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ASTEROID COMPOSITIONAL TYPES AND
THEIR DISTRIBUTIONS

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A sample of 359 minor planets with available colorimetric, spectrophoto-metric, thermal-radiometric, and/or polarimetric data are classified into broadly defined compositional types C (carbonaceous), S (silicaceous), M (metal-rich), E (metal-free; enstatite?), O (ordinary-chondritic?), T (Trojan; uniden-tified composition), and U (unclassifiable; none of the above).

The small asteroids in Mars- or earth-crossing orbits are almost invariably of type S or O. For the main belt between 2.2 and 3.5 AU., distributions of the various types over diameter and orbital parameters are derived with corrections for observational selection bias. For 560 main-belt asteroids with diameters >50 km, 76% are of type C, 16% of type S, 5% M, and 3% of other types. The S objects become progressively less common with distance. The shapes of the diam-meter-frequency relations for primitive (C) and evolved (S + M) types are statistically indistinguishable, both showing a change of slope at 160-km diameter.

While large asteroids avoid the Kirkwood gaps more strongly than small ones, we find no significant gap-related anomalies in the relative frequencies of compositional types. Thus most of the observational basis for models in which primitive and evolved asteroids respond differently to collisional evolution has been removed.

INTRODUCTION

In recent years several observational techniques have been applied to large numbers of asteroids for remote sensing of their surface properties. In-frared radiometry at thermal wavelengths measures the diameter and, together with the visual magnitude, the geometric albedo (Hansen 1976; Morrison and Chap-man 1976; Morrison 1977; and reviews in this volume by D. Morrison and O. Han-sen). Optical polarimetry gives indications of surface structure and albedo and hence also permits the computation of diameters (Zellner and Gradie 1976a; A. Dollfus in this volume). Narrow-band spectrophotometry at visible and near-infrared wavelengths gives the most direct information on surface mineralogy (Johnson and Fanale 1973; McCord and Chapman 1975a,b; McCord and Gaffey in this volume). Broad-band or UBV photometry (Zellner *et al.* 1975, 1976; Bowell 1977) generally permits recognition of the major types identified by more sophisticated techniques and can be pushed to substantially fainter magnitude limits.

Diversity is a fundamental characteristic of the asteroid population. While individual asteroids seem to have remarkably uniform surfaces, hardly any

two well-observed objects are optically indistinguishable, and as many as 34 distinct types of reflection spectra have been identified by McCord and Chapman. Nevertheless, five or six broad but distinct *classes* appear in the results from all compositionally sensitive techniques. The prevalence of the S ("silicaceous") and C ("carbonaceous") types, together accounting for more than 90% of the asteroid population, was first recognized by Chapman on the basis of colors and by Zellner on the basis of polarimetric parameters and is beautifully demonstrated in the albedo histogram by Morrison in this volume.

The distinctness of the major groups throughout the asteroid population as seen by independent techniques strongly suggests to us that the groupings have a high degree of physical significance as well as practical utility. The broad classification scheme permits the examination of distributions over diameter, heliocentric distance, etc. in ways not statistically possible for minutely specified compositional species. An asteroid observed by only one technique, such as UBV photometry, can usually be classified with confidence or else recognized as an unusual object. Finally, let us emphasize that these groups are based entirely on observational parameters, and their validity is not compromised if interpretations in terms of meteoritic analogues, etc. must be modified.

Our purpose in this paper is to classify as large a sample of asteroids as currently available observations permit and to derive distributions of the various types over diameter and orbital parameters with correction for observational selection biases. Our preliminary results are examined in more detail by Bowell *et al.* (1977). Such an analysis was first attempted by Chapman *et al.* (1975), who concluded that: (1) most asteroids can be classified C or S, with a sprinkling of the other types; (2) the frequency of type S with respect to type C generally decreases with distance outward through the main belt; (3) M asteroids tend to fall near the Kirkwood gaps, and C objects to avoid the gaps widely; and (4) different diameter-frequency relations, suggestive of different collisional evolution histories, are found for the C and S populations. Now, with a sample of asteroids more than three times larger than that available to Chapman *et al.* we can confirm the first two statements. The third appears to be false, however; and the fourth must be substantially modified.

TYPES AND DIAMETERS

The major types can be displayed in a variety of ways using spectroscopic, radiometric, or polarimetric data. We are limited by space requirements to Figure 1, which separates out the groups as well as any two-dimensional plot.

The moderate albedos and reddish curving spectra of the S asteroids are attributable to a mixture of free metal and transition-metal ions in a silicate lattice (Gaffey 1974; McCord and Gaffey 1974). Near-infrared absorption bands characteristic of pyroxene and/or olivine silicates are often but not invariably present. Although good matches with laboratory reflection spectra have proven difficult, the S asteroids will no doubt be ultimately identified with various stony-iron meteorites or iron-rich ordinary chondrites.

The low albedos and rather flat spectra of the C asteroids are almost certainly due to an admixture of carbon, while a characteristic drop-off in the ultraviolet implies the presence of ferrosilicates as well. These objects are probably the parent bodies of at least some carbonaceous chondrites.

A third major type is provided by the M ("metallic") objects with albedos similar to those of the S group but flatter, featureless reflection spectra characteristic of free metal as in the nickel-iron meteorites and enstatite chondrites. A class O, as yet poorly defined, has higher albedos (up to 0.26) and spectra similar to certain metal-poor ordinary chondrites. Three E objects have been identified with quite high albedos (≳0.3) and colorless spectra strongly suggestive of the metal-free enstatite achondrites (Zellner 1975; Morrison *et al.* 1977). Observations of several Trojans, here denoted as class
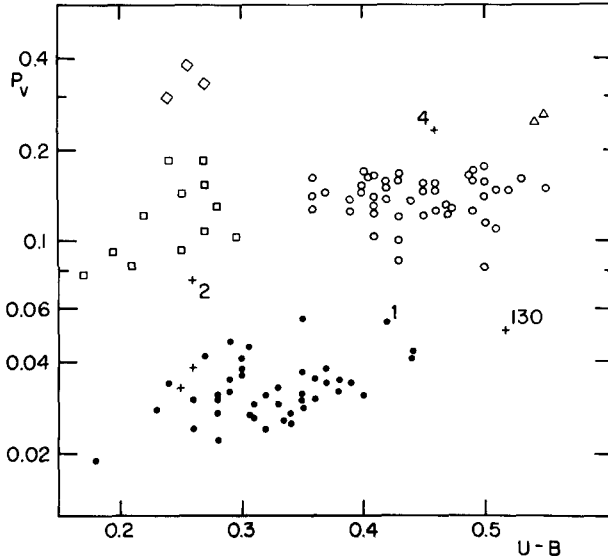
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FIGURE 1. *Albedo versus ultraviolet minus blue color index for 43 C asteroids (filled circles), 47 of type S (open circles), twelve of type M (open boxes), three of type E (open diamonds), two of type O (open triangles), and five of other types (+). Geometric albedos are on the radiometric scale, as listed by D. Morrison in this volume.*

T, have revealed quite low albedos and unique spectra not corresponding to any identified meteorite or mineral assemblage.

A small fraction of the observed asteroids belongs to none of the above types and is designated by the symbol U ("unclassifiable"). They are either unique or belong to types yet to be described. The U asteroids include some of the very largest objects; 4 Vesta has a unique basaltic surface (McCord *et al.* 1970; Larson and Fink 1975), while 2 Pallas has a rare combination of optical properties and 1 Ceres itself is a rather unusual C asteroid.

There is no observational evidence that any asteroid has a surface of variegated albedo or composition. Recent polarization observations of 433 Eros (Zellner and Gradie 1976b) showed the albedo to be constant over rotation and aspect to one part in forty, and narrow- and broad-band colors did not vary measurably with rotation (*e.g.*, Pieters *et al.* 1976; Millis *et al.* 1976).

Table I gives compositional types chosen by us for 336 main-belt asteroids, twelve Mars-crossers, two Hildas, and nine Trojans. The data base consists of observational parameters in the TRIAD computer file[1] and further preliminary results by several observers. By rough count we have 100 asteroids with polarimetric data, 126 with reflection spectra, 165 with radiometric diameters, and 300 with UBV colors.

The type assignments range in quality from quite secure to highly provisional. We used classification criteria very similar to, but slightly looser than, those tabulated by Bowell *et al.* (1977). That is, we did not exclude an

[1] *The Tucson Revised Index of Asteroid Data contains all reliable physical information for minor planets and is maintained at the University of Arizona by B. Zellner. Contributors and their areas of responsibility are: D. Bender, orbital elements; E. Bowell, UBV colors; C. Chapman, spectrophotometric parameters; T. Gehrels, magnitudes and lightcurve parameters; T. McCord, digital reflection spectra; D. Morrison, radiometric parameters; and B. Zellner, polarimetric parameters.*

Table I. Compositional Types and Diameters

No.	Type	Diam	No.	Type	Diam	No.	Type	Diam	No.	Type	Diam	No.	Type	Diam	No.	Type	Diam
1	C	1003	66	C	76	145	C	176	293	C	59	478	S	75	801	C	34
2	U	608	67	S	62	146	C	135	295	S	27	481	C	102	804	C	162
3	S	247	68	S	126	148	S	106	306	S	43	497	M	31	825	S	12
4	U	538	69	U		149	O	16	308	U	138	498	C	71	830	S	43
5	S	117	70	C	151	150	C	109	313	U		505	C	91	853	C	29
6	S	201	71	S	115	151	S	41	321	C	52	508	C	126	863	O	35
7	S	209	72	C	96	152	S	64	324	C	246	509	S	60	887	S	4.5
8	S	151	76	C	144	153	C	184	326	C	82	510	M	34	888	S	36
9	S	151	77	S	65	154	C	191	335	U		511	C	323	911	T	155
10	C	450	78	C	140	156	C	104	336	M	34	516	M	63	924	C	78
11	S	150	79	S	76	159	C	140	337	S	55	524	C	61	932	C	56
12	S	126	80	U	83	162	C	95	338	M	60	532	S	130	946	C	47
13	C	224	81	C	112	163	C	76	342	C	53	537	C	103	963	S	9.2
14	S	158	82	S	65	164	C	102	344	C	145	540	S	13	969	U	
15	S	272	83	C	111	166	U		345	C	89	545	C	115	976	M	43
16	M	250	84	C	90	170	U		349	O	144	550	S	41	977	C	68
17	S	109	85	C	147	172	S	67	350	C	123	554	C	103	1001	M	38
18	S	150	86	C	108	173	C	142	351	S	45	558	M	64	1011	S	7.2
19	C	215	87	M	119	176	C	119	354	S	153	560	C	43	1036	S	35
20	S	131	88	C	210	177	C	68	356	C	150	563	S	51	1043	S	35
21	M	115	89	S	155	178	S	39	357	C	105	569	C	54	1048	C	70
22	M	177	90	C	124	179	S	72	360	C	130	579	S	76	1052	S	12
23	S	111	91	C	104	181	S	82	362	C	90	584	S	55	1058	S	13
24	C	211	92	C	244	182	S	48	363	C	95	588	T	110	1087	C	58
25	S	72	93	C	168	183	S	33	364	S	32	591	M	23	1140	S	26
26	S	93	94	C	188	185	C	169	365	C	99	596	C	134	1143	T	124
27	S	108	95	C	167	186	M	49	367	S	20	602	C	137	1171	C	65
28	S	123	97	M	95	189	M	41	370	I		617	T	148	1172	T	131
29	S	195	100	S	80	192	S	94	372	I		618	C	126	1173	T	88
30	S	91	102	C	85	194	C	191	377	M	53	623	C	35	1178	C	24
31	C	334	103	S	90	195	C	92	381	C	126	624	T	182	1212	C	69
32	S	93	104	C	122	196	S	161	384	S	36	631	S	49	1263	I	24
34	C	114	105	C	125	200	C	123	386	C	191	639	S	72	1266	C	79
36	C	96	106	C	166	203	C	92	387	S	112	654	C	116	1268	C	91
37	S	95	107	C	211	204	S	50	388	M	66	658	S	24	1287	S	19
39	S	163	108	S	61	206	C	101	389	S	81	660	S	40	1291	S	26
40	S	100	109	C	75	208	S	42	393	C	129	661	S	36	1314	S	8.5
41	C	204	110	C	170	209	M	67	395	C	49	674	S	102	1329	S	24
42	S	97	111	C	143	210	C	77	397	S	50	675	S	74	1362	C	58
43	S	82	113	S	47	211	C	166	402	S	46	676	C	71	1401	C	10
44	E	82	114	C	122	213	C	90	404	C	86	679	S	73	1437	T	126
45	C	226	115	S	93	214	M	44	409	C	211	680	I		1500	S	7.0
46	C	133	116	S	80	216	M	128	410	C	134	694	C	88	1504	S	13
47	C	135	117	C	137	219	S	37	415	C	75	702	C	205	1547	U	
48	C	248	119	S	57	221	U		416	S	76	704	U	350	1566	O	1.4
49	C	176	120	C	173	224	M	71	426	C	104	705	I		1567	C	72
51	C	151	122	C	139	230	S	121	432	S	55	714	S	46	1580	C	6
52	C	289	123	S	47	236	S	65	433	S	23	735	C	68	1583	T	109
53	C	97	124	S	67	238	C	154	434	E	11	737	S	54	1620	S	3.4
54	C	180	125	M	58	241	C	179	435	I		739	C	105	1627	S	7.0
55	M	75	126	S	40	247	C	142	441	M	66	744	U		1636	S	10
56	C	146	129	M	115	250	M	107	444	C	141	747	C	205	1681	S	14
57	S	109	130	U	173	258	S	65	446	O	40	755	M	37	1685	U	3.2
58	C	99	131	M	35	264	S	63	451	C	276	776	C	147	1694	C	17
60	S	51	135	M	78	268	C	106	454	C	85	778	U		1707	S	8.8
61	S	87	137	C	143	270	S	51	455	C	93	779	C	108	1864	O	2.2
62	C	105	139	C	163	275	C	94	462	S	37	782	S	15	600A	S	15
63	S	91	140	C	103	276	C	107	471	S	143	785	M	49	60UA	U	
64	E	56	141	C	133	281	S	13	472	S	45	790	C	176	76AA	S	1.0
65	C	309	144	C	130	284	C	53	476	C	106	796	I				

Notes to Table I. Compositional types are italicized where observations by one technique only are available. Italicized diameters rerer to objects for which albedos have not been derived from radio-metric or polarimetric observations but only assumed according to the type. (See text). The last three entries signify unnumbered objects 1960 OA, 1960 UA, and 1976 AA.

object from a likely class if some measured parameter fell just outside the nominal class boundaries.

We use the class designation I (indeterminate) in a few cases where the only available parameters fall in ambiguous color or albedo domains and no real choice is possible. The designation U, by contrast, is used for objects *known* to fall *outside* the domains of all recognized (C, S, M, E, O, T) classes in one or more parameters.

Diameters in Table I are taken from Morrison (this volume), where radiometric, polarimetric, or combined results of weight 2 or higher are available. In other cases the diameters are computed from

$$2 \log (D/2) = 5.642 - 0.4V(1,0) - \log p_V.$$

Absolute visual magnitudes $V(1,0)$ were computed from the blue magnitudes listed by Gehrels and Gehrels (1977) and B-V colors either known or estimated according to the type. For the geometric albedo p_V, we used adopted values of 0.14 for type S, 0.12 for type M, 0.037 for type C, and 0.23 for type O. As demonstrated by Morrison, the mean albedo is probably more reliable in a particular case than a low-weight polarimetric or radiometric value.

We emphasize that the diameters used here are all based on the radiometric albedo scale, which gives somewhat lower albedos and larger dimensions than the polarimetric calibration. We ourselves have confidence in the polarimetric values, at least for albedos greater than 0.06, but we use the radiometric scale for convenience and ease of comparison with other results. The following analysis depends rather critically on the choice of relative albedos, but only weakly on the absolute values.

THE MAIN BELT: BIAS-CORRECTED DISTRIBUTIONS

The sample of main-belt asteroids classified in Table I is *complete* to mean opposition apparent magnitude $B(a,0) = 12$; it is 65% complete to magnitude 14 and has significant sampling to the limit of completeness of the numbered asteroids at about magnitude 15.5

The selection in favor of bright objects in observational programs is a bias against asteroids which are small, distant, and of low albedo. For evaluation and correction of the selection effects, we assume that the bias is, over broad distance zones, a *function of the mean opposition apparent magnitude only.* This assumption is a slight oversimplification since some survey programs contained deliberate attempts to sample objects from particular Hirayama familes, etc., and other more subtle selection effects. Since the compositional type is unknown before observation, however, the true bias effects cannot depend on the type; for this reason the "indeterminate" classifications of Table I are kept in the sample. Results with slightly modified assumptions are examined by Bowell *et al.* (1977).

Thus *bias factors* are computed at any apparent magnitude as the ratio of the count for the whole numbered population to the count for the classified sample. For the normalization we used 1330 numbered main-belt objects with $B(a,0) \leq 16$ from the tabulation of Gehrels and Gehrels (1977). Modest corrections for incompleteness of the numbered sample were applied beyond magnitude 15.

While Figure 2 illustrates the process for the whole main belt, the actual computations were made separately in three distance zones, and the resulting (smoothed) bias factors are also plotted. For example, asteroid 342 Endymion with $B(a,0) = 14.31$ in zone 2 has bias factor 4.67, and it is *entered with this weight* for the summation of bias-corrected distributions. We feel confident of the results for apparent magnitudes up to about 14.7 or weights up to 10. The statistics are ragged at the faint end, and also at the bright end because of the small numbers of asteroids actually present.
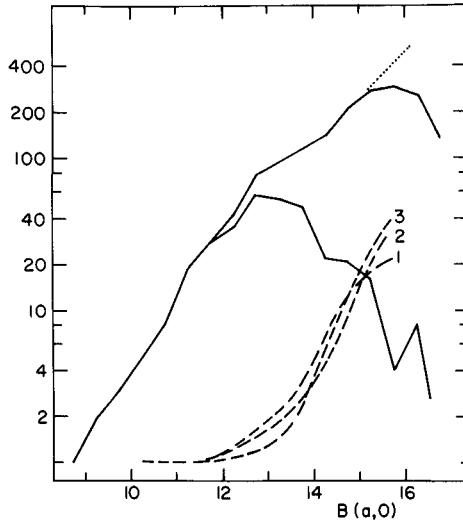
FIGURE 2. *Total number of main-belt asteroids (upper solid line) and classified main-belt asteroids (lower solid curve) per 0ᵐ5 interval in mean opposition apparent magnitude B(a,0). The dotted line indicates correction for incompleteness of the catalogued asteroid population beyond apparent magnitude 15. Dashed curves are bias factors, computed as the (smoothed) ratio of the two solid curves, but in three distance zones: (1) 2.19 ≤ a < 2.50; (2) 2.50 ≤ a < 2.83, (3) 2.83 ≤ a ≤ 3.49 .*

FREQUENCIES OF THE COMPOSITIONAL TYPES

In the outer parts of the main belt, $\underline{C}$ asteroids with diameters smaller than 50 km have apparent magnitudes fainter than the completeness limit of the numbered population and hence beyond reach of the bias analysis. Similar limits for types $\underline{S}$ and $\underline{M}$ are on the order of 25 km. For the entire main belt and diameters above 50 km we have observed 141 $\underline{C}$ objects, and the bias weights add up to 422. For type $\underline{S}$ the corresponding numbers are 73 and 91, and for type $\underline{M}$, 19 and 25. Thus the corrected frequency ratios are:

$$C : (C + S + M) = 0.78$$

$$S : (C + S + M) = 0.17.$$

$$M : (C + S + M) = 0.05.$$

For types $\underline{E}$, $\underline{O}$, $\underline{U}$, and $\underline{I}$ no rigorous bias analysis is possible since the statistics are poor and reliable diameters are often missing. With diameters *probably* greater than 50 km we have nine $\underline{U}$ asteroids, two E's, and a single O, for which the total bias weights add up to 14; and four asteroids classified $\underline{I}$ with total weight 10, of which half are probably of type $\underline{C}$ and half $\underline{M}$. Finally, it is probable that one or two of the asteroids classified $\underline{M}$ on the basis of UBV colors alone are actually of type $\underline{E}$ and $\underline{U}$.

Thus we estimate that the main belt contains 562 asteroids with D > 50 km, of which 76% ±6% are of type $\underline{C}$, 16% ±2% of type $\underline{S}$, 5% ±1% of type $\underline{M}$, and 3% ±1% of other types. If the adopted relative albedos of the principal types are correct, these proportions should not be in error by more than the indicated statistical uncertainties.

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DISTRIBUTIONS OVER DIAMETER

Figure 3 gives bias-corrected results for the diameter-frequency relation of types C, S, and M. We note that, relative to the C distribution, the S objects become slightly less numerous at smaller diameters, and the M objects more numerous. However, consider Figure 4, in which we have plotted the same distribution for type C and the combined distribution for types S and M. According to current ideas of their chemistry and origin, the two curves may be loosely described as representing "primitive" and "evolved" objects.
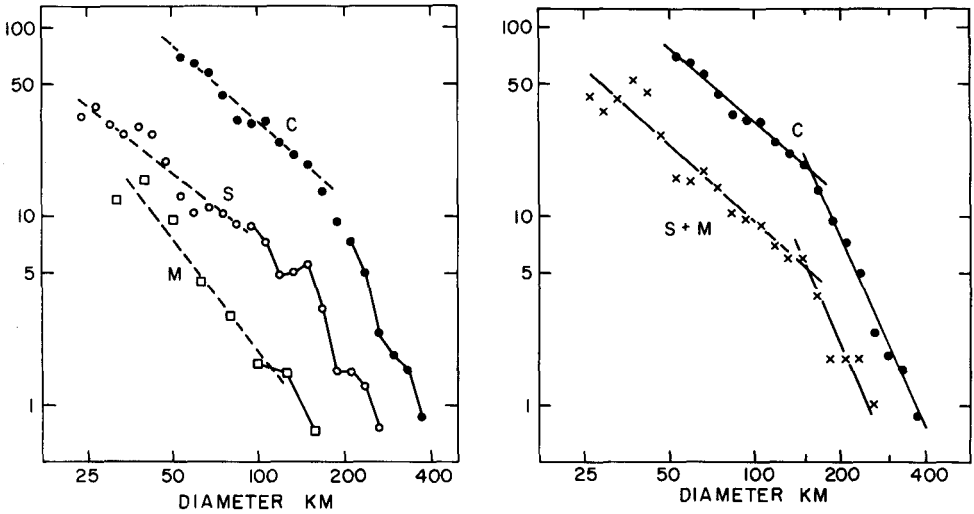
FIGURE 3. Bias-corrected number of asteroids of types C (filled circles), S (open circles), and M (open boxes) in intervals of 0.05 in log diameter. Connected points represent diameter ranges over which the sampling is essentially complete. The data are somewhat smoothed in regions of poor statistics.

FIGURE 4. As in Figure 3, but for types C (filled circles) and the sum of types S and M (x).

Within statistical noise limits the diameter-frequency functions for types C and S + M are *parallel* both showing a break or change in slope at about 160 km. At all diameters the C objects are more numerous than types S + M by a factor of 3.5. The break at 160 km produces the well-known slope change in the magnitude-frequency relation at about absolute magnitude 9 (*e.g.,* van Houten 1971). For small objects the slope is 1.3, and for diameters greater than 160 km it is 3.4

Thus the "silicate bump" or excess of evolved asteroids near 160 km first seen by Chapman *et al.* (1975) is present in absolute numbers, but no longer confined to type S. The conclusion reached two years ago evidently arose from insufficient observations of small C objects. The interpretations advanced by Chapman (1974,1976) and Chapman and Davis (1975) in terms of high collisional fragmentation strengths for stony-iron cores must be re-evaluated.

DISTRIBUTIONS OVER HELIOCENTRIC DISTANCES

For distributions of the C, S, and M types over orbital semi-major axis we

divided the main belt into eleven distance zones of roughly equal depth, five
containing major Kirkwood gaps and six with no major gaps. For all types we
found that the gap zones tend to fill in and become relatively better populated
toward smaller diameters. This remarkable effect, that large asteroids avoid
the Kirkwood gap regions more strongly than small ones, seems to have gone
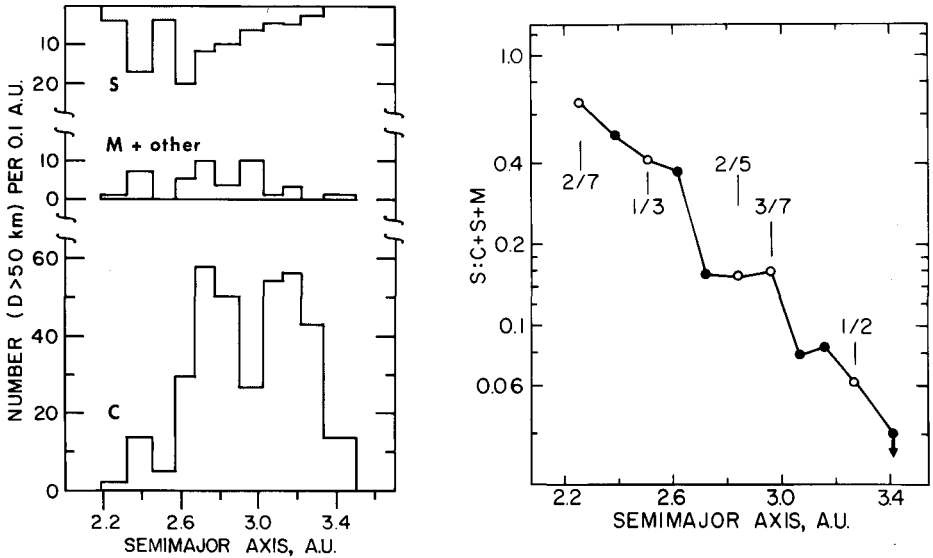previously unnoticed but is easily demonstrated for the whole numbered popula-
tion.

FIGURE 5. *Bias-corrected distributions of $\underline{C}$, $\underline{S}$, and other compositional types
over orbital semi-major axis, for diameters >50 km. Distance zones
containing Kirkwood gaps are shaded.*

FIGURE 6. *Ratio of bias-corrected counts as a function of orbital semi-major
axis, for $\underline{S}$ asteroids, and the sum of types $\underline{C}$, $\underline{S}$, and $\underline{M}$ for all diam-
eters >50 km. Open circles are used for distance zones containing
major Kirkwood gaps, and fractions indicate the ratio of sidereal
periods with respect to Jupiter.*

Bias-corrected type abundances as functions of semi-major axis are plotted
in Figure 5. Figure 6 clearly shows the general decrease of the relative fre-
quency of type $\underline{S}$ with distance noted by Chapman *et al.* (1975); $\underline{S}$ asteroids tend
to fall in the inner and central parts of the belt, $\underline{C}$ objects in the central and
outer parts, and $\underline{M}$ and other types most frequently in the central regions.

Contrary to earlier conclusions, we see no significant depletion of type $\underline{C}$
relative to $\underline{S}$, $\underline{M}$, or $\underline{U}$ in the Kirkwood gap zones. In Table II we have recon-
structed Table 4 of Chapman (1976). His conclusion that the relative frequency
of $\underline{S}$ asteroids is greatly enhanced near the Kirkwood gaps was an artifact of the
size effect noted above. That is, he used no specific diameter cut-off and
hence was comparing small $\underline{S}$ asteroids with large $\underline{C}$ objects.

Chapman *et al.* (1975) noted an unusual distribution of types near the
cluster of Kirkwood gaps around 2.9 A.U. Our data show one marked peculiarity
in this region, namely, an excess of large (>80 km) $\underline{M}$ asteroids and a deficiency
of smaller ones relative to type $\underline{S}$. The statistics are poor, however, comprising
four $\underline{M}$ objects in each diameter range. Analogous effects are not seen in other
gap zones.

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TABLE II

DISTRIBUTIONS OF TYPES WITH RESPECT TO KIRKWOOD GAPS

Asteroid Type	Fraction within 0.06 A.U. of Kirkwood Gaps		Fraction far from Kirkwood Gaps	
	Chapman	This Paper[*]	Chapman	This Paper[*]
C	11%	38%	89%	62%
S	36%	34%	64%	66%
M	31%	37%	69%	63%
Other		35%		65%

[*] Diameter >50 km

In summary, the new analysis has removed most of the observational basis for models in which C and S asteroids respond differently to collisional fragmentation, both with respect to the diameter-frequency relations and with respect to the Kirkwood gaps.

THE OUTLIERS: MARS-CROSSERS, HUNGARIAS, HILDAS, AND TROJANS

Figure 7 illustrates the run of broad-band color with heliocentric distance
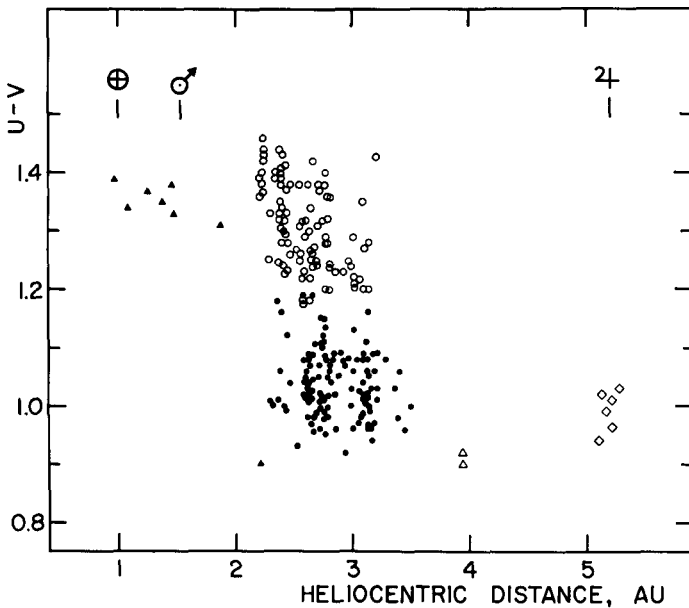
FIGURE 7. U-V color index for main-belt C (filled circles) and S (open circles) asteroids, Hildas (open triangles), Trojans (open diamonds), and Mars-crossers (filled triangles). Main-belt objects of types other than C or S are omitted for clarity. Adapted from Zellner et al. (1976).

for the whole minor planet domain. This overall view shows the main belt to
be a transition zone between predominantly reddish colors due to ferrosilicate
compositions and the more neutral tones of carbon-bearing materials. As may be
seen in Figure 6, the proportion of carbonaceous objects increases exponentially
with a distance scale length of less than 0.5 A.U.

The dozen small objects in our sample in Mars- or Earth-approaching orbits
(433, 887, 1011, 1036, 1566, 1580, 1620, 1627, 1685, 1864, 1960UA, and 1976AA)
were all observed by special efforts during favorable apparitions so that no
meaningful bias analysis is possible. With a single proven exception, however,
all of them have optical properties of types $\underline{S}$ or $\underline{O}$; and these are among the
prime candidates for the parent or "carrier" bodies that supply us with the
common stony meteorites (e.g., Levin et al. 1976). The anomaly is 1580 Betulia,a
dark, neutrally colored 6-km body which is formally classifiable as type $\underline{C}$, but
which may be an extinct cometary nucleus (Lebofsky et al. 1977).

Of the Hungaria family of small asteroids just inside the main belt at
1.9 A.U., only the largest, 434 Hungaria itself at 12-km diameter, has been
observed. Surprisingly, it turns out to be one of the rare $\underline{E}$ type (Morrison
et al. 1977). Two Hilda asteroids (1212 and 1268) at the two-thirds resonance
with Jupiter near 4 A.U. have been observed, by UBV photometry only. The colors
are quite similar and suggestive of dark objects, but a composition distinct
from the main-belt $\underline{C}$ asteroids is not yet excluded.

For the distant Trojans near the equilateral Lagrangian points of Jupiter,
initial results indicated low albedos characteristic of carbonaceous material,
but with reflection spectra quite unlike anything in the main belt (McCord and
Chapman 1975b; Cruikshank 1976; Zellner et al. 1976). Recent observations,
however, show a normal $\underline{C}$-type spectrum for 1173 Anchises (Chapman, personal
communication). Thus the view of the Trojan clouds as a separate, homogeneous
population may have to be abandoned.

FUTURE WORK

Brighter than apparent magnitude 14, roughly 130 objects remain unobserved
by the classification techniques. Further survey work will lead to better
definition of the various compositional types, especially those for which few
members are known at present. It is also probable that distinct new types will
be recognized. Closer examination of known $\underline{E}$, $\underline{O}$, and $\underline{U}$ objects may give
critical insight into geochemical processes and relationships with meteorites.

It is within our power but clearly unnecessary to classify more than 1500
of the numbered asteroids. For statistical purposes, further survey work in the
main belt will be most profitable at apparent magnitudes near 15. In Table I
we have 36 objects with $14.5 \leq B(a,0) \leq 15.5$, with bias factors ranging up to
30. In one observing season we could double or triple this sample, thus reduc-
ing the bias factors to 10 or so and greatly increasing our confidence level for
the 30-to-60-km diameter range. At magnitude 16 we reach the unexplored frag-
mental tail of the size-frequency distribution, but the numbered asteroid popu-
lation is incomplete, and evaluation of bias factors would require supporting
work of the type undertaken for the Palomar-Leiden Survey.

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DISCUSSION

ARNOLD: Do the Hirayama families have compositional significance?

ZELLNER: The general rule seems to be heterogeneity among family members. However some of the dynamically best-proven families have no bright members or only one bright member, and are essentially unexplored.

WILLIAMS: It was stated that asteroid families are heterogeneous in composition. The results we have seen are on a few of the less well determined families and restricted to the few brightest members of the families. To conclusively determine whether families have a single composition, or a few compositional types, or are completely heterogeneous will require observing members of the best defined families (such as Eos or Koronis) and to go to faint members of these families.

SCHOBER: I would like to know, what you are really thinking about the existence of the E-type group of asteroids? Are the three objects only an exception, not be assigned to any other group?

ZELLNER: The three identified E asteroids, 44 Nysa, 64 Angelina, and 434 Hungaria, have uniquely high albedos and uniquely flat spectra, hence a high degree of recognizability. That does not imply a unique mineral, or course.

WASSON: You stated that the general change from S to C type asteroids with increasing distance seemed inconsistent with my hypothesis that the parent bodies of some mteorites formed at locations outside the asteroid belt, but as a result of planetary perturbations, now be present in asteroidal orbits. This represents a misunderstanding of my picture. The bulk of material in the asteroid belt probably formed in that region. The exotic materials are probably much rarer, but as a result of the Mars perturbations necessary for capture into asteroidal orbits, have a much higher probability of perturbation into earth crossing orbits that would allow them to fall as meteorites.

ANDERS: You said that all Mars crossers were S or O objects. How certain is this for Icarus? In two respects (spherical shape, eccentricity) it looks like an extinct cometary nucleus, and at least I find it hard to believe that a cometary nucleus should have S or O (i.e., ordinary chondrite) composition.

JOHNSON: Icarus was observed by Tom Gehrel's group at UBVRI. The low value of the I reflectance indicates that this object is similar to other Apollos, such as Toro and has a chondritic type composition - not like Betulia for instance.

ZELLNER: Icarus came by before we really knew what we were doing, and it is somewhat difficult to fit it into the current picture. However it is certainly S- or O-like, and certainly not carbonaceous.

WASSON: It appears that in attempting to associate asteroid properties with meteorite categories you have assumed that all or most asteroidal materials can be found in terrestrial meteorite museums. It is important to bear in mind that our terrestrial selection of meteorites is biased and incomplete. Many inter- mediate types must exist, and some of these may be important constituents of asteroids.

ZELLNER: No such assumption is necessary. The optical types of asteroids would still be seen even if we had no meteorites to study. Classification of asteroids and identification with meteorites are two separate steps.

KELLER: You suggested that 1580 Betulia might be an extinct cometary nucleus. What is its diameter?

ZELLNER: The polarimetry indicates a C-like object with a diameter near 6 km; radar results from Arecibo give about 7 km. Thermal radiometry by L. Lebofsky, analyzed with the usual asteroid models, gives about 3 km.
    We have never seen that kind of anomaly before. Unless some mistake has been made, the thermal properties must be very strange. But let me emphasize that these are highly preliminary results.

WETHERILL: I would just like to clarify the earlier answer regarding the mini- mum distance of 1580 Betulia from the sun. As a consequence of the free os- cillations of its elements, as calculated by Williams, on a time-scale of

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~10^4 years this object repeatedly becomes not only earth-crossing but Venus-crossing as well.

WEISSMAN: On the problem of finding extinct cometary nuclei there is an object, periodic comet Arend- Rigaux, which is widely recognized as a comet about to become extinct. It will have a favorable opposition in February, 1978 and efforts should be made to observe it at that time, employing modern asteroid study techniques. Another similar object, Neujmin I, will make a favorable opposition in 1983.