A REVIEW OF SPECTROPHOTOMETRIC STUDIES OF ASTEROIDS*

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It has long been realized that studies of the colors of asteroids provide useful clues to their composition. However, only since the development of photoelectric photometry have measurements of asteroid colors proven to be reliable. Recently, with advances in sensors and data systems, it has become possible to measure precisely the spectral reflectivity curves of asteroids from 0.3 to 1.1 μm with higher spectral resolution than that of the *UBV* system.

Until recently, attempts to determine asteroid composition by comparing color indices for asteroids with spectral reflectivities or color indices for meteorites and terrestrial rocks have not been fruitful (Kitamura, 1959; Watson, 1938). It has been noted that the mean color indices for asteroids fall within the range for rocks and meteorites. However, there are far too many minerals for a one-dimensional characterization of asteroid color (color index) to suggest even a compositional class, let alone a specific composition. But when the full spectral reflectivity curve is well defined, for instance in the 24 narrowband interference filters we have been using, the measurements are considerably more diagnostic. Especially diagnostic are well-defined absorption bands as have been found for Vesta (McCord et al., 1970) and a few other asteroids. For instance, the position of the center of the prominent band near 0.9 μm due to Fe^{2+} is dependent on mineralogy. Spectral reflectivity measurements of rocks and meteorites that have been published show a variety of spectral features ranging in strength from a percent to a few dozen percent that are repeatable for different rocks of identical mineralogy. An understanding of the basic physics of the production of absorption bands in solids is well developed, and it is possible to infer mineralogy from spectra containing such bands with considerable confidence. On the other hand, some solids show relatively featureless spectra, characterized only by their sloping trend and perhaps a few inflection points. Obviously such spectra cannot be uniquely

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diagnostic, but they can certainly rule out many possible compositional classes. A complete catalog of spectral reflectivities for all common rocks and meteorites has not yet been assembled, though many measurements have been made (Adams, unpublished; Adams and Filice, 1967; Hunt and Salisbury, 1970; Hunt and Salisbury, 1971). Once such a catalog is constructed it should be possible to determine much about the mineralogical composition of measured asteroids, particularly those with absorption bands in their spectra.

Of great interest is the possibility of relating the many distinct classes of meteorites to specific asteroids, asteroid families, or portions of the asteroid belt, and of extending the many results of meteoritics to the asteroids. It is significant that the first conclusive identification of asteroid composition (McCord et al., 1970) shows that Vesta has a composition very similar to the Nuevo Laredo basaltic achondrite. It should soon be possible to relate the common classes of meteorites to specific asteroid families or parts of the belt, which will be a test of our understanding of the processes that transport asteroidal fragments into Earth-crossing orbits. Because the gross characteristics of most asteroid orbits probably have not changed substantially during the age of the solar system, what understanding has been achieved of the thermal and chemical environments where meteorites were formed (Anders, 1971) can then be tied to a specific location in the early solar system.

Even when unique compositional identifications are not possible, spectral reflectivity measurements permit a sorting of asteroids into classes of similar composition. Asteroids with similar reflectivities may well be genetically related, especially when the asteroid population is examined statistically. Thus we will attempt to correlate asteroid colors with orbital characteristics, size, and lightcurves. We now describe some kinds of correlations that should be searched for and some implications such correlations might have if found.

Correlation between color and semimajor axis a or the Jacobi constant (Tisserand invariant) may well be indicative of differences in the condensation of the solar nebula as a function of distance from the Sun. To the extent that it may be possible that ices could be stable over long durations in the outer parts of the asteroid belt (Watson, Murray, and Brown, 1963), some correlations with a could reflect on-going processes or conditions in the asteroid belt integrated over the age of the solar system.

Asteroids with unusual inclinations or eccentricities have orbited the Sun in a different space environment than have most asteroids. In particular, the spatial density of small asteroids, meteoroids, micrometeoroids, and interplanetary dust is probably substantially lower away from the main part of the asteroid belt. On the other hand, the relative impact velocities against such space debris will be higher for asteroids in inclined or eccentric orbits. The glasses produced by hypervelocity micrometeoroid bombardment of the lunar regolith modifies spectral reflectivity curves for the Moon, primarily by lowering albedo and diminishing absorption band intensity (Adams and McCord, 1971). Also, it seems possible that there could be a greater meteoritic component (i.e., a contamination of the original asteroidal composition by material not originating on that asteroid) in asteroidal regoliths than the few percent determined for the lunar mare regolith. In fact, depending upon the mass-frequency relation for the population of impacting particles to which an asteroid is subject, a substantial regolith may never form on some asteroids. Any correlation of asteroid spectral reflectivity with variables correlated with an asteroid's impact environment may shed light on these processes.

Several dozen Hirayama families, possible families, or jetstreams of asteroids with similar orbital elements have been recognized (e.g., see Arnold, 1969). It is particularly interesting to examine the colors of asteroids as a function of family. Though it is widely believed that members of a family are products of a collision or collisions, alternative hypotheses have been proposed. Fragmental family members might generally be expected to have identical colors, but differences within a certain family could be interpreted in terms of a highly differentiated asteroid being broken up or of the collisional fragmentation of two asteroids of similar size. Some asteroids have unusual rotation periods that may result from collisions. Other asteroids have large-amplitude lightcurves, suggesting either a markedly nonspherical shape or great differences in surface albedo on different sides of the asteroid. Either might result from initial conditions or from a major collision. Correlations between such characteristics and color might prove valuable, especially if these asteroids can also be related to particular meteorite groups.

It is clear that studies of asteroid spectral reflectivities have great promise for shedding light on the origin, history, and current processes and state of the region of the solar system between 2 and 4 AU. But it is also clear that there are many variables to consider and hence much data are required for definitive conclusions. Future programs should take into account the following requirements:

(1) It is imperative that the largest possible number and variety of asteroids be observed. This means that very faint (hence small) asteroids must be observed as well as the major ones. Several members of each asteroid family should be observed and of unusual classes of asteroids such as Apollo asteroids, Trojans, and dead comets.

(2) Asteroids should be observed at as many wavelengths throughout the visible and as far into the infrared (where most absorption bands occur) as possible. Ability to recognize reflectivity features at the 1 percent level would be desirable, and ability to measure band positions to 0.01 μm would be valuable.

(3) Individual asteroids should be observed over a complete rotation and at a variety of solar phase angles. Reflectivity curves undoubtedly vary with phase angle and probably differently for different asteroids. Some small variation of color with rotation has been detected for at least one asteroid.

EARLY STUDIES OF ASTEROID COLORS

Photographic

It had long been assumed that asteroids were gray reflectors of the solar spectrum and they have been used from time to time as comparison stars. Bobrovnikoff (1929) first questioned this premise and attempted to measure the characteristics of asteroid spectra. He compared microphotometric tracings of photographic spectra with *G*-type stars; he concluded that (1) he was observing reflection spectra with no emission features, (2) that Ceres and Vesta lacked any major absorptions in the visible like those of Jupiter, (3) that asteroids have relatively low reflectivity in the violet and ultraviolet, and (4) that there were differences between asteroids. Bobrovnikoff's tracings seem to show definitely that Pallas is relatively more reflective near 0.4 μm than other asteroids studied. But Watson (1938) regards many of Bobrovnikoff's conclusions as uncertain because of a lack of standardization of the spectra. Certainly there are some discrepancies with recent photoelectric data for some asteroids discussed by Bobrovnikoff.

Microphotometric tracings of spectra of three asteroids by Johnson (1939) yielded the incorrect result that these asteroids were substantially bluer than the Sun. Recht (1934) reached a similar erroneous conclusion from a more extensive study of the color indices of 34 asteroids obtained from magnitude measurements on normal photographic and panchromatic plates. Recht's measurements have been criticized by several subsequent writers. They show a large scatter because, among other reasons, the measurements of the two colors were often made from plates taken on different nights, and there is a strong correlation between the color index derived by Recht and the apparent magnitude of the asteroid–such a correlation being indicative of a spurious systematic error in the photographic measurements. There is little if any agreement between Recht's color indices and recent *UBV* photoelectric photometry. Watson (1940) obtained more realistic color indices for seven asteroids, but their reliability is difficult to gage.

Perhaps the most ambitious and reliable of the early photographic colorimetry is that of Fischer (1941). Though Fischer's data show less scatter than Recht's, the random errors are nevertheless uncomfortably large. Of the 30 asteroids for which Fischer obtained color indices, a fair number have photoelectric $B - V$ colors that correlate reasonably well in a relative sense with Fischer's values. In figure 1, Fischer's color indices have been rescaled and plotted so that their mean and range match the photoelectric values, but no absolute calibration is intended. It is probably true that most of Fischer's bluer asteroids are in fact bluer than his redder ones, but finer distinctions probably have no meaning. Fischer reported statistically significant correlations between color index and two related orbital characteristics: semimajor axis and Jacobi constant. The correlation is in the same sense as evident in subsequent photoelectric work (see later section), but one should be aware of the potential

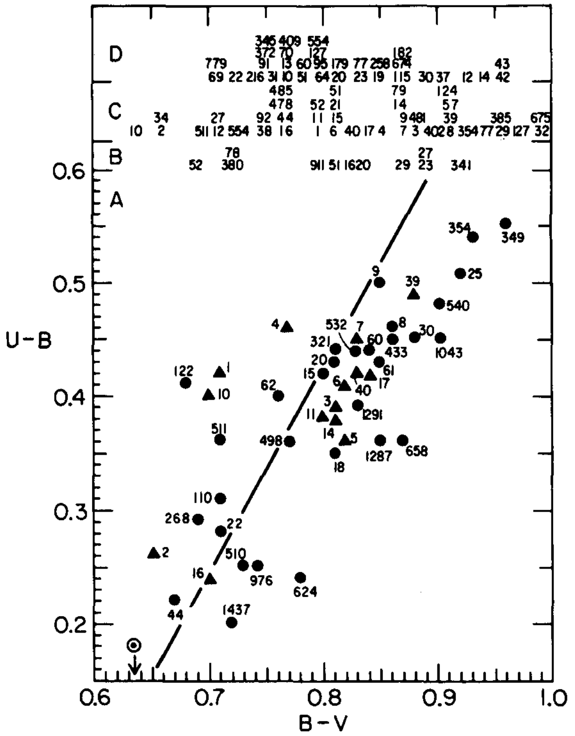

Figure 1.–Asteroid colors from photoelectric and photographic photometry. (A) $B - V$, $U - B$ colors for asteroids summarized in Gehrels (1970). Triangles indicate those asteroids that have also been observed in the present authors' spectral reflectivity program. The line is the stellar main sequence and its intersection with the arrow in the lower left is the *UBV* color of the Sun. (B) $B - V$ colors for asteroids for which no *U* color has been measured (Gehrels, 1970). (C) Approximate scaling of photoelectric color indices of Kitamura (1959). (D) Approximately rescaled photographic color indices of Fischer (1941); probably only the gross distinction between asteroids on the left and to the right is meaningful for Fischer's colors. Also see figure 1 of the paper by Hapke.[1]

in this early photographic work for systematic apparent-magnitude-dependent errors that themselves would be weakly correlated with semimajor axis.

The largest sample of asteroids for which photographic color indices have been determined is contained in the work summarized by Sandakova (1962). At the time of writing, we have not been able to obtain the original published description of these data and their reduction. It is worth noting that seven asteroids with color indices reported in Sandakova (1962) show poor agreement with recent *UBV* work and that very large scatter is evident in the data for the 10 asteroids reported. Sandakova reports no correlation of colors

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[1] See p. 69.

in the complete sample with *a*, but a large difference in color between asteroids with unusually small and unusually large orbital Jacobi constants.

Photoelectric

An early photoelectric program to study asteroid colors was carried out by Kitamura (1959) in the mid-1950's. Forty-two asteroids were measured with a 1P21 photomultiplier in two colors with effective wavelengths somewhat longward of the standard *B* and *V* colors. From a graph presented by Kitamura of the color indices of six stars with known $B - V$ colors, it is possible to make an approximate conversion of his color index to $B - V$. The resulting values have a slightly redder mean and greater range than $B - V$ colors obtained by Gehrels, Kuiper, and their associates, so we have applied some corrections to Kitamura's colors for plotting in figure 1. The several cases of multiple measurements of the same asteroid show small scatter in Kitamura's data and the agreement for those asteroids for which $B - V$ colors are known is good. Kitamura reports negative attempts to correlate his color indices with the proper orbital elements, magnitude $B(1, 0)$, and rotation period. Though his figures show no correlation with $B(1, 0)$ or mean motion, there appears to be a definite correlation with proper eccentricity e'. The sign of the correlation is such as to amplify the expected correlation of the Jacobi constant with respect to a correlation with *a*. His table also shows a possible correlation of color index with extreme *a*, such that asteroids with $a > 3$ AU are bluer than those with $a < 2.3$ AU (but the statistics are poor).

UBV PHOTOELECTRIC PHOTOMETRY

Since the mid-1950's Gehrels, Kuiper, and their associates have published a series of papers on photoelectric photometry of asteroids in the standard *UBV* system. Gehrels has published a table summarizing these results (Gehrels, 1970) and we have plotted them in parts A and B of figure 1. The plotted colors include the small corrections made by Gehrels for reddening with phase; he used lunarlike phase relations, the applicability of which to asteroids has been largely untested. The consistency of most of the *UBV* data is quite good, and most of the plotted asteroids are probably known to at least 0.05 mag in both colors. Of course, there are rarely sufficient data to determine the ranges of variation in color with rotation and phase for the individual asteroids, and such variations would contribute to the scatter. One asteroid, 1566 Icarus, has a typical $B - V$ color but its $U - B$ value is so large that the point is off the scale of the figure.

There is a fair spread of asteroid colors evident in the figure with a trend somewhat redder than the stellar main sequence. There is a major clumping around $(B - V, U - B) = (0.83, 0.4)$ and a lesser one near $(0.7, 0.25)$. There is some spread of the main clump both to the upper right and to the left. The numbers of several asteroids for which only $B - V$ colors exist are plotted in part B of the figure. In sum, there is a general dearth of asteroids with $B - V$

colors near 0.75. For purposes of comparison, Kitamura's rescaled colors are plotted in part C of the figure and Fischer's rescaled colors in part D. In general, these three sets of data show fair agreement, but there are discrepancies.

Parts A and B of figure 1 are replotted in figure 2 showing the distribution in color of five groupings by asteroid semimajor axis. A correlation is evident, though it is due almost entirely to the extreme values of *a*. Ten of the 13 asteroids with $a > 3.0$ have $B - V \leqslant 0.8$ whereas none of the five asteroids with $a < 2.3$ is so blue. Asteroids with $2.75 < a < 3.0$ show the greatest range of colors. If several times as many asteroids could be plotted, we might begin to see statistically significant clusterings of *a* values in the plane of figure 2, but it is premature to draw strong conclusions from the present sample.

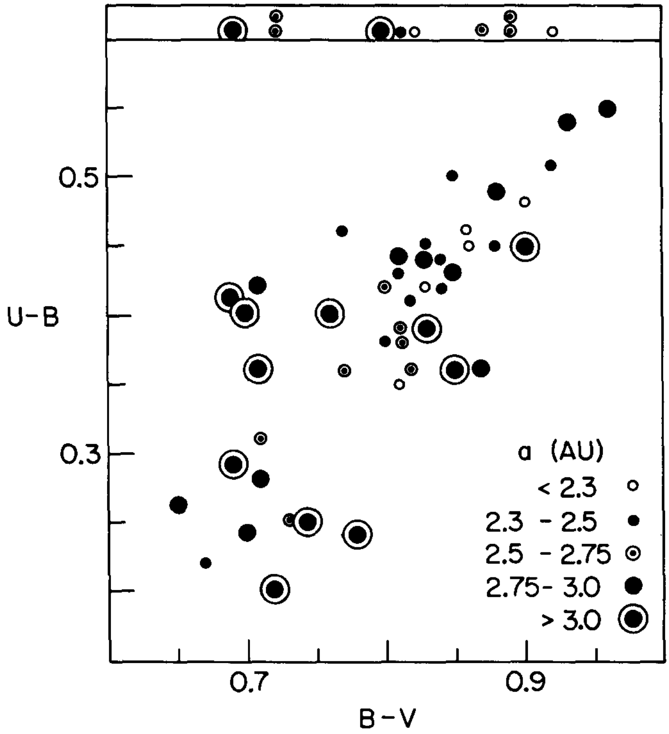

Figure 2.–Color of asteroids from parts (A) and (B) of figure 1 plotted in five groups according to size of semimajor axis.

We have noted that the correlation of *UBV* asteroid colors is somewhat stronger with the Tisserand invariant against perturbation by Jupiter (Jacobi constant) than with *a* alone. Nevertheless, the correlation is far from perfect and there are several extreme exceptions.

SPECTRAL REFLECTIVITY FROM NARROWBAND FILTER PHOTOMETRY

McCord and his associates have been undertaking a program of measuring the spectral reflectivities of all major solar system objects from 0.3 to 1.1 μm, and out to 2.5 μm when possible. After enticing results were obtained for Vesta, a program was begun to look at as many other asteroids as possible. This program constitutes the major portion of Chapman's doctoral dissertation, now in preparation. Although a program of strictly asteroid photometry has not yet been funded, telescope time has been available for asteroid observations during hours when other objects of high priority were below the horizon. To date we have observations of some sort of 32 asteroids, of which 12 have been partly reduced and will be discussed later.

McCord's (1968) double-beam photometer has been used in making observations of asteroids in a variety of modes on several telescopes at Mt. Wilson, Mt. Palomar, and Kitt Peak. A set of 24 narrowband interference filters from 0.3 to 1.1 μm are used concurrently, sometimes in a spinning-filter-wheel mode (3 rpm), and sometimes incrementally over a period of about 1 hr. The sky is observed in the second beam of the photometer with a 10 Hz chopping system and is subtracted from the signal. For some runs an S-1 phototube is used over the entire range 0.3 to 1.1 μm, whereas for others the S-20 is substituted for the wavelengths to which it is sensitive. Most of the data reported in this paper were taken with the S-1 tube alone. A pulse-counting data system is used. Air-mass corrections are determined from observations in each filter of the standard stars of Oke (1964) by taking values at equal air mass and correcting for time-dependent changes. The data are reduced to spectral reflectivity using the stellar standardizations and the solar spectrum of Labs and Neckel (1968). However, integration over solar spectral lines and bands with square-wave filter response produces error, especially near large solar lines in the ultraviolet. All standard stars are ultimately tied to α-Lyrae by Oke and Schild (1970) and, therefore, systematic errors in α-Lyrae's flux distribution will affect our results. However, theoretical models for α-Lyrae and observations presently agree to within a few percent over our spectral range. Deviations of a few percent of particular filters from the general trends that are observed for all solar system objects are smoothed out. All sources of error are very small, however, so the accuracy of our standardizations is a few percent, except for one or two ultraviolet filters. The relative comparisons between solar system objects are even more precise. The reflectivity curves are scaled to unity at 0.56 μm for purposes of comparison.

Reflectivity curves obtained in this manner bear some relation to *UBV* colors but provide much more information. Asteroids with identical *UBV* colors may differ greatly in the red and near infrared regions where important absorption bands are common. In fact, the details of spectral reflectivity curves in the 0.3 to 0.6 μm region can differ somewhat for asteroids with identical *UBV* colors, although the overall trends must correlate. Thus, far more information is contained in the complete reflectivity curve than in *UBV* measurements, but they can still be related to each other. It would, of course, be desirable to extend the range of reflectivity measurements, particularly into the infrared where there are a variety of highly diagnostic solid absorption bands, but nearly all asteroids are so faint that they are difficult to observe with available systems beyond 1.1 μm.

EARLY SPECTRAL REFLECTIVITY MEASUREMENTS OF THE FOUR MAJOR ASTEROIDS

The first spectral reflectivity study of an asteroid by McCord and his associates (1970) turned out to be particularly exciting. Measurements of Vesta made at Cerro Tololo in December 1969 and with a different filter set at Mt. Wilson in October 1968 showed a very deep absorption band centered near 0.915 μm. The band is the most prominent absorption band yet found on any solid solar system body. McCord, Adams, and Johnson have interpreted the composition indicated by the spectral reflectivity curve of Vesta to be that of certain basaltic achondrite meteorites (Mg-rich orthopyroxene or pigeonite). This identification, of course, refers to the composition of the Vesta *surface* minerals that, because of their abundance and albedo, contribute the bulk of Vesta's reflected light.

A subsequent study of Vesta (Johnson and Kunin, 1971) has shown that the primary characteristics of the spectral reflectivity curve do not change as Vesta rotates. The asteroid was observed continuously for a few hours with the Mt. Wilson 152 cm reflector and no changes were detected except for statistically marginal evidence for the dark side being somewhat more reflective (relatively) than the light side in the violet. This change is in the same direction as a correlation of *UBV* color with lightcurve reported by Gehrels (1967). Two runs showing approximately opposite sides of the asteroid are presented in figure 3. It is particularly noteworthy that the 0.9 μm absorption band remains unchanged in position on opposite sides of the asteroid because band position is a sensitive indicator of mineralogical composition. Evidently the gross surface composition of Vesta is quite homogeneous on a large scale.

We observed the three other bright asteroids (Ceres, Pallas, and Juno) in June 1970, using twilight time on the 508 cm reflector. Good signals were obtained during the short intervals available to us for observing, but standardization was difficult because of lack of time. Certain fluctuations for individual filters in the reduced data for two of the asteroids can be ascribed to the poor calibration of the particular standard star against which they were observed. These have been smoothed out, but the smoothings do not change the major characteristics of the spectral reflectivity curves. The spectral reflectivities of the three asteroids are plotted with Vesta as a reference in figure 4.

Pallas is much brighter than the other asteroids in the violet, confirming Bobrovnikoff's early conclusion and *UBV* data. Juno shows a reflectivity

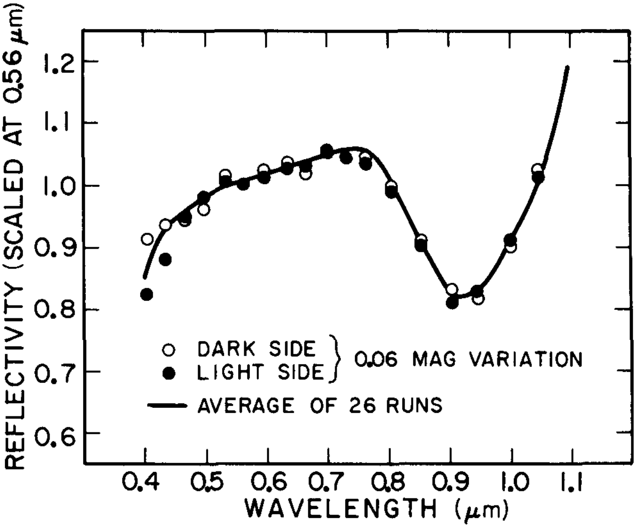

Figure 3.–Spectral reflectivity of 4 Vesta. Individual runs on approximately opposite sides of the asteroid are plotted on the mean curve of 26 runs. Mt. Wilson 152 cm reflector, February 16, 1970.

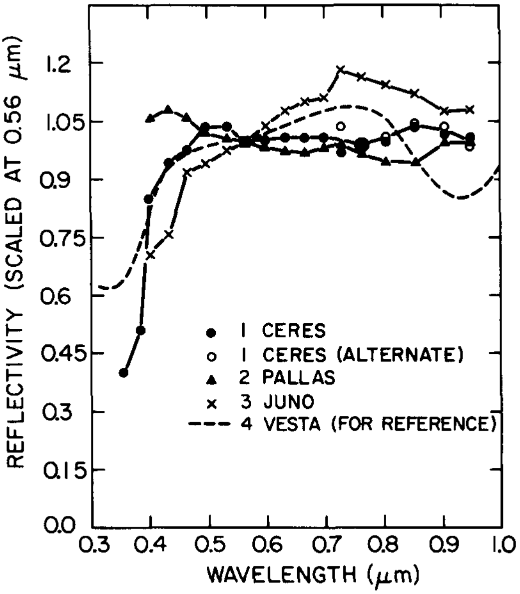

Figure 4.–Spectral reflectivity curves for Ceres, Pallas, and Juno (with Vesta for comparison); Mt. Palomar 508 cm reflector, June 24 to 29, 1970. Square indicates scaling to unity at 0.56 μm. Alternative methods of reducing Ceres data against ξ^2-Ceti shown for $\lambda > 0.7$ μm. Some smoothing applied to Pallas and Juno to correct for deviations due to the standard star η-Piscium.

peak near 0.7 μm and has a much redder slope in the visible than the other three major asteroids. None of the first three asteroids shows a noticeable absorption band to compare with that of Vesta, although Juno does diminish in reflectivity near 1.0 μm. Ceres is quite bright in the blue but falls off sharply in the ultraviolet, which confirms its unusual *UBV* color shown in figure 1. All four major asteroids are different in color, but we do not feel confident of making a unique identification on the basis of these preliminary data. The flat, even bluish, trend of the reflectivity curve for Pallas is suggestive of ices, but the low albedos that have been inferred for Pallas (Matson;[2] Veverka, 1970) are inconsistent with ices. John Adams has told us that metallic meteorites show similar flat spectral reflectivities, but no definitive identification is possible until a wide variety of meteorites (such as carbonaceous chondrites) have been studied and their reflectivities cataloged.

SPECTRAL REFLECTIVITIES OF 11 ASTEROIDS

We used the Mt. Wilson 152 cm reflector in October 1970 to measure the spectral reflectivities of 11 asteroids. An example of the data for one of these asteroids (192 Nausikaa) is shown in figure 5. The error bars are standard deviations of the means of nine runs. A fairly prominent absorption band is

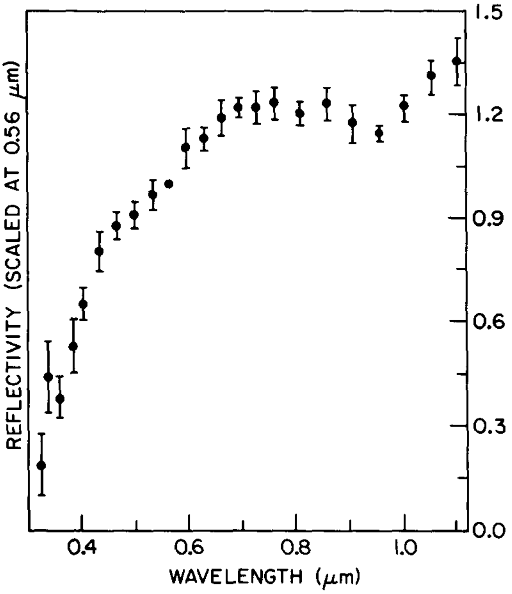

Figure 5.–Spectral reflectivity for 192 Nausikaa, mean of 9 runs; Mt. Wilson 152 cm reflector, October 10, 1970. ξ^2-Ceti was used as the standard star. Error bars are standard deviations of the mean. Preliminary reduction.

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[2] See p. 48.

apparent, though less deep than that of Vesta. We wish to postpone attempting a conclusive mineralogical identification until further observations of 192 have been reduced. Chapman (1971) will discuss the final reduction for these 11 asteroids and others observed after October 1970.

The spectral reflectivity curves for the 11 asteroids, including 192, are shown in figure 6. An approximate indication of the standard deviations of the points in the middle portions of the reflectivity curves is indicated in the figure. The smooth curves were drawn through the error bars. Most of the indicated features are probably real, but some of the smaller bumps and dips should await confirmation and improvements in our standardization.

The reflectivity curves have been plotted in three groups in figure 6. The Vesta curve is also shown for comparison with each group. The top curves are those with the bluest trend and the bottom group contains the reddest, but we do not intend to suggest three distinct groupings from what may be a more or less continuous spectrum of color trends.

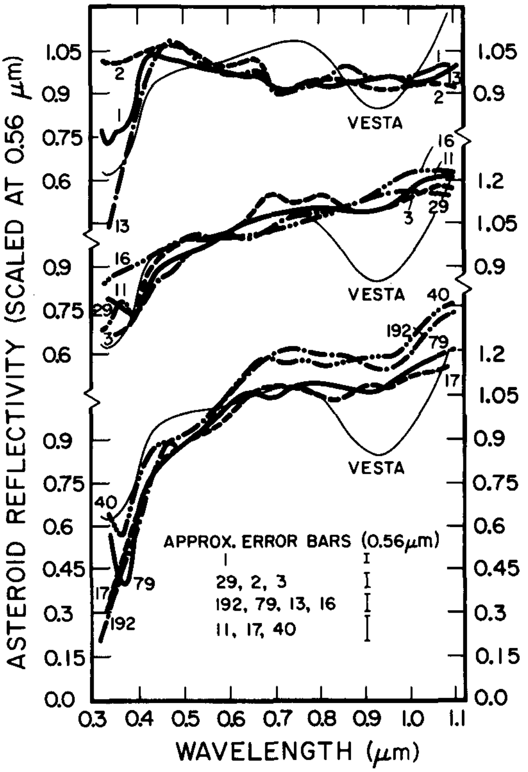

Figure 6.–Spectral reflectivity curves for asteroids 1, 2, 3, 11, 13, 16, 17, 29, 40, 79, and 192 (with Vesta for comparison). Mt. Wilson 152 cm reflector, October 9 to 12, 1970. Observations reduced against ξ^2-Ceti and smooth curves scaled approximately to unity at 0.56 μm; typical error bars are indicated.

Although the reflectivities shown here have not been corrected for any reddening with phase and the observations cover a range of phases among the various asteroids shown, there is no correlation between the phase angle at time of observation and the apparent color trend. The differences between most of these asteroid spectral curves far exceed effects due to phase angle, particle size, and similar variables. These differences are almost certainly due to compositional variations among the asteroids. The wide range of compositions implied is most significant. An imperfect correlation between color trend and semimajor axis is evident for these 12 asteroids, but of course the statistics are poor.

The members of the reddish group are very dark in the ultraviolet and show prominent inflection points near 0.4 and 0.7 μm. (The upturns in the far ultraviolet for 40 Harmonia and 79 Eurynome may not be real.) A possible cause for the broad relative absorption near 0.5 μm for the reddish asteroids is a band due to Ti^{3+}. Asteroids 1 Ceres, 2 Pallas, and 13 Egeria show a bluish trend, except that Ceres and Egeria have sharp turndowns toward the ultraviolet. Except for 3 Juno, the intermediate asteroids (11 Parthenope, 16 Psyche, and 29 Amphitrite) lack the rise near 0.7 μm characteristic of the redder asteroids. All the intermediate asteroids are moderately reflective in the ultraviolet, except 16, which is very reflective by comparison. Some of the asteroids other than 4 and 192 show hints of the 0.9 μm absorption band, but we must await reduction of additional observations of these objects to be sure. It is certainly a fair generalization that absorption bands as prominent as that of Vesta are unusual.

Two of the 12 asteroids studied are members of the same Hirayama family (Brouwer's 25th family). These two asteroids (17 Thetis and 79 Eurynome) have reflectivity curves that are identical to each other to within observational errors. This observation is consistent with the hypothesis that the family is composed of fragments from a single asteroid. We are attempting to observe other pairs of family members to see if this is a general rule.

SUMMARY AND CONCLUSIONS

The results of the MIT program that have been presented here are preliminary. Altogether we have obtained fairly comprehensive spectral reflectivity observations for 23 asteroids, and some data on 9 others. Of these, 12 have been partially reduced and described in this paper; the remainder will be reduced very soon. Through cooperation with Dennis Matson, we have obtained data on 12 asteroids that were included in his thermal infrared program.[3] These preliminary results are most promising because they demonstrate that the asteroids have a wide variety of surface compositions and that many of the spectral reflectivities do contain diagnostic bands and inflections that may lead to precise mineralogical identifications. Even when explicit

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[3] See p. 45.

identification is not possible, these data at 24 wavelengths permit the separation of asteroids with far greater discrimination than is possible in the three-color *UBV* work.

The full value of spectral reflectivity studies will only be achieved, however, once spectral reflectivities of many dozens or several hundred asteroids have been studied and once a comprehensive catalog of meteorite and rock spectral reflectivities has been assembled. Both of these goals can be achieved within a couple years, and we hope to make progress in these directions.

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DISCUSSION

BRATENAHL: What is the limit in apparent magnitude your technique can be pushed to?

CHAPMAN: We have had no difficulty measuring several asteroids per night brighter than 12 mag. The problem is with the interesting wavelength interval beyond the response limit of S-20 photomultipliers (~750 nm). With sufficient time on a large telescope it should be possible to measure 15 and 16 mag objects to some precision out to 1050 nm, using an S-1 tube. Still fainter asteroids could be measured shortward of 750 nm provided they could be accurately located with respect to a guide star.

GEHRELS: Lightcurves have been obtained by direct visual setting on a moving asteroid—with the B or V filter, 1P21 tube, and an integration time of a minute—down to $V \sim 16.5$ with a 154 cm telescope; the precision is about ±0.004 mag.

JOHNSON: In comparing spectral reflectivity measurements with standard *UBV* photometry, several things should be kept in mind: (1) our filters have considerably narrower bandpasses; (2) we must observe sequentially in 24 of them instead of one, two, or three; (3) the S-1 surface has a low quantum efficiency (about 0.1 percent compared to ~10 percent for an S-20); and (4) our program requires frequent measurements of standard stars at all 24 wavelengths.