement. The asteroid types are defined by Chapman* et al. *(1975).*

still the possibility that an asteroid may have different colored faces. While this remains a very exciting possibility, it has been the common experience to find that all asteroids which have been carefully examined do not have any significant (*i.e.*, easily detectable) color variation across their surfaces. The effect of phase on R_λ (1.6 μm) and R_λ (2.2 μm) has been investigated by Veeder *et al.* (1977). 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.

Infrared reflectance data is quite useful for asteroid classification. This can be shown in one way by plotting the visual geometric albedo versus R_λ (2.2 μm) as in Fig. 2. On this plot the "C" asteroids are clearly separated from the others. The cluster of points to the left contains not only "S" but also other asteroids such as 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. 44 Nysa has a very high albedo, perhaps in excess of 0.3 or 0.4 (Zellner 1975; Morrison 1977), but has a R_λ (2.2 μm) otherwise characteristic of "C" asteroids. Zellner (1975) has suggested that Nysa is of an enstatite-achondrite-like composition. 2 Pallas and 51 Nemausa represent the extremes of the "C" asteroids observed in the infrared. The data of Fig. 2 suggest that we are seeing either a surface compositional or a surface morphological sequence within both the "C" and "S" classes.

U-V has proved to be a useful parameter and plotting it against m(0.56 μm) - m(2.2 μm) provides a better separation of asteroid types than does the albedo which is more strongly affected by morphological parameters such as grain size. A color versus color plot is used to display the data in Fig. 3. The "C" and "S" groups have well defined regions. Asteroids 16, 22, and 129 now cluster tightly, and are separate from the "S" objects.

From an inspection of Table I it is obvious that asteroids that have large values of R_λ (1.6 μm) also have high values of R_λ (2.2 μm). This is illustrated by plotting the two reflectances in Fig. 4. Once again the "C" and "S" objects are separated. The fact that 2 Pallas is different from other "C" objects is strongly indicated here as it was in Figs. 2 and 3. The "C" asteroid 51 Namausa has the same infrared reflectances as some of the "S" asteroids. However, its

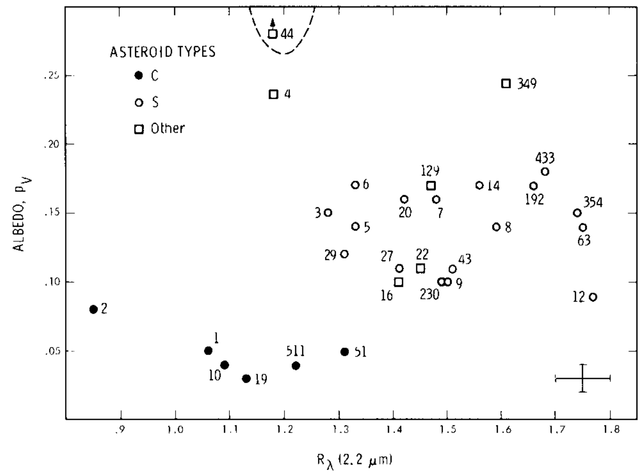

Figure 2. Geometric albedo (p_V) versus R_λ (2.2 µm). The albedos were determined by the radiometric method and are from the published values of Morrison (1974, 1977) and Morrison and Chapman (1976). Infrared relative reflectances are from Veeder et al. *(1977). Typical error bars [estimated relative error] are indicated in the lower right corner. Much of the error is systematic and does not change the relative positions of the plotted data. The asteroid types are defined by Chapman* et al. *(1975).*

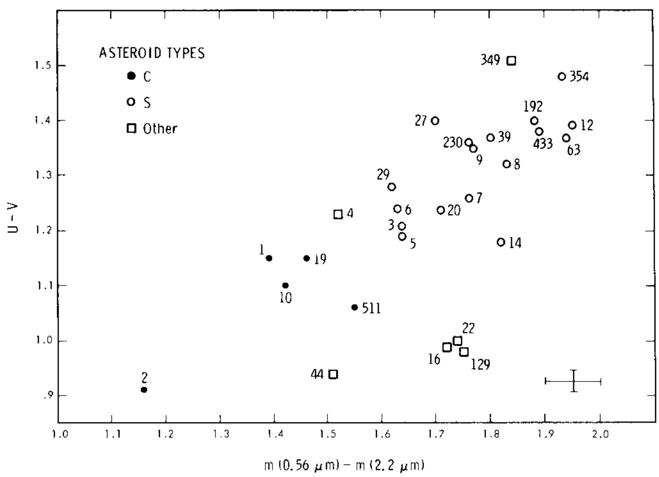

Figure 3. Comparison between ultraviolet and infrared colors. This U-V versus m(0.56 µm) - m(2.2 µm) plot was constructed using data from Zellner et al. *(1975, 1977) and Veeder* et al. *(1977). Typical error bars [estimated relative error] are indicated in the lower right corner. Much of the error is systematic and does not change the relative positions on the plot. The asteroid types are defined by Chapman* et al. *(1975).*

https://doi.org/10.1017/S0252921100070123 Published online by Cambridge University Press

visual wavelength reflectance spectrum and p_V place it in the "C" class. Thus, again we see evidence for a surface compositional or a morphological sequence among both the "C" objects and "S" objects.

DISCUSSION

Why are some of the asteroids so red? Meteorites which contain metallic phases have high infrared reflectances and thus provide good compositional hypotheses for these asteroids. On the other hand, the Moon which does not have these phases present on its surface has an extremely high 2.2 μm reflectance. Can the surfaces of asteroids be reddened by the presence of lunar-like glass in their regoliths? The reasoning presented in the next few paragraphs will lead us to conclude that the presence of a metallic phase is required.

A. Space Weathering

Alteration of surface optical properties on a planetary object, as a result of exposure to the space environment, has been an important and challenging problem ever since it was realized that the Moon is very different, optically, from ordinary rocks or rock powders. The Moon has a low albedo (~0.11) and a very red spectrum (reflectance at 2.2 μm is over three times its value at 0.56 μm, McCord and Johnson 1970) with a weak absorption near 0.95 μm (*e.g.*, Adams and McCord 1971). Study of returned samples from the Apollo and Lunar programs has greatly improved our understanding of the processes responsible for altering the optical properties of the lunar surface. While there is still debate concerning some of the processes involved and their relative importance, there is agreement on several important points: (1) lunar optical properties are dominated by the opaque fines in the lunar soil; (2) the glassy agglutinate fraction in the soil is primarily responsible for these properties causing a lowering of albedo, a reddening of the continuum and suppression of the 0.95 μm pyroxene feature; and (3) maturation of the soil is accompanied by the build up of the agglutinates and proceeds rapidly to produce "average" lunar optical properties such that only the youngest craters on the Moon (*e.g.*, Aristarchus, Tycho, etc.) are relatively unaffected by the process. Debate centers on whether vitrification and dispersal of transition metal ions (primary Fe and Ti) in the glass (*e.g.*, Adams and McCord 1971a,b; Nash and Conel 1971) or whether metal coatings (Gold *et al.* 1971) or dispersed submicron metal particles (Hapke and Wells 1976) are the primary causes of the changes in optical properties. For our purposes we will regard "space weathering" in general as the process which produces the dark, red lunar-type soils.

How has space weathering affected other solar system objects, including the asteroids? First, we note that Mercury, although drastically different from the Moon in bulk properties (particularly density), has nearly identical optical properties. In particular, the reflectance spectrum of Mercury from 0.3 to 1.1 μm is striking like the lunar curve (McCord and Adams 1972) have a nearly identical slope within the small errors and showing only slight evidence of a 0.95 μm absorption (Vilas and McCord 1976). Accurate 2.2 μm data for Mercury are not available (this wavelength is near the cross-over point between reflected sunlight and emitted thermal radiation for Mercury) but data from Kuiper (Harris 1961) indicates a 2.0 μm to 1.0 μm reflectance ratio of over 3.0, placing it in the same very red category as the Moon. Thus, Mercury also appears to have been affected by space weathering to about the same extent as the Moon, suggesting similar (although not necessarily identical) surface composition and modification processes.

The asteroids, however, present a very different picture. When the first detailed reflectance spectra were obtained for Vesta, it was immediately noted that the deep 0.95 μm band in its spectrum resembled the laboratory spectra of fresh rock powder and was similar to spectra of basaltic achondrites or lunar basalts (rock surfaces and powders, *not* fines) (McCord *et al*. 1971). McCord *et al*. concluded that the surface of Vesta was not composed of lunar-like soil with dark glassy agglutinates, even though its composition was very simliar to lunar basalts. Further studies of asteroid spectral properties in the 0.3 μm to 1.1 μm spectral range have shown that few, if any, asteroids have spectral properties at all resembling those of the Moon (*e.g.*, Chapman *et al*. 1974 and

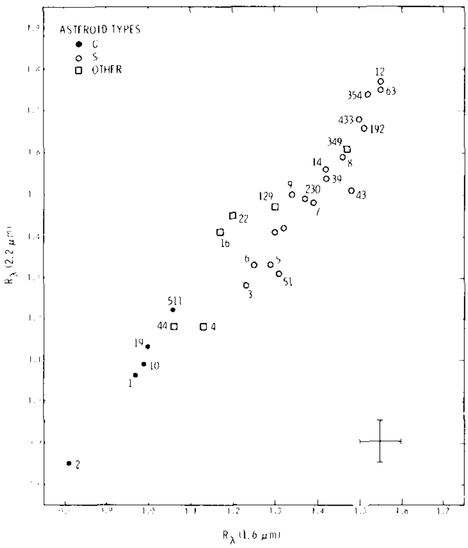

Figure 4. Color plot: R_λ (2.2 μm) versus R_λ (1.6 μm) from Table I. Typical error bars [estimated relative error] are indicated in the lower right corner. Much of the error is systematic and does not change the relative positions on the plot. The asteroid types are defined by Chapman et al. *(1975).*

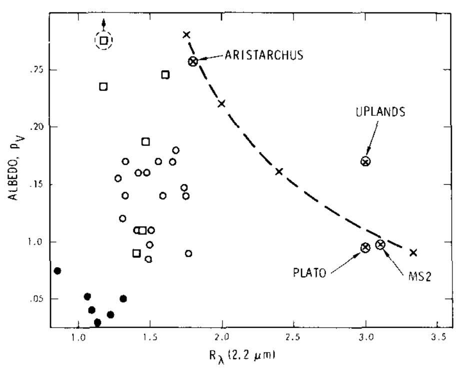

Figure 5. Geometric albedo, p_V, versus R_λ (2.2 μm). The lunar data are taken from McCord and Johnson (1970), van Diggelen (1965), and Gehrels et al. *(1965), as discussed in the text. The dashed line shows the trend observed for the reddening process in a laboratory study by Adams and McCord (1971). This plot suggests that the same process is not acting in a significant way on the asteroids.*

Chapman and McCord 1975a,b). In addition to the general shape of asteroid spectra being less red than the Moon's, there are a number of asteroids in addition to Vesta which show moderate to deep absorptions near 0.95 μm, including 8 Flora, 349 Dembowska, and 192 Nausika. As pointed out above, lunar-like space weathering characteristically suppresses such absorptions. In this context it is very important to note that of the four reddest asteroids at 2.2 μm three of them have bands in their reflectance spectra (*e.g.*, 12, 433, and 354).

The 1.6 and 2.2 μm data discussed in this paper (Section II) are very different from lunar values. Fig. 5 shows telescopic data for various lunar features (2.2 μm reflectances from McCord and Johnson 1970, and normal albedos from van Diggelen 1965 and Gehrels *et al.* 1964). Also shown are data from a laboratory study of mixtures of anorthositic fragments with lunar agglutinates (Adams and McCord 1971). [These data are hemispherical reflectances; they have been approximately converted to geometric albedos using a relation between geometric albedo and the phase integral derived from Lane and Irvine 1973]. It can be seen that none of the measured asteroids are as red at 2.2 μm as the average lunar value of ~3.0 by a wide margin. In addition, there is no evidence of any correlation between albedo and 2.2 μm reflectance for the non-C type asteroids. This is in sharp contrast to the correlation of darker albedo with redder spectra expected for space weathering and illustrated by the lunar and sample data in Fig. 5.

We conclude from the above arguments that space weathering is not significantly affecting the optical properties of the asteroids. Dollfus (1977, this volume) has reached the same conclusion based on analysis of polarization data. There are basically two classes of possible explanations for this result: (1) space weathering does not occur at all on asteroids and is somewhow specific to the Moon and (probably) Mercury and (2) space weathering occurs but does not dominate the optical properties of the body. We will briefly discuss the implications that result from some of these possibilities.

Taking the first case, it is clear that any process related to the sun or general interplanetary space conditions must operate at some level on all the airless bodies. If the process is related to micrometeoroid bombardment then the only way to satisfy the data would be to postulate that all the micrometeoroids originate at the asteroid belt and not beyond it. While this is possible, it is currently believed that comets provide an important contribution to the present day bombardment and Pioneer 10 continued to record impacts out to Jupiter's distance (Soberman *et al.* 1974a,b,c).

In the second case, that space weathering does not dominate, one obvious possibility is that asteroids have entirely different compositions from the Moon or Mercury and therefore have weathered to different end states. As discussed above, this argument is not valid at least for Vesta, since Vesta's deduced surface composition is very close to lunar basalt. There is now enough information on other asteroid compositions to evaluate this possibility more generally. Carbonaceous materials might indeed be expected to produce different optical properties under space weathering, as suggested by Johnson and Fanale (1973) on the basis of some laboratory simulations. While many of the asteroids appear to have opaque, carbonaceous chondritic-type optical properties (*e.g.*, Johnson and Fanale 1973; Chapman and Salisbury 1973; Gaffey 1976), these asteroids all have low infrared reflectances. Most of the moderate albedo, red asteroids in Fig. 5 must have compositions which are basically silicates, with iron bearing minerals such as pyroxene and olivine and perhaps free metal (McCord and Gaffey 1974). These compositions should yield soils with similar optical properties to lunar soils if subjected to identical conditions since opaques, particularly the transitions metals apparently abundant in these asteroids, tend to dominate reflection spectra. Thus, if composition is to be considered as a major cause of differences in the end products of space weathering, then space weathering

https://doi.org/10.1017/S0252921100070123 Published online by Cambridge University Press

may only operate significantly on the carbonaceous type asteroids, not the silicate and metal rich ones.

There are two major differences between asteroids and the Moon and Mercury which may affect the degree of space weathering: (1) their greater heliocentric distance and (2) their weaker gravity. Most solar dependent space weathering processes which have been proposed (such as sputter deposition of metal films) should have at least an inverse square dependence on heliocentric distance. The fact that both the Moon and Mercury appear to have weathered to nearly identical current states while the asteroids appear unaffected places severe constraints on any strictly solar process. More complicated models, involving, for instance, gardening of a regolith with solar weathering of exposed surfaces, might be affected by gravity effects as well.

In terms of the effect of gravity on space weathering, the major point is that the asteroids are in an erosional regime relative to impact while the Moon and Mercury retain almost all of the material ejected from impact produced craters. This leads to mature, reworked soils on the larger objects while limiting strongly the amoung of reworking possible for asteroid regoliths. This can operate to reduce the effect of space weathering in at least two ways. First, the dark glassy material produced in impacts may be concentrated in the high velocity component of the ejecta which is more likely to escape from asteroids. Second, asteroid regoliths are expected to be thinner thus reducing the significance of "spot" melting at particle or grain contact points (Kieffer 1970, 1971). Finally, individual particles in the soil on an asteroid are less likely to be melted or shocked many times before escape, which may be important in producing lunar soil like characteristics.

We conclude: (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 ateroid spectra with powdered (but "unweathered") meteorite and other rock samples is valid.

B. Comparisons with Meteorites

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 Fig. 6. In this figure, the smaller unlabeled symbols are the asteroid data plotted on the same scale as in Fig. 4.

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 Fig. 6 is considered in detail it remains obvious that there are asteroids, numbers 16 and 22 for example, 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 Fig. 6 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 com-

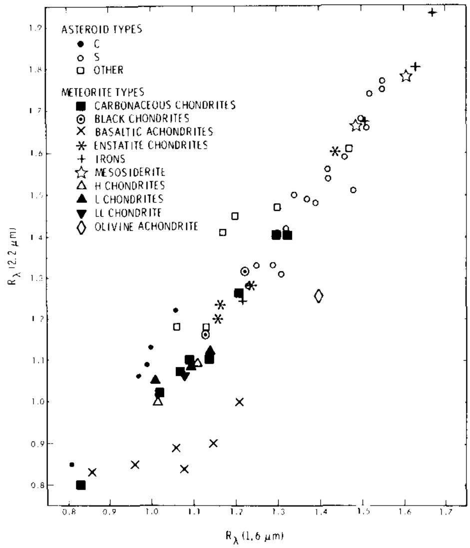

Figure 6. Comparison of asteroid and meteorite data on a color plot: R_λ (2.2 μm) versus R_λ (1.6 μm). The smaller symbols are the asteroid data already shown in Fig. 4. The meteorite data are from Gaffey (1974, 1976). While the meteorites plotted here are unlikely to be fragments from any of the asteroids 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. 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.

plete. Furthermore, there are cases of samples of the same meteorite being considerably different. The Cl meteorite Orgueil provides such an example. 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 these are very likely possibilities. Zellner (1976) has also noticed a similar effect in the UBV data. Thus, the "C" asteroids are not exactly the same as carbonaceous chondritic meteorites. We are not yet able to detail the nature of their 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 strong evidence that they are compositionally very similar.

C. Further Work

There are a number of important problems toward which work can be directed profitably. (a) It is important to determine if the degree of redness (*e.g.*, R_λ(2.2 μm)) can be correlated quantitatively with the metal content. (b) The presence of significant amounts of metal has implications for the radiometric and the polarimetric methods of asteroid size determination. Under some circumstances the effect can be of major importance (Matson 1975). (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

https://doi.org/10.1017/S0252921100070123 Published online by Cambridge University Press

1975b). These objects need to be observed at 1.6 and 2.2 μm. (d) Theoretical studies using the asteroid optical data as well as the meteorite data as boundary conditions should be conducted on the origin and evolution of the asteroids.

SUMMARY

The asteroids are found to have a wide range of reflectance in the 1 to 3 μm infrared. These data, considered together with visual wavelength data, suggest that the asteroids have not been reddened by any space weathering processes in contrast to the Moon and Mercury. The high 2.2 μm reflectances of many asteroids is probably due to the presence of a metal phase in their surface compositions. The optical properties of meteorites span this range of reflectances. However, when their detailed optical properties are considered, there are meteorites for which there are no known analogies among the asteroids. Conversely, there are asteroids such as 324 Bamberga and the Trojans for which no similar meteorites have yet been discovered. These situations may be clarified somewhat in the future as the size of both samples is increased.

ACKNOWLEDGMENT

This research was supported in part by grant NGL 05-002-207 from the National Aeronautics and Space Administration and grant GP-35535X from the National Science Foundation. G.J.V. was supported by a National Research Council Resident Research Associateship during part of the period of this research. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract NAS 7-100, sponsored by the National Aeronautics and Space Administration.

REFERENCES

Adams, J. B., and McCord, T. B. 1971, in *Proc. Lunar Sci. Conf. 2nd*, 2183-2195.
Adams, J. B., and McCord, T. B. 1972, *Geochim. Cosmochim. Acta, 36, Suppl., 3*, 3021.
Chapman, C. R., McCord, T. B., and Johnson, T. V. 1973, *Astron. J., 78*, 126-140.
Chapman, C. R., Morrison, D., and Zellner, B. 1975, *Icarus, 25*, 104-130.
Chapman, C. R., and Salisbury, J. W. 1973, *Icarus, 19*, 507-522.
Dollfus, A. 1977, this volume.
Gaffey, M. J. 1974, Ph.D. Thesis, Massachusetts Institute of Technology.
Gaffey, M. J. 1976, *J. Geophys. Res., 81*, 905-920.
Johnson, T. V., and Fanale, F. P. 1973, *J. Geophys. Res., 78*, 8507-8518.
Johnson, T. V., Matson, D. L., Veeder, G. J., and Loer, S. J. 1975, *Astrophys. J., 197*, 527-531.
Gehrels, T., Coffeen, T., and Owings, D. 1964, *Astron. J., 69*, 826-852.
Gold, T., Champbell, M. J., and O'Leary, B. T. 1970, in *Proceedings of the Apollo Lunar Science Conference, 3*, 2149-2154.
Hapke, B., and Wells, E. 1976, *Lunar Science VII*, 345-347.
Harris, D. L. 1961, in *The Solar System Vol. 3: Planets and Satellites*, G. P. Kuiper and B. Middlehurst, eds., University of Chicago Press, 272.
Kieffer, S. W. 1970, Ph.D. Thesis, California Institute of Technology, Pasadena, California.
Kieffer, S. W. 1971, *J. Geophys. Res., 76*, 5449.
Lane, A. P., and Irvine, W. M. 1973, *Astron. J., 78*, 267-277.
Larson, H. P., and Fink, U. 1975, *Icarus, 26*, 420-427.

Larson, H. P., Fink, U., Treffers, R. R., and Gautier, T. N. 1976, *Icarus, 28,* 95-103.
Matson, D. L. 1975, *B.A.A.S., 7,* 377.
McCord, T. B., and Adams, J. B. 1972, *Icarus, 17,* 585-588.
McCord, T. B., Adams, J. B., and Johnson, T. V. 1970, *Science, 168,* 1445-1447.
McCord, T. B., and Chapman, C. R. 1975a, *Astrophys. J., 195,* 533-562.
McCord, T. B., and Chapman, C. R. 1975b, *Astrophys. J., 197,* 781-790.
McCord, T. B., Charette, M. B., Johnson, T. V., Lebofsky, L. A., Pieters, C., and Adams, J. B. 1972, *J. Geophys. Res., 77,* 1349-1359.
McCord, T. B., and Gaffey, M. J. 1974, *Science, 186,* 352-355.
McCord, T. B., and Johnson, T. V. 1970, *Science, 169,* 855-859.
Morrison, D. 1976, *Astrophys. J.*
Morrison, D. 1976, *Icarus, 28,* 125-132.
Morrison, D. 1977, this volume.
Müller, G. 1897, *Die Photometrie der Gestirne,* Leipzig, Engelmann.
Nash, D. B., and Conel, J. E. 1973, *J. Geophys. Res., 79,* 1615-1621.
Schroll, A., Haupt, H. F., and Maitzen. 1976, *Icarus, 27,* 147-156.
Soberman, R. K., Neste, S. L., and Lichtenfeld, K. 1974, *J. Geophys. Res., 79,* 3685-3694.
van Diggelen, J. 1965, *Planet. Space Sci., 13,* 271-279.
Veeder, G. J., Matson, D. L., Bergstralh, J. T., and Johnson, T. V. 1976, *Icarus, 28,* 79-85.
Veeder, G. J., Matson, D. L., and Hansen, O. L. 1977, *Icarus.*
Veeder, G. J., Matson, D. L., and Smith, J. C. 1977, *Astron. J.,* submitted.
Vilas, F., and McCord, T. B. 1976, *Icarus, 28,* 593-599.
Zellner, B. 1975, *Astrophys. J., 198,* L45-L47.
Zellner, B. 1976, *Icarus, 28,* 149-153.
Zellner, B., and Bowell, E. 1977, this volume.

DISCUSSION

ARNOLD: How precise can you be in distinguishing between metal and glass as a source of linear reddening in asteroid spectra, especially if a mixture of both is present?

MATSON: The claim made in this paper is merely a statistical one based upon the spread in the data of objects with the larger values of R (2.2 μm); that is the production of glass is not ubicuous among the asteroids. We can say with some certainty that red asteroids with high albedo do not have much glass in their regoliths. In the case of (4) Vesta, where a deep band is present at 0.95 μm, we can also say that the glass content is not significant because if it were then the band would not be observed, as is our experience in observing lunar mare. However, for red asteroids with low albedo we cannot yet rule out dark red glasses on the basis of R(2.2 μm).

MORRISON: It is perhaps appropriate to recall Larson's earlier comment that the JHK photometric bands are not well placed for the derivation of diagnostic information on composition. Unfortunately, telluric water bands are so located as to limit our ability to observe at the most interesting wavelengths. Thus, while H and K photometry is undoubtedly of use, it is not clear that it represents as fertile a technique as the many others for study of the surface composition of asteroids.

MATSON: Photometry and spectroscopy are highly complementary techniques. For *example, over the last several years the sensitivty of infrared astronomical interferometers has increased dramatically. Such an instrument has been applied to the asteroids and high resolution spectra of 4 Vesta and 433 Eros are now available (Larson and Fink 1975; Larson* et al. *1976). These spectra allow precise band centers to be determined and as such are very important for compositional identifications. It is indeed lamentable that there is not an abundance of asteroid with observable infrared bands. Based on the statistics of asteroid types (Chapman* et al. *1975; Zellner and Bowell 1977) we estimate that some eighty to ninety percent of the asteroids will exhibit 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 spectral investigations.*