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PHYSICAL OBSERVATIONS AND TAXONOMY OF ASTEROIDS

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Since 1970 the physical study of asteroids has been dramatically extended by wide application of four types of observations: spectrophotometry from 0.3 to 1.1 µm; broad-band UBV photometry; visible photopolarimetry; and broad-band thermal radiometry. More than a quarter of the numbered asteroids have been studied with these techniques, and for most of them the data are adequate to determine approximate size and albedo and to provide a rough classification related to mineralogical composition. The specific CSM taxonomic system of Chapman *et al.* (1975) and Bowell *et al.* (1978) is described and used to organize these new data. The CSM taxonomy is also compared with more compositionally specific taxonomies, and some future directions for both observation and classification are indicated.

INTRODUCTION

During the relatively brief span of years from the Tucson Asteroid Conference (Gehrels, 1971) to the present, there has been explosive growth in observational data on asteroids. During the first half of the 20th century and well into the 1960's, asteroid science had been limited almost entirely to searches for new objects and establishment of photographic magnitudes and accurate orbital elements for the fewer than 2000 asteroids that were named and numbered. During the 1960's, the first major efforts to accumulate more physical data (photoelectric magnitudes and lightcurves, with some colorimetric and polarimetric work) were undertaken, primarily by G. P. Kuiper and T. Gehrels at the University of Arizona. Only a few dozen of the brighter objects were studied, however, and the interpretation of the observations was quite limited. The major watershed appears now to have been in about 1970, when C. R. Chapman, T. B. McCord, and their collaborators began a systematic program to obtain spectrophotometry of a large number of asteroids and, perhaps more important, to interpret their observations in terms of composition and mineralogy. Thus for the first time it became possible empirically to test speculations concerning the relationships between distant asteroids and the meteorite samples under intensive study in terrestrial laboratories.

The first interpretation of asteroid spectrophotometry was presented by McCord, Adams, and Johnson (1970), who showed that the reflectivity of Vesta was matched extremely well by that of the rare basaltic achondrites. Shortly thereafter, Chapman, McCord, and Johnson (1973) published reflectivity curves for 23 asteroids and demonstrated the existence of a wide variety of mineralogical types, and about the same time empirical interpretations of these data based on comparisons with meteorite spectra were suggested by Chapman and Salisbury (1973) and Johnson and Fanale (1973).

At the same time that spectrophotometry was emerging as a major diagnostic tool, other new techniques for physical observations of asteroids also were applied. During the 1960's an empirical relation between the shape of the polarization-phase curve and the albedo of a particulate (dusty) surface was recognized, but it was not until a series of papers published beginning in 1971 that J. Veverka applied this relation to derive albedos and diameters of asteroids. At the same time D. Allen first used measurements of thermal infrared radiation (which, unlike reflected light, is greater for a dark asteroid than for a light one) to derive what he called an "infrared diameter" for Vesta, and this work was soon extended to about a dozen asteroids by D. Matson. At the time of the 1971 Tucson conference these new methods for determining sizes and albedos were still suspect to many workers, but within another two years they had clearly demonstrated their value and were being widely applied. An important early result was the discovery by Matson (1971) that at least one asteroid--324 Bamberga--had an albedo about a factor of two lower than that for any previously known object in the solar system. Subsequent studies have shown that most asteroids are in fact members of this low-albedo class.

By 1974 the three techniques of spectrophotometry, polarimetry, and infrared radiometry, as well as revitalized programs of UBV photometry, had been applied to about 100 asteroids. A first attempt to utilize these data collectively to characterize the main belt asteroid population, including the definition of broad classifications based on physical rather than dynamical properties, was published by Chapman, Morrison, and Zellner (1975). This paper has been widely quoted and can be taken to represent a significant benchmark in the rapid recent development of asteroid science. I will use it as the point of departure for the present paper, which is limited primarily to results obtained since 1974.

As of the date of this meeting, physical observations have been made for nearly 600 asteroids--more than a quarter of the named and numbered minor planets. I will discuss briefly the nature of these observations and will then describe several classification schemes that have been used to organize this sudden wealth of data. For the most part, I will be summarizing the original work of Bender *et al.* (1978) and Bowell *et al.* (1978). I am particularly indebted to Ted Bowell, Clark Chapman, and Ben Zellner, who have been responsible for so much of the work discussed here.

THE OBSERVATIONS

Four kinds of physical observations have been widely applied to asteroids in the past four years: UBV photometry; 0.3 to 1.1 μm spectrophotometry; photoelectric polarimetry; and infrared radiometry. Each of these techniques has been applied to at least 100 asteroids. There are, in addition, several other very promising approaches that have not yet had such wide application. Infrared (JHK) photometry has been obtained for about three dozen (Johnson *et al.*, 1975; Chapman and Morrison, 1976; Matson, Johnson and Veeder, 1977; Leake, Gradie and Morrison, 1978); high-resolution infrared spectra exist for Vesta and Eros (Larson and Fink, 1975; Larson *et al.*, 1976; Larson, 1977); Ceres and Vesta have been detected by their thermal radio emission (Ulich and Conklin, 1976; Conklin *et al.*, 1977); and the radar reflectivities of Ceres, Eros, Toro, and Icarus have been measured (*e.g.*, Campbell *et al.*, 1976; Jurgens and Goldstein, 1976). In this paper, however, I will limit discussion to the four most widely applied techniques.

The UBV photometry has been carried out primarily at Lowell Observatory and at the University of Arizona. The principal published sources are: Taylor (1971), Zellner *et al.* (1975, 1977b), and Degewij *et al.* (1978). However, the majority of the data are unpublished observations made between 1975 and 1977 by E. Bowell at Lowell Observatory and referred to by Zellner and Bowell (1977) and Bowell *et al.* (1978).

Spectrophotometry with about two dozen filters between 0.3 and 1.1 μm has been reported for 98 asteroids by McCord and Chapman (1975a,b) and Pieters *et al.* (1976). Three parameters used to date for classification are R/B, the ratio of spectral reflectance at 0.70 μm to that at 0.40 μm; BEND, a measure of the curvature of the visible part of the reflectance spectrum, and DEPTH, a measure of the strength of the olivine-pyroxene absorption feature near 0.95 μm.

Linear polarization of reflected light as a function of phase angle constitutes the third class of data. The observations are all from Zellner *et al.* (1974) and Zellner and Gradie (1976 and unpublished). The parameter P_{min}, the maximum depth of the negative polarization branch, has been measured for 98 objects and is sensitive to grain opacity and hence roughly to albedo. The polarimetry also yields geometric albedo p_v more directly, from the slope of the ascending polarization branch and a recently recalibrated slope-albedo law (Zellner *et al.*, 1977c,d). For albedo greater than 0.07, the polarimetric results are in quite satisfactory agreement with albedos and diameters from thermal radiometry. It is now recognized, however, that previously published polarimetric albedos less than 0.07 are inaccurate due to saturation of the slope-albedo law, and furthermore that reliable visual albedos p_v cannot always be inferred from polarimetric data in blue light. Whereas polarimetric albedos were listed for as many as 52 objects by Zellner and Gradie (1976), the elimination of the low albedo objects and those observed only in the blue reduces the number of polarimetric albedos to 24.

The final observational technique is 10 and 20 μm radiometry, carried out primarily by D. Morrison and his collaborators at the University of Hawaii and at Kitt Peak and by O. Hansen at Cerro Tololo. The individual observations have been published by Cruikshank and Morrison (1973), Morrison (1974, 1977a), Hansen (1976), and Morrison and Chapman (1976); all are summarized in a review by Morrison (1977b). In Morrison (1977b), all of the observations have been reduced uniformly with a model based on that described by Jones and Morrison (1974), although entirely equivalent results could also be obtained with the alternative model by Hansen (1977).

In order to use all of these data for classification or any other purpose, it has been necessary to bring them together in a readily accessible format. Thus, beginning in 1976, a number of observers have joined to create a computer file of these data called TRIAD (Tucson Revised Index of Asteroid Data), described by Bender *et al.* (1978). The types of data included and the individuals responsible for the files are given in Table 1. Subject to certain limitations, contents of the TRIAD file can be made available in computer printout or machine-readable form to other researchers with a serious professional interest. Inquiries should be directed to Ben Zellner, who has primary responsibility for unkeep of TRIAD.

Table 1. The TRIAD File

Data Type	Responsibility	No. of Objects[a]
Orbital Elements	D. Bender/JPL	2042
Magnitudes	T. Gehrels/U of AZ	517
Rotational Elements	E. Tedesco/NMSU	150
UBV Colors	E. Bowell/Lowell Observatory	517
Photometric Spectra	M. Gaffey/U of HI	98
Spectral Parameters	C. Chapman/PSI	98
Polarimetric Parameters	B. Zellner/U of AZ	102
Radiometric Diameters	D. Morrison/NASA HQ	165

[a] As of end of 1977.

One of the first projects undertaken with the TRIAD file has been the definition of a simple empirical classification scheme (Bowell *et al.*, 1978). In the following section I will describe this taxonomy, and in the final section I will briefly compare it with more interpretive classifications, based primarily on the spectrophotometric subset of these data, defined by Chapman (1976) and by Gaffey and McCord (1977, 1978).

THE CSM TAXONOMY

The clear separation of many of the larger asteroids into two albedo-color groups was recognized by a number of authors (*e.g.*, Zellner, Gehrels, and Gradie, 1974; Morrison, 1974), and in Chapman *et al.* (1975) this natural division was the basis for the definition of classes called C and S. The C objects are dark and neutral in color and appear to be mineralogically similar to the carbonaceous chondrites, while the S objects appear to contain pyroxene and olivine together with some metallic iron. The terms C (for carbonaceous) and S (for siliceous) were chosen with this compositional identification in mind, but it should be emphasized that these classes were *defined* purely in terms of an empirical clumping of observational parameters. Figure 1, which is a histogram of measured asteroid albedos (Morrison, 1977b), clearly demonstrates the reality of this distinction between high- and low-albedo objects. In fairness it should be noted, however, that the division is less obvious in some other observable parameters.

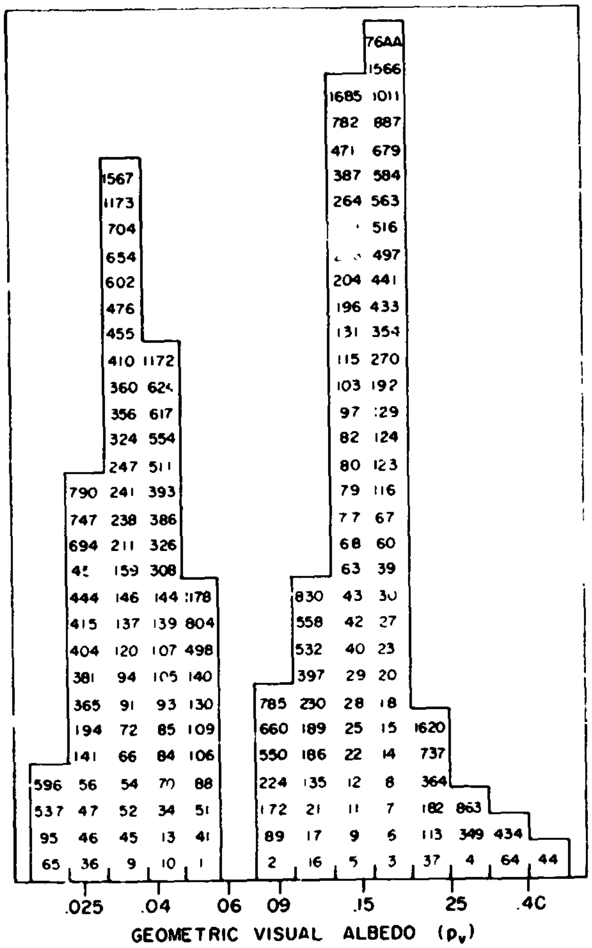


Fig. 1. Distribution of directly determined geometric visual albedos for 187 asteroids. In the CSM taxonomy, the low-albedo peak corresponds to the C asteroids, while the broader high-albedo peak is dominated by the S asteroids. Note the strong bimodality; in spite of a real spread in albedo within each peak, the two albedo populations are distinct and do not overlap (from Morrison, 1977b).

Chapman *et al.* (1975) used five observable quantities in their classification, and they were able to identify several well-observed objects, such as Vesta, that did not fall into the C or S groups. In subsequent papers two additional classes were defined: M objects with reddish colors, intermediate albedos, and little indication of spectral structure near 0.95 μm (Zellner and Gradie, 1976); and E objects, with flat spectra and very high albedos (Zellner *et al.*, 1977a).

The taxonomy of Bowell *et al.* (1978) is a further development of the classification begun by Chapman *et al.* (1975). Seven, rather than five, observational parameters are used to distinguish the classes. It is based on directly observed optical parameters and, compared with other classifications, it is independent of interpretations of asteroid mineralogy. The system depends upon the existence of discrete clusters in parameter space, with genuine gaps (or at least significant depletions) between the clusters. Only where such natural divisions exist are meaningful distributions defined. Following previous usage, this system retains the class names C, S, M, and E, and it adds a new class, R. I call this the *CSM Taxonomy*.

For those asteroids observed in sufficient detail, many different surface types may be distinguished and, indeed, each asteroid may ultimately be recognized as unique. In the CSM taxonomic system, it should be understood that each class contains a substantial spread of mineralogical assemblages; for instance, there is a variation of a factor of three in the albedos of C asteroids, and the S asteroids encompass a wide range of pyroxene and olivine contents as indicated by the depth and centroid of the absorption band near 0.95 μm.

In assigning boundaries between classes for each parameter, Bowell *et al.* adopted the philosophy of *minimizing the number of misclassifications*. Where there is serious doubt as to correct classification of an individual asteroid, the CSM taxonomy carries several possibilities rather than trying to make a questionable unique classification. Note that this philosophy is to be contrasted with one like that of Zellner and Bowell (1977), who attempted to assign the most likely class to each asteroid.

In addition to classes C, S, M, E, and R, Bowell *et al.* introduce a designation U for unclassifiable. The objects designated U are those that are not in the other five classes. I emphasize that U does not simply indicate lack of information or noisy data, but refers to objects that are known to be intrinsically outside the domains of the other classes. It is of interest to note that, of 163 asteroids classified by Bowell *et al.* from both albedo-sensitive and color-sensitive observations, only 16 (10%) are classified U.

The five classes are formally defined by the range of parameters listed in Table 2. As illustrations to help motivate these definitions, however, I now discuss several two-parameter plots taken from the TRIAD file.

Figure 2 displays the geometric visual albedo p_V as a function of UV color index. (This albedo is derived primarily from thermal radiometry, but in a few cases also depends on polarization data.) The plot clearly distinguishes the major C, S, M, and E groups, and it also illustrates the significance of class R, the members of which have high albedo and are distinctly redder in UV than the S objects.

Figure 3 is a similar plot in which the polarization parameter P_{min} is substituted for geometric albedo. It is apparent that P_{min} distinguishes the S and C classes even more strongly than albedo, with only a small group of M asteroids having intermediate values of P_{min} near 1.0.

The easiest observational technique to apply in a survey of physical properties is UBV photometry, which yields colors in the near ultraviolet to visible range. It is thus important to determine to what extent simple color data of this sort, without any albedo-sensitive parameters, can serve to classify asteroids in the CSM system. Figure 4 illustrates UBV colors for 465 objects. Those for which albedo is known independently are denoted by special symbols (*e.g.*, filled circles for C, open circles for S), while the others are

Table 2. Definition of Classes[a]

Parameter	C	S	M	E	R
Albedo, p_V	≤ 0.065	0.065 - 0.23	0.065 - 0.23	≥ 0.23	≥ 0.16
P_{min} %	1.20 - 2.15	0.58 - 0.96	0.86 - 1.35	≤ 0.40	≤ 0.70
R/B	1.00 - 1.40	1.34 - 2.07	1.06 - 1.34	0.9 - 1.70[b]	≥ 1.70
BEND	0.05 - 0.26	0.05 - 0.25	≤ 0.11	≤ 0.15[b]	≥ 0.25
DEPTH	0.95 - 1.00	0.80 - 1.00	0.90 - 1.00	0.90 - 1.00[b]	≤ 0.90
B-V	≥ 0.64[c]	d	0.67 - 0.77	0.60 - 0.79	e
U-B[f]	0.23 - 0.46[c]	≥ 0.34[d]	0.17 - 0.28	0.22 - 0.28	e

a. From Bowell *et al.* (1978).

b. No examples have been measured.

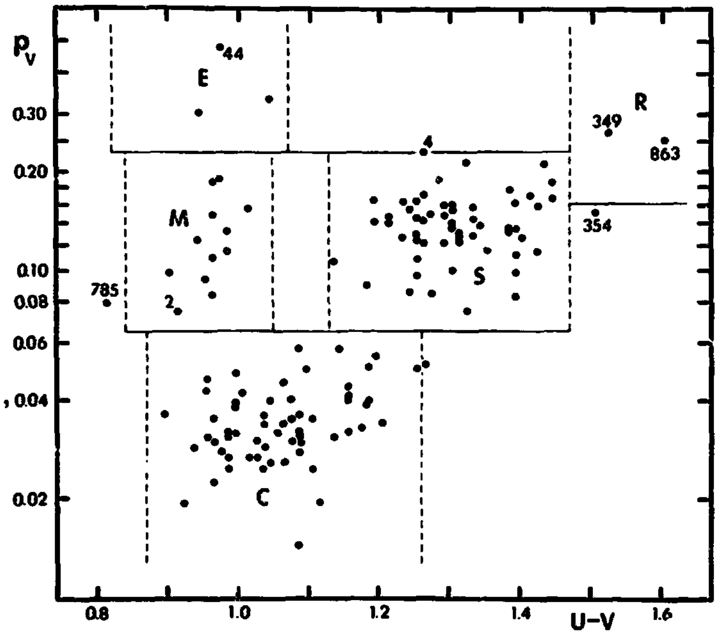
c. Additionally 4.60 (B-V) - 3.17 $\leq$ (U-B) $\leq$ (B-V) - 0.27. Type U allowed $0\overset{\mathrm{m}}{.}02$ inside limits when only UBV photometry is available.

d. Additionally B-V $\geq$ (U-B)/7.0 + 0.74; 1.70 (B-V) - 1.12 $\leq$ (U-B) $\leq$ (B-V) - 0.33; (U-V) $\leq$ 1.47. Type U allowed $0\overset{\mathrm{m}}{.}02$ inside limits, except for the last, when only UBV photometry is available.

e. (U-V) $\geq$ 1.47.

f. Type U always allowed for U-B $\leq$ 0.28, when only UBV photometry is available.

Fig. 2. Geometric albedo (p_V) versus U-V color index for 144 asteroids with semimajor axis less than 3.6 AU. Domains indicate allowable parameters on the CSM classification system for asteroids of types C, S, M, E and R; objects outside these domains are unclassifiable, designated U. The albedo boundaries (solid lines) are those given in Table 2, but the limits in U-V (dotted lines) are more complex, as shown in Figure 5. Unusual objects 2 Pallas, 4 Vesta, 44 Nysa, 349 Dembowska, 354 Eleonora, 785 Zwetana, and 863 Benkoela are indicated by number (from Bowell *et al.*, 1978).



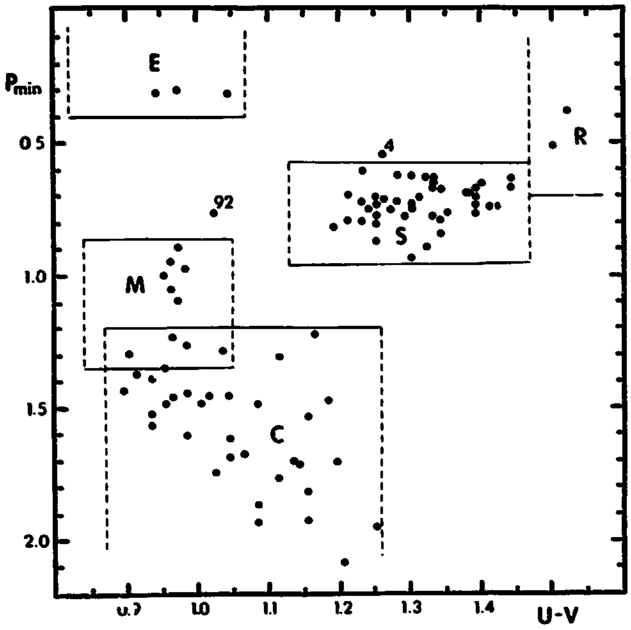


Fig. 3. Depth P_{min} of the negative polarization branch versus U-V color index for 93 asteroids with semimajor axis less than 3.6 AU. Class boundaries are as indicated for Figure 2. Unusual objects indicated by number are 4 Vesta and 92 Undina (from Bowell *et al.*, 1978).

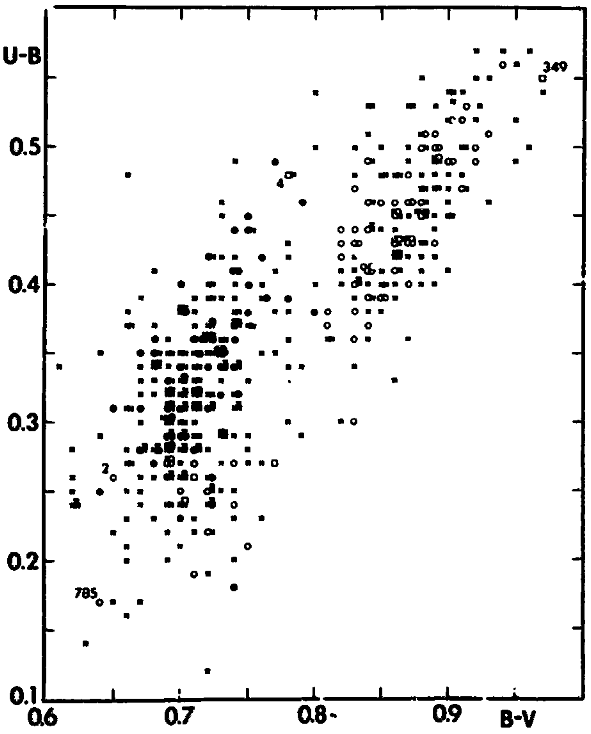


Fig. 4. B-V and U-B colors for 465 asteroids with semimajor axis less than 3.6 AU. Symbols indicate measured albedos, where available, as independent indications of type: ● for $p < 0.065$; o for $0.065 < p < 0.23$; □ for $p > 0.23$. Where no albedo is known the colors are indicated by x. Two asteroids, 863 Benkoela and 1685 Innes, have colors that are off the scale of this graph. Unusual asteroids 2 Pallas, 4 Vesta, 349 Dembowska, and 785 Zwetana are indicated by number (from Bowell *et al.*, 1978).

indicated by x. The domain of the S objects is clear on this plot, but without albedo it is difficult to distinguish the dark, neutral-colored Cs from the lighter, but still neutral-colored Ms and Es. Figure 5 shows the actual boundaries of the classes in the UBV plane as adopted by Bowell *et al.*

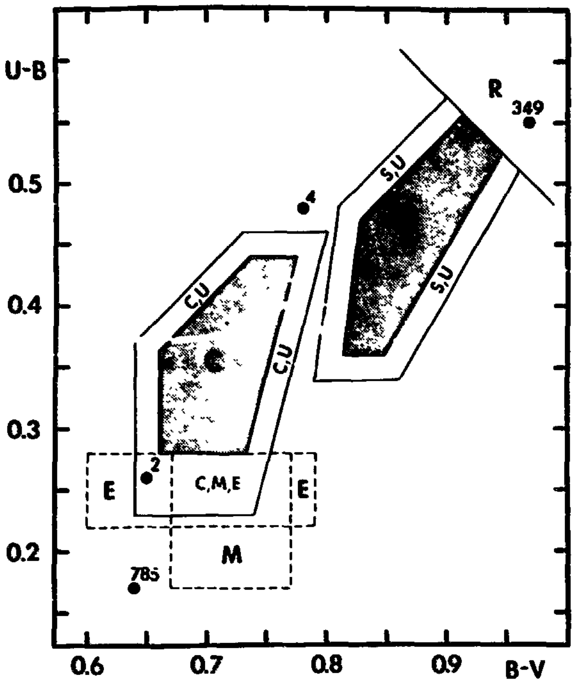


Fig. 5. Similar to Figure 4, but showing adopted domains of types C, S, M, E and R in UBV colors in the CSM taxonomy. Numerical coefficients representing the type boundaries are given in Table 2. Neutral colors plot in the lower left (*e.g.*, 785 Zwetana), red colors in the upper right (*e.g.*, 349 Dembowska). Note that UBV colors clearly separate R from S from C asteroids, but become degenerate for neutral colors where the C, M, and E domains overlap (from Bowell *et al.*, 1978).

Four examples show how the taxonomic definition illustrated in Figures 2-5 and listed in Table 2 can be used to classify asteroids. We begin with a typical, thoroughly observed C asteroid. 19 Fortuna; the observational parameters are given in Table 3. The UBV colors fall within the C domain of Figure 5, and the albedo of 0.030 and the P_{min} of 1.72 also clearly place Fortuna in the low-albedo C class. Of the spectrophotometric parameters, BEND allows either C or S, R/B allows C, M, or E, and the absence of the pyroxene absorption band (DEPTH = 1.00) serves only to exclude membership in class R. Thus the classification would be ambiguous if only the spectrophotometric parameters were available, but is clearly tied down by both UBV colors and the albedo-sensitive observations.

As an example of an S object, Table 3 also lists the parameters for 5 Astraea. This classification could be made unambiguously from UBV colors alone or from R/B alone. The other parameters are consistent with the S classification, but none considered alone is sufficient; the albedo allows types S or M, P_{min} and DEPTH allow S or R, and BEND any type except R. For the S asteroids, UBV colors are particularly diagnostic.

Asteroid 44 Nysa in Table 3 is a prototype E object. The high albedo and small P_{min} suggest E but by themselves are also consistent with the limits for class R. The UBV colors fall within the ambiguous domain allowing C, M, E, or U but not S or R. Thus both color and albedo data are required to place an object uniquely in class E, and the only proven E objects are 44 Nysa, 64 Angelina, and 434 Hungaria. None of these, unfortunately, has as yet been observed spectrophotometrically.

Table 3. Four Examples of Classification

Asteroid	Type	B-V	U-B	BEND	R/B	DEPTH	p_V	P_{min}	Type
19 Fortuna	C	0.75	0.38	0.21	1.09	1.00	0.03	1.72	✓
	S			0.21		1.00			
	M				1.09	1.00			
	E				1.09	1.00			
	R								
5 Astraea	C			0.10					
	S	0.83	0.38	0.10	1.63	0.84	0.144	0.70	✓
	M			0.10			0.144		
	E			0.10					
	R					0.84		0.70	
44 Nysa	C	0.71	0.26						
	S								
	M	0.71	0.26						
	E	0.71	0.26				0.467	0.31	✓
	R						0.467	0.31	
4 Vesta	C			0.14	1.33				
	S			0.14			0.226		
	M				1.33		0.226		
	E			0.14	1.33				
	R					0.74	0.226	0.55	
	(U)	0.78	0.48						✓

Perhaps the most prominent example of an unclassifiable asteroid is 4 Vesta. In Table 3 the relatively high albedo allows classes R or (just barely) S or M, but the very unusual P_{min} of 0.55 excludes types S and M. The spectrophotometric parameters BEND and R/B exclude type R, however, and the UBV colors fall outside the domains of any of the recognized classes. Thus Vesta can only be classified U.

Table 4 lists the adopted classifications for 344 asteroids from the TRIAD data file. Also given are diameters obtained either from direct observation or calculated on the assumption that the object has the albedo of an average member of its class (see footnote to Table 4). The asteroids listed in Table 4 are those used by Zellner and Bowell (1977) and by Zellner (1978) to study the distribution of types, but the actual data are updated to include the TRIAD values as of early 1978. In the expanded classification of 523 asteroids by Bowell *et al.* (1978), there are 189 C objects, 142 S objects, 12 of type M, 3 of type E, and 3 of type R. The classification U is obtained for 55 objects, while 119 (25%) receive uncertain or ambiguous classifications. Most of these ambiguities presumably could be cleared up if additional observational techniques were applied. However, there is no guarantee that smaller and fainter objects will have the same distribution as those already studied, most of which have diameters greater than 50 km.

In the above statistics the C objects are much underrepresented, of course, because of their low albedos and generally larger distances. In the following paper, Zellner discusses corrections for these selection effects. The E and R types, however, must be genuinely quite rare. Zellner and Bowell (1977) have noted that in the whole main belt there appear to be only two E objects with diameters greater than 50 km, and it now appears that R objects must be similarly unusual. In a bias-corrected sample, neither of these classes would constitute as much as 1% of the asteroid population.

Table 4. Asteroid Classification[a] and Diameters[b]

Asteroid	B(1,0)	D (km)	Type	Asteroid	B(1,0)	D (km)	Type
1 Ceres	4.48	1018	U	60 Echo	9.98	50	S
2 Pallas	5.02	629	U	61 Danae	8.90	87*	S
3 Juno	6.51	247	S	62 Erato	9.85	103*	C
4 Vesta	4.31	548	U	63 Ausonia	8.96	89	S
5 Astraea	8.13	122	S	64 Angelina	8.84	56	E
6 Hebe	6.98	195	S	65 Cybele	7.99	308	C
7 Iris	6.84	210	S	66 Maja	10.51	76*	C
8 Flora	7.73	153	S	67 Asia	9.66	61*	S
9 Metis	7.78	153	S	68 Leto	8.22	124	S
10 Hygeia	6.50	450	C	69 Hesperia	8.17	134?	U
11 Parthenope	7.80	151	S	70 Panopaea	8.93	154	C
12 Victoria	8.38	135	S	71 Niobe	8.28	114*	S
13 Egeria	8.15	241	C	72 Feronia	10.15	92*	C
14 Irene	7.49	153	S	76 Freia	9.11	143?	CMEU
15 Eunomia	6.42	245	S	77 Frigga	9.70	61*	M
16 Psyche	6.88	252	M	78 Diana	9.17	139*	C
17 Thetis	9.08	96	S	79 Eurynome	9.25	75	S
18 Melpomonene	7.69	152	S	80 Sappho	9.22	86	U
19 Fortuna	8.45	220	C	81 Terpsichore	9.64	112*	C
20 Massalia	7.73	137	S	82 Alkmene	9.52	64	S
21 Lutetia	8.61	111	M	83 Beatrix	9.76	106*	C
22 Kalliope	7.28	178	M	84 Klio	10.34	81	C
23 Thalia	8.23	114	S	85 Io	8.92	146	U
24 Themis	8.27	209*	C	86 Semele	9.71	107*	C
25 Phocaea	9.30	65	S	87 Sylvia	8.12	224?	CMEU
26 Proserpina	8.80	90*	S	88 Thisbe	8.07	206	C
27 Euterpe	8.44	116	S	89 Julia	8.15	168	S
28 Bellona	8.16	122*	S	90 Antiope	9.41	124*	C
29 Amphitrite	7.13	194	S	91 Aegina	10.00	105	C
30 Urania	8.82	90	S	92 Undina	7.95	150?	U
31 Euphrosyne	7.28	332*	CM	93 Minerva	8.71	167	C
32 Pomoma	8.76	93*	S	94 Aurora	8.71	190	C
34 Circe	9.59	113*	C	95 Arethusa	8.83	165*	C
36 Atalante	9.82	103*	C	97 Klotho	8.75	94	M
37 Fides	8.43	93	S	100 Hekate	9.08	79*	SU
39 Laetitia	7.44	164	S	102 Miriam	10.28	83*	C
40 Harmonia	8.32	121	S	103 Hera	8.84	89*	S
41 Daphne	8.23	176	C	104 Klymene	9.44	121*	C
42 Isis	8.81	96	S	105 Artemis	9.42	124*	C
43 Ariadne	9.19	76*	S	106 Dione	8.80	169*	C
44 Nysa	7.85	72	E	107 Camilla	8.28	209*	C
45 Eugenia	8.31	227	C	108 Hecuba	9.69	60*	S
46 Hestia	9.56	133	C	109 Felicitas	10.13	74	C
47 Aglaja	9.24	134*	C	110 Lydia	8.75	169*	C
48 Doris	7.99	147?	U	111 Ate	9.11	143*	C
49 Pales	8.67	178*	C	113 Amalthea	9.86	47	S
51 Nemausa	8.68	158	U	114 Kassandra	9.46	121*	C
52 Europa	7.62	289	C	115 Thyra	8.84	93	S
53 Kalypso	9.97	96*	C	116 Sirona	8.89	80	SR
54 Alexandra	8.87	177	C	117 Lomia	9.18	138?	CMEU
55 Pandora	8.71	172?	CMEU	119 Althaea	9.82	57*	S
56 Melete	9.49	143	C	120 Lachesis	8.78	174	C
57 Mnemosyne	8.41	108*	S	122 Gerda	9.16	139*	CU
58 Concordia	9.92	96*	C	123 Brunhild	10.13	49*	S

Table 4 (continued)

Asteroid	B(1,0)	D (km)	Type	Asteroid	B(1,0)	D (km)	Type
124 Alkeste	9.39	67	S	216 Kleopatra	8.21	218?	CMEU
125 Liberatrix	9.77	64?	U	219 Thusnelda	10.68	38*	SM
126 Velleda	10.58	40*	S	221 Eos	8.94	97?	U
129 Antigone	7.85	114	M	224 Oceana	9.79	59*	M
130 Elektra	8.46	121?	U	230 Athamantis	8.65	114	S
131 Vala	11.03	35	SM	236 Honoria	9.51	65*	S
133 Cyrene	9.18	78*	S	238 Hypatia	9.23	153	C
135 Hertha	9.24	78	M	241 Germania	8.61	179*	C
137 Meliboea	9.14	142*	C	247 Eukrate	9.31	14?	C
139 Juewa	9.16	139*	C	250 Bettina	8.49	192?	CMEU
140 Siwa	9.58	102	C	258 Tyche	9.54	65*	S
141 Lumen	9.58	115*	C	264 Libussa	9.67	63	S
144 Vibilia	9.15	132	C	268 Adorea	9.76	106*	C
145 Adeona	8.67	175*	C	270 Anahita	10.03	50	S
146 Lucina	9.30	131*	C	275 Sapientia	10.04	94*	C
148 Gallia	8.47	106*	S	276 Adelheid	9.74	106?	CMEU
149 Medusa	11.94	24?	U	281 Lucretia	13.11	15?	U
150 Nuwa	9.33	129?	CMEU	284 Amalia	11.28	52*	C
151 Abundantia	10.53	41*	S	293 Brasilia	11.07	58*	C
152 Atala	9.60	63*	S	295 Theresia	11.41	27*	S
153 Hilda	8.82	99?	U	306 Unitas	10.02	52*	S
156 Xanthippe	9.81	103*	C	308 Polyxo	9.28	136	U
159 Aemilia	9.32	133	C	313 Chaldaea	10.10	92*	C
162 Laurentia	10.01	97*	C	324 Bamberga	8.07	251	C
163 Erigone	10.80	65*	C	326 Tamara	10.32	81*	C
164 Eva	9.84	101*	C	335 Roberta	9.93	48?	EU
166 Rhodope	10.91	38?	U	336 Lacadiera	10.96	33?	MEU
170 Maria	10.72	41?	U	337 Devosa	9.90	99?	CS
172 Baucis	10.09	67	S	338 Budrosa	9.78	58*	M
173 Ino	8.82	162*	C	342 Endymion	11.29	52*	C
176 Iduna	9.52	72?	U	344 Desiderata	9.09	145*	C
177 Irma	10.75	67*	C	345 Tercidina	10.15	89*	C
178 Belisana	10.69	38*	S	349 Dembowska	7.24	144	R
179 Klytaemnest	9.31	71*	S	350 Ornamenta	9.45	122*	C
181 Eucharis	9.06	79*	S	351 Yrsa	10.30	45*	S
182 Elsa	10.24	47*	S	354 Eleonora	7.48	169	U
183 Istria	10.98	33*	S	356 Liguria	9.27	149	C
185 Eunike	8.75	168*	C	357 Ninina	9.82	104*	C
186 Celuta	10.46	45	U	360 Carlova	9.42	129	C
189 Phthia	10.76	41	S	362 Havnia	10.13	89*	C
192 Nausikaa	8.61	93	S	363 Padua	10.05	94*	C
194 Prokne	8.84	193	C	364 Isara	11.08	31?	SMR
195 Eurykleia	10.07	92*	C	365 Corduba	10.32	99	C
196 Philomela	7.72	160	S	367 Amicitia	12.10	19*	S
200 Dynamene	9.47	121?	CME	370 Modestia	11.72	43*	C
203 Pompeja	10.08	91*	C	377 Campania	10.04	95?	CMEU
204 Kallisto	10.07	50*	S	381 Myrrha	9.68	126	C
206 Hersilia	9.84	101*	C	384 Burdigala	10.81	36*	S
208 Lacrimosa	10.48	42	S	386 Siegena	8.60	174	C
209 Dido	9.47	121?	CMEU	387 Aquitania	8.47	112	S
210 Isabella	10.45	77*	C	388 Charybdis	9.52	119?	CMEU
211 Isolda	9.02	167	C	389 Industria	9.40	69*	S
213 Lilaea	10.12	46?	EU	393 Lampetia	9.32	121	C
214 Aschera	10.41	43?	MU	395 Delia	11.49	48*	C

Table 4 (continued)

Asteroid	B(1,0)	D (km)	Type	Asteroid	B(1,0)	D (km)	Type
397 Vienna	10.54	50	S	660 Crescentia	10.60	39*	SM
402 Chloe	10.28	46*	S	674 Rachele	8.65	97*	S
404 Arsinoe	9.99	94*	C	679 Pax	10.40	42	S
409 Aspasia	8.31	207*	C	680 Genoveva	10.68	69?	CMEU
410 Chloris	9.47	124*	C	694 Ekard	10.11	90*	C
415 Palatia	10.54	74*	C	702 Alauda	8.29	205*	C
416 Vaticana	9.24	76*	S	704 Interamnia	7.24	338	C
426 Hippo	9.81	103*	C	705 Erminia	9.55	117?	CMEU
432 Pythia	10.33	45*	S	714 Ulula	10.30	46*	S
433 Eros	12.40	15	S	Marghanna	10.73	67*	C
434 Hungaria	12.45	10	E	737 Arequipa	9.93	54*	S
435 Ella	11.33	51?	CMEU	739 Mandeville	9.79	63?	U
441 Bathilde	9.45	61	M	744 Aguntina	11.25	32?	U
444 Gyptis	9.11	142*	C	747 Winchester	8.81	205	C
446 Aeternitas	10.21	47*	R	755 Quintilla	10.75	37?	MEU
451 Patientia	7.67	326	C	776 Berbericia	8.70	173*	C
454 Mathesis	10.27	83*	C	778 Theobalda	10.58	36?	EU
455 Bruchsalia	9.86	101*	C	782 Montefiore	12.68	15*	SM
462 Eriphyla	10.77	40?	U	785 Zwetana	10.73	45	U
471 Papagena	7.78	148	S	790 Pretoria	9.09	177	C
472 Roma	10.39	44*	S	796 Sarita	10.16	88*	C
476 Hedwig	9.82	103*	C	804 Hispania	8.86	162*	C
478 Tergeste	9.22	75*	S	825 Tanina	13.04	13*	S
481 Emita	9.86	101*	C	830 Petropolita	10.52	41*	S
497 Iva	10.71	38*	M	853 Nansenia	12.61	28*	C
498 Tokio	10.34	72	C	863 Benkoela	10.31	49*	R
505 Cava	10.10	50?	ME	887 Alinda	15.43	5.2	U
508 Princetonia	9.41	125*	C	888 Parysatis	10.82	36*	S
509 Iolanda	9.67	60*	S	911 Agamemnon	9.01	94?	U
510 Mabella	10.96	61?	CMEU	924 Toni	10.45	77*	C
511 Davida	7.36	341	C	932 Hooveria	11.12	55*	C
516 Amherstia	9.37	63	M	946 Poesia	11.53	46*	C
524 Fidelio	10.99	60*	C	963 Iduberga	13.83	9.2*	S
532 Herculina	6.96	230	S	969 Leocadia	13.58	9.1?	EU
537 Pauly	9.94	97*	C	976 Benjamina	10.51	75?	CMEU
540 Rosamunde	12.25	18*	S	977 Philippa	10.76	66*	C
545 Messalina	9.72	107*	C	1001 Gaussia	10.70	38?	MEU
550 Senta	10.53	41*	S	1011 Laodamia	14.24	7.2	S
554 Peraga	9.85	103*	C	1036 Ganymed	10.61	39*	S
558 Carmen	10.08	65	SM	1043 Beate	10.93	34*	S
563 Suleika	10.00	53*	S	1048 Feodosia	10.66	70*	C
569 Misa	11.26	53*	C	1052 Belgica	13.27	11*	S
584 Semiramis	9.82	54	S	1058 Grubba	13.01	13?	SR
588 Achilles	9.73	61?	MEU	1140 Crimea	11.59	25*	S
591 Irmgard	11.77	23?	MU	1143 Odysseus	9.48	62?	EU
596 Scheila	9.98	133	U	1171 Rusthawelia	10.81	64?	CMEU
602 Marianna	9.45	137	C	1172 Aneas	9.35	128*	C
617 Patroclus	9.05	88?	U	1173 Anchises	10.18	87*	C
618 Elfriede	9.38	126*	C	1178 Irmela	12.99	23*	C
623 Chimaera	12.20	34*	C	1212 Francette	7.99	238?	CMEU
624 Hektor	8.65	110?	U	1263 Varsavia	11.75	42*	C
631 Philippina	10.16	49*	S	1266 Tone	10.43	77*	C
654 Zelinda	9.51	72?	U	1268 Libya	10.07	92?	CMEU
658 Asteria	11.70	23*	SU	1314 Paula	13.96	8*	S

Table 4 (continued)

Asteroid	B(1,0)	D (km)	Type	Asteroid	B(1,0)	D (km)	Type
1329 Eliane	12.22	19*	SU	1583 Antilochus	9.76	60?	MEU
1362 Griqua	12.42	31*	C	1620 Geographos	16.67	2*	S
1401 Lavonne	13.53	10*	S	1681 1948WE	12.84	14*	S
1437 Diomedes	9.39	125?	CMEU	1685 Toro	14.60	8?	U
1500 Jyvaskyla	14.43	7*	S	1694 Kaiser	13.73	17*	C
1504 Lappeenrant	13.03	12*	S	1707 1932RL	13.89	8.7*	SU
1547 1929CZ	11.96	24?	U	1864 Daedalus	16.34	3?	U
1566 Icarus	17.62	1.7?	U	1960UA	15.00	9*	CU
1567 Alikoski	10.64	75	C	1976AA	18.40	0.9	U
1580 Betulia	15.80	6.5*	C	1977RA	16.71	2*	SU

[a] Classifications are from Bowell *et al.* (1978) and follow the definitions in Table 2. Multiple classes indicate ambiguity.

[b] Diameters followed by * are computed for the mean albedo of the class, rather than determined directly. Diameters followed by ? correspond to an adopted albedo of 0.1 and could be in error by as much as a factor of three. For a summary of directly measured diameters, see Morrison (1977b).

It is of interest to note that the largest asteroids do not fit into the CSM taxonomy. Vesta, as discussed above, is unique in a number of parameters. Pallas is C-like in some respects and M-like in others, but clearly unclassifiable. Ceres is loosely describable as a C type, but has a rather high albedo (0.054) and an unusual spectrum with uncommonly reddish U-B and uncommonly neutral R/B colors. Thus Ceres is now formally designated as a U object, and should not in any case be thought of as a prototype for the C class. Among the six largest asteroids (Morrison, 1977b), Ceres, Pallas, and Vesta are unclassifiable, Euphrosyne has been observed only in P_{min}, with Pallas-like results, 704 Interamnia is a peculiar C object, and only Hygiea is a normal C. Thus the true C-dominated asteroid population only begins at diameters of 300 km and smaller. Note, too, that well over half the mass in the asteroid belt is accounted for by these unusual asteroids which do not fit the CSM classification system.

COMPARISON OF THE CSM TAXONOMY WITH OTHER SYSTEMS

Taxonomic schemes have an important function in organizing observational data, but because the number of classes and subclasses and their exact boundaries are largely arbitrary, they can also be a source of misunderstanding and dispute. The CSM taxonomy attempts to divide its classes along natural lines with a minimum of interpretation. It is thus of limited use in studies of asteroid mineralogy, and indeed some very different mineralogical assemblages may be grouped together in the CSM scheme. In this final section of my paper, I briefly consider some comparisons between the CSM and two other taxonomies, following the more detailed discussion in Bowell *et al.* (1978).

In the first alternate taxonomy, Chapman (1976) used the available spectrophotometry for 98 asteroids to establish 13 groups, each of which he interpreted to have similar surface composition and mineralogy. For instance, one group is interpreted as being due chiefly to the signatures of nickel-iron plus olivine while another is suggestive of a C2 (CM) carbonaceous chondritic composition.

Even more recently, Gaffey and McCord (1977, 1978) have developed a separate classification for 62 of the spectra, emphasizing interpretations of mineralogical assemblages. This scheme is described in more detail in this volume by McCord (1978). Fifteen groups were defined, mostly consisting of subdivisions of several broader groups symbolized by R (for reddish spectra, both with and without prominent 1.0 μm absorption features), T (for transition), and F (for flat).

In general the Chapman and Gaffey-McCord classifications group asteroids in a consistent manner. However, in a few cases there are real differences as discussed by Bowell *et al.* (1978) and Gaffey and McCord (1978).

A continuing controversy in all three taxonomic systems concerns the significance of the class called M in the CSM classification. The name for this class suggests its interpretations as metallic (Zellner and Gradie, 1976); that is, the characteristic spectral signature of these asteroids is suggestive of nickel-iron. However, it is agreed by both Bowell *et al.* (1978) and Gaffey and McCord (1978) that these objects could be either nearly pure metal or finely divided metal in a neutral silicate matrix (*e.g.*, like the enstatite chondrites). There is clearly a great geochemical difference between these two interpretations, and present observations do not seem capable of distinguishing between them. A complicating factor is that Gaffey and McCord interpret another group of asteroids (their class RF) as also of iron or enstatic-chondritic composition, while Chapman interprets the spectra as indicating a broad, weak absorption feature due to either olivine or olivine-plus-pyroxene. If Gaffey and McCord are right, then asteroids of nickel-iron or enstatite chondrite composition are distributed among both the M and S types of the CSM system, in spite of a wide gap in UBV colors between these classes.

In spite of its low level of direct interpretability in terms of mineralogy, the CSM taxonomy does have some significant advantages. First, it can be applied widely, since it depends upon only a few observational parameters. Second, it involves albedo information directly, and thus it permits investigation of differences in the size distributions and orbital distributions for the separate classes. Through its strict accounting of albedos, the CSM taxonomy permits a reasonable correction for bias to be applied to the available statistics, such as accomplished by Chapman *et al.* (1975), Morrison (1977b), Zellner and Bowell (197[illegible]), and Zellner (1978). Third, the CSM system requires no revision when mineralogical identifications are modified or improved, since it is based strictly on observational parameters.

The CSM taxonomy has proved useful for outlining the structure of the asteroid belt, and it will probably be extended during the next year or two to nearly half the numbered asteroids. The usefulness of its applicability to the Earth-approaching asteroids or to those beyond 3.6 AU, where different populations may exist, has yet to be demonstrated, however. The reconnaissance data exemplified by the CSM taxonomy are not sufficient, however, for understanding the mineralogy of asteroid surfaces. It seems clear that detailed analysis of reflection spectra supported by albedo data and by laboratory and theoretical work is required as well, and our understanding of the nature of the asteroids in the next few years will probably be best advanced by a two-pronged attack involving both continuing reconnaissance studies and the intensive acquisition and interpretation of spectrophotometry of a smaller number of representative asteroids.

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DISCUSSION

VEVERKA: Are the magnitudes that are included in the TRIAD file the ones that have been measured recently or are they from some previous compilation?

MORRISON: There are several sources for these magnitudes. Gehrels has provided photoelectric magnitudes for many. A lot more of the magnitudes are only photographic. The goal was to obtain the best magnitude for every numbered asteroid. However, for many individual objects, especially faint objects, these magnitudes can still be very bad--with brightness uncertain by as much as a factor of two.

CHAPMAN: Another advantage of this classification scheme which I think is important is that a relatively simple observing program in which only radiometry and UBV photometry are used can detect the anomalous or unusual objects. The taxonomy alerts us to unusual asteroids we should go out and look at in more detail with spectrophotometry and other techniques.

MORRISON: About 10% are Us, so you can improve the efficiency of observations by a factor of ten for the more elaborate techniques if you decide to concentrate on the unclassified objects.

ANDERS: I wonder if the time hasn't come to analyze this population to see how homogeneous these classes are and whether any of them break up into subsets.

ZELLNER: Remember that the data are extremely heterogeneous and, to do anything that is very formal mathematically, one needs a better set of data.

MORRISON: The number of objects for which we have all seven of those parameters must be well under 100. Most of them are S, of course, because of the observational bias in favor of bright objects. Even so, the high albedo ones, like Vesta, the Es, or the Rs are extremely rare. Zellner will talk about how much rarer they are in the population as a whole when bias corrections are included. It is very curious that we are able to think of these rare objects as having very close relationships to certain meteorite classes. However, the data base is rapidly expanding, and within the next year it may be appropriate to apply more sophisticated statistical techniques, such as cluster analysis.