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SPECTROPHOTOMETRIC STUDY OF ASTEROIDS

Final Report
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Submitted by:

C. R. Chapman
Principal Investigator

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Planetary Science Institute
252 W. Ina Road, Suite D
Tucson, Arizona 85704

I. INTRODUCTION

This program is one of two phases of research concerning asteroids being conducted at the Planetary Science Institute. Three Quarterly Reports were prepared previously (November 15, 1973; February 15, 1974; and May 15, 1974). In this Final Report, a summary of progress during the fourth quarter is provided as well as some detailed interpretations and analysis summarizing the entire year's work. A follow-up program has been proposed to the same office at NASA for the forthcoming year and it is hoped that the fruitful leads suggested by the conclusions of this year's study may be pursued.

There have been four distinct sub-tasks involved in the current effort. (1) Observations of particular faint asteroids of interest, in particular the Trojans, were carried out during an observation run at Kitt Peak National Observatory (1.3 meter telescope) in September 1973. The observational phases of this program are conducted jointly with T. McCord of MIT. (2) An attempt has been made to study the compositional variation within Hirayama families, through analysis of all PSI/MIT asteroid spectrophotometry with the new Hirayama family lists calculated by J. G. Williams of JPL and kindly provided by him. (3) A particularly important study was initiated during the past year to observe spectrophotometrically certain asteroids which have been proposed by Wetherill, Zimmerman, and Williams as potential source-bodies for meteorities. (4) Lastly, a program has been undertaken to coordinate the spectrophotometry program with polarimetric and thermal-infrared observation programs being conducted in the first instance by B. Zellner and associates at the University of Arizona, and in the second by D. Morrison at the University of Hawaii. Considerable progress has been made at synthesizing these diverse data for asteroids common to all three observing programs.

The spectrophotometric observing run in September 1973, designed to measure faint asteroids, was unusually successful and has been described completely in previous Quarterly Reports (see, for instance, the figures in the Third Quarterly Report). Therefore the discussion will not be repeated here. A draft manuscript, by McCord and myself, describing these and other observations has been prepared and will be submitted soon for publication.

One incidental by-product of that observing run was the acquisition of "reconnaissance lightcurve" photometry of a number of asteroids. It has been hoped during the fourth quarter to reduce this data, but work has been impeded by a troublesome tape-format problem. The data are recoverable, and the lightcurves can be processed during future months if funding is forthcoming, but processing could not be completed during the present year. Of course, all the proposed spectrophotometry contracted for (as distinct from lightcurve measurements) have been completely reduced.

Most of the fourth quarter effort has been devoted to analysis of goals (2), (3), and (4), as described above. The results are described in the following sections of this final report. I begin with a brief description of several of the most interesting faint asteroids observed in September 1973.

II. OBSERVATIONS

The instrumentation, observing procedures, and data reduction techniques for the September 1973 observing run are similar to those described in previous papers (McCord and Chapman, 1975; Chapman et al, 1973a), except for the following modifications: The narrowband interference filter set was augmented so as to improve our spectral resolution in the near-infrared. Also we frequently used a gallium-indium-arsenide "B" photomultiplier, sensitive to about 0.95 μm. Usually the S-1 data were taken in the last ten filters in a sequential mode of 45-second integrations per filter. These data were scaled to unity at 0.56 μm by matching to the overlapping S-20 or gallium-arsenide observations.

The two Trojan asteroids 624 Hektor and 911 Agamemnon are the first asteroids we have measured that lie beyond the main asteroid belt. Both objects were very faint, so we were unable to obtain thoroughly adequate infrared data, but the UV and visible data suffice to show that both objects share the same unusual spectral characteristics (see Fig. 1 of Third Quarterly Report). Although these objects are almost neutral in color in the visible, they are relatively dark in the ultraviolet and show striking increases in reflectivity in the red and near infrared. This spectral signature may be potentially identifiable, but for now all that can be said is that no common meteorite minerals show such spectra. It is nevertheless significant that these two objects, trapped together in the same Jovian Lagrangian point perhaps from the earliest solar system epochs, have similar compositions.

Asteroid 446 Aetermitas, a member of Ceres' Hirayama family according to Williams (1974), shows by far the reddest spectrum yet measured for an asteroid. An equally unusual asteroidal spectrum is that of 170 Maria, the namesake of a major Hirayama family. It is rather steeply sloping and reddish, virtually identical to spectral reflectances of many lunar maria soils. These and other faint asteroids measured for purposes of studying Hirayama families and meteorite sources will be discussed in subsequent sections of this report.

III. HIRAYAMA FAMILIES

In a series of papers (the latest being McCord and Chapman, 1975a), McCord and I have presented spectral reflectance curves for 67 asteroids. We report in a paper in preparation further spectrophotometric observations of nine asteroids previously observed and of 31 additional asteroids. The total number of asteroids observed spectrophotometrically is now 98. Reliable approximate colors (R = red, M = medium, F = flat spectrum) can be derived for 147 asteroids using the R/B parameter for the 98 asteroids we have observed and other colorimetry as given in Table IX of Chapman et al, (1973a).

The question of compositional homogeniety of Hirayama family members can now be addressed using our sample of 98 asteroid spectra (included within the 147 asteroids of known color) since J. G. Williams (1975; also see Hartmann et al, 1975) has published his final compilation of proper orbital elements and Hirayama family lists. A total of 63 asteroids with known color (including 36 with measured spectra) represent 43 Hirayama families in the main asteroid belt deemed significant by Williams. To these I will add three Trojan asteroids.

In Table 1 I compare the spectra and colors of pairs or triplets of asteroids representing 16 families. For asteroids with measured spectra, the color sequence F, MF, M, MR, R,VR, VVR, VVVR based on the R/B value and defined by McCord and Chapman (1975) is employed. The column discussing identical spectra is based on actual comparisons of the spectra, however, and not just on these colors. For comparing other asteroid colors I employ the less precise sequence f, m, mr, vr, applying lower-case letters to designate the four color groups defined by Chapman et al (1973a). In cases where colors are very poorly known, "fm" designates f or m and "r" designates mr or vr. It appears from the table that a majority of the Hirayama families are composed of fragments with different surface compositions.

IV. ASTEROIDS AS METEORITE PARENT-BODIES

Although it had usually been assumed since the discovery of the first asteroids at the beginning of the 19th century that meteorites are asteroidal fragments, there has been little understanding of the precise mode of getting meteorites to the earth from the asteroid belt. Collisional processes alone will not suffice since the required acceleration necessary to change an asteroidal orbit into an earth-crossing one would vaporize the rock. During the 1960's, Öpik and Wetherill were among those who examined possible dynamical modes for accomplishing the transfer and found none. Finding a cometary origin for meteorites unpalatable, Anders (1964, 1971) described the plausibility of getting fragments from high-velocity asteroids (those having high eccentricities and inclinations on the inner edge of the main belt). But Anders has yet to demonstrate dynamically that fragments can be derived from high-velocity asteroids.

More recently, two special modes havebeen discovered that show promise for accomplishing the task (see review by Wetherill, 1974). The first mode, proposed by Zimmerman and Wetherill (1973), imagines fragments knocked off asteroids located near the 2:1 Jupiter resonance at 3.27 A.U. Fragments entering the resonance will be perturbed by Jupiter and can be converted to earth-crossing orbits of the appropriate type to account for meteorites. The second mode, proposed by Williams (1973), is analogous to the first, but involves secular

TABLE 1: COMPARISONS OF ASTEROID COLORS IN HIRAYAMA FAMILIES

Family No.	Spectral Reflectance Sample			Colorimetry Only Sample		
	Ast. No.	Color	Identical Spectra?	Ast. No.	Color	Similar Color?
1	24	F(f)		62	m	two similar, one different
				268	f	
2	221	R(mr)		1287	vr	two similar, one different
				1291		
3	462	R(mr)		321	mr	two similar, one different
				658	vr	
4	714	R	no			
	170	VR				
67	1	F	no			
	39	VR				
	446	VVVR				
132	58	MF	yes			
	210	MF				
138	145	MF(f)	prob. no	70	fm	70 may be similar to either 145 or 166
	166	MR(m)				
140	15	R	no			
	85	MF	prob. yes			
	141	MF				
141				77	r	yes
				124	r	
148	402	MR(m)		510	m	yes
158	19	MF?	maybe			
	21	MF				
162				20	mr	yes
				182	r	
163	115	R	yes			
	584	VVR				
171	12	R	no			
	84	M				
189	8	VR(vr)		341	vr	yes
Trojans	624	MR(m)	yes	1437	f	no
	911	MR(m)				

resonances rather than the 2:1 Jupiter commensurability. Secular resonances are zones in a-e-i space; if fragments from asteroids located near these resonances approach the resonance, they will also be accelerated into earth-crossing orbits.

Although the yield of meteorites on earth has been predicted to only order-of-magnitude approximation for the first mode, and not at all for the second, we can expect suitable candidate meteorite parents to be located as close as possible to these resonances or the 2:1 commensurability. Additionally, the yield will presumably be higher for larger objects which have a greater collisional cross-section. On the other hand, until quantitative calculations are made, we cannot be sure of the degree to which the sporadic nature of collisional events may sample these objects non-representatively. In any case, spectral reflectance measurements of candidate asteroids and comparisons with known meteorite types can provide an observational test of the workability of these two modes for deriving meteorites from the asteroid belt.

In Tables 2 and 3 below I give a shopping list of probable sources for meteorites, tabulated with regard to absolute magnitude g and an approximate measure of the proximity to the relevant resonance. Those asteroids shown in italics have already been sampled in our program.

We have sampled a reasonable fraction of possible meteorite sources for g = 7 and brighter only. It can be said that these largest potential source objects are not dominantly responsible for the meteorites that fall on the earth. But do the largest, best-situated objects we have measured contribute any meteorites? The ones in question are 2 Pallas, 6 Hebe, 130 Elektra, and 511 Davida. Pallas and Davida have spectra not precisely represented among meteorites measured so far in the laboratory (e.g. Gaffey, 1974), although the very rare Karoonda meteorite is not too dissimilar and the general spectral characteristics of these asteroids suggest a carbonaceous composition. Possibly these asteroids are so large that their gravitational fields inhibit meteorites from being placed efficiently in the resonances. While 6 Hebe does not match a measured meteorite, it may well be of stony-iron composition so that mesosiderites could be derived from Hebe. 130 Elektra has spectral characteristics similar to C2 meteorites. The other candidate sources that we have sampled probably can be reconciled with known meteorite types, as well. Thus the complete observational evidence so far obtained does not rule out the proposed mechanisms for bringing asteroidal fragments to earth.

Further observations of objects listed in Tables 2 and 3 are very important and will be carried out next year if funding is obtained.

TABLE 2: SECULAR RESONANCE SOURCE

g =	5	6	7	8	9	10
best	$\underline{2}$		$\underline{130}$	154 386	36 426 466 772 1317	304 329 501 581 582 605 631 739 $1\overline{390}$
fair		$\underline{6}$	31	89 $1\overline{94}$ $\overline{849}$	344 683 790 814 895	132 136 186 234 795 863 907 1005
possible			8 $1\overline{3}$ $\underline{\overline{18}}$		43 80 $1\overline{15}$ $\overline{176}$ $\overline{654}$ $1\overline{093}$	183 270 345 439 584 $\overline{694}$ 733

TABLE 3: KIRKWOOD GAP SOURCE

g =	7	8	9
best			$\underline{108}$ 122 175 381 895 1317
fair	$\underline{511}$	154	$\underline{176}$ 184 469 545 758 760
possible	31 92	57 94 106 488 702 849	199 489 490 491 508 595 618 762 814

V. SYNTHESIS OF ASTEROID SPECTROPHOTOMETRY, RADIOMETRY AND POLARIMETRY

Until recently, physical studies of statistically significant samples of asteroids were limited to UBV photometry and lightcurve photometry. However, in the past four years, three new techniques for studying the surface properties of asteroids have been perfected and many dozens of asteroids have been measured. The three techniques are (1) visible and near-infrared narrow-band spectrophotometry, (2) precise polarimetry as a function of phase angle, and (3) infrared radiometry near 10 and 20 μm.

The first technique yields reflection spectra, which often show diagnostic absorption features of certain silicate minerals. The asteroid spectra may be compared with laboratory measurements of various mineral assemblages, such as meteorite classes, and inferences concerning asteroidal surface compositions can be made.

Without knowledge of the diameters of the asteroids, spectrophotometry describes only the wavelength-dependent reflection properties of the surface but not the absolute reflectivity or albedo. Its diagnostic power is enhanced if it may be calibrated absolutely from measurements of diameters (or albedos) of asteroids determined by the polarimetric and radiometric techniques. Certain characteristics of the polarization-vs-phase curve have been found to be empirically correlated with the albedo of a wide variety of laboratory samples; the empirical relationship may be applied to asteroid polarimetry and absolute albedos may be inferred. Once the albedo is known, the asteroid diameter may be calculated from the observed visible magnitude.

The third technique, infrared radiometry, provides an independent measure of asteroid albedos (and hence diameters). Unlike polarimetric albedos, which are inferred from an empirical relationship which has a poorly understood physical basis, radiometric albedos are deduced from the physics of the thermal balance of the asteroid with the solar radiation. There are, however, some modelling assumptions involved, and the calibration of the infrared observations is less secure than photometry or polarimetry in the visible. The redundancy of the polarimetric and radiometric studies, therefore, permits us to evaluate the reliability of the two techniques and the resulting diameters and albedos of asteroids.

Spectral Albedos

There are 47 asteroids for which albedos have been determined by either the polarimetric or the radiometric method, or by both methods (Zellner et al, 1974; Morrison, 1974). Chapman and McCord have obtained spectral reflectivities for 36 of these asteroids. Geometric albedos for the 36 asteroid have been plotted as a function of wavelength, from 0.32 to about 1.1 μm. The spectral reflectivities were scaled to albedos based on the comparisons of the radiometric and polarimetric techniques given by Chapman, Morrison, and Zellner (1975): (a) The absolute scaling of the polarimetry was given greatest weight; hence the radiometric albedos were all revised upward by 10% of their values. (b) For albedos in excess of 6%, radiometric and polarimetric results were given equal weight, except half weight for instances where the authors indicate uncertainties in their data or for radiometric values of asteroids having unusually large lightcurve amplitudes. (c) Zero weight was given to polarimetric albedos below 6%.

It should be emphasized that for the purposes of mineralogical identification, albedos provide only a rough guide and high precision is unnecessary. It is well-known (e.g. Adams and Filice, 1967) that particle size differences produce substantial variations in albedos, but only relatively small changes in color. In addition Gaffey (1974) has found that there is a spread in albedos of similar sized powders of different meteorites of the same mineralogical classification of about a factor of two.

Previous work on mineralogical interpretations of asteroid spectral reflectivities (McCord et al 1970; Chapman, 1971; Chapman and Salisbury, 1973; Egan et al, 1973; Fanale and Johnson, 1973; Gaffey, 1974; and McCord and Gaffey, 1974) have relied almost entirely on the color characteristics of the asteroids as compared with laboratory samples of meteorites or other mineral assemblages. Indeed, the most important mineralogical information resides in the normalized spectral characteristics and these are much more constant for mineralogically similar meteorite classes or for samples having different particle sizes than are absolute albedos. Gaffey has found relatively small ranges of normalized spectral properties for meteorites of the same class, and Salisbury and Hunt (1974) suggest that at least part of the remaining differences are due to terrestrial weathering effects of meteorite samples.

Nevertheless, the mineralogical identifications made on the basis of asteroidal spectral characteristics now can be checked against the approximate ranges of albedos. Since the new data show that asteroid albedos span a factor of ten and typical albedo variations in samples of similar mineralogy are only a factor of 2, there is room for useful comparisons.

The groupings of asteroids shown in such spectral albedo plots to some degree follow the groupings established by McCord and Chapman (1975) on the basis of spectral characteristics alone. Seven asteroids with reddish colors and weak infrared absorption features centered near 0.95 μm, deemed by McCord and Chapman to be spectrally similar, are evidently all moderately reflective asteroids and show a spread in albedo of just about a factor of 2. Ten reddish asteroids, also having 0.95 μm absorption features, all show different detailed spectral characteristics (except for 5 and 89) in comparisons of their normalized spectra. They also are reasonably reflective objects and show a spread of a factor of 2 in albedo.

Seven reddish asteroids lack a prominent 0.95 μm absorption band, although several of them have absorption bands centered beyond 1.0 μm. They are all reasonably bright asteroids, with albedos similar to those of the middle and brighter members of the previous groups.

Twelve asteroids show reasonably neutral or only slightly reddish colors. With the exception of 4 Vesta, which is the brightest asteroid of all, these objects show low to very low albedos. Two pairs of asteroids deemed spectrally similar by McCord and Chapman (511 and 554; also and 324) are similar in albedo, giving added confidence to the spectral groupings. All other asteroids in the spectral albedo plots seem spectrally dissimilar, although 16 Psyche and 21 Lutetia which have nearly identical albedos are only slightly different from each other in spectral properties.

The apparent correlation between reddish color and high albedo is not a general characteristic of minerals, nor even of the more limited assemblages of minerals found in meteorites, as can be seen from the spectral albedos for different meteorite classes measured by Gaffey (1974). Not only are the dark angrites very highly colored, but the moderately bright subrites are neutral in color. The correlation would be expected, however, if the dominant differences between the asteroids were due to reasonably bright reddish minerals (such as olivines and pyroxenes) being mixed with different quantities of a neutral opaque, such as carbon. Indeed, this is precisely the cause for the predominent differences in color and albedo characteristics for the different chondrites. The curves for the L3 and black chondrites show that low metamorphic grade and high degree of shock both are correlated with low albedo, as well; but absorption bands are not completely erased as is the case of the quenching of olivine and pyroxene absorptions by the carbon in the carbonaceous chondrites. Most previous discussions of the probable compositions of the neutral-colored asteroids have suggested carbonaceous chondrites as a likely comparison. The albedos of asteroids 1, 2, 10, and 511 are all in accord with the albedos of C2 and C3 carbonaceous chondrites. Of the four known petrologic grades of carbonaceous chondrites that have been measured by Johnson and Fanale (1973), Hunt and Salisbury (1974) (see also Chapman, and Salisbury, 1973), and Gaffey (1974), C2's tend to have the lowest albedos, followed by C1, C3, and C4. The C2 curves also show a relative absorption feature near 0.65 μm which, although present weakly in many asteroid spectra, is particularly prominent in the dark asteroids of intermediate color -- 19, 51, and 324 -- which include the two darkest asteroids yet measured. Johnson and Fanale ascribe the spectral characteristics of Ceres and Pallas to those of C1 chondrites, yet the relatively high reflectivity of these asteroids in the violet has been difficult to match with any actual meteorites (Gaffey, 1974). There is a better match to a C1 or ultraprimitive construct made by Johnson and Fanale, and the albedo of their construct (8 1/2% agrees with the measured albedos for Ceres and Pallas. The aubrites are probably too bright to match Ceres and Pallas, although the spectral characteristics match. 511 Davida matches the only measurement of a C4 meteorite (Karoonda) in both color (Chapman and Salisbury, 1973) and albedo.

Asteroids 16 and 21 have the spectral properties of nickel-iron meteorites but are more than a factor of 2 lower in albedo than most laboratory measurements of irons. The great difficulties in producing suitable laboratory samples, and uncertainties concerning the possible surface structure of an iron asteroid exposed to space bombardment, preclude my ruling out irons as possible matches for these meteorites. However, the more metal-rich enstatite chondrites (such as Abee), agree very nicely in albedo and color with these two asteroids and support the suggestion by Chapman and Salisbury (1973) of a match.

The albedo of Vesta agrees very nicely with the eucritic composition first proposed on the basis of spectral properties alone by McCord et al (1970). Similarly high albedos are found for several other achondrites and for the ordinary chondrites of high petrologic class (type 6), all of which differ spectrally from Vesta. Although the brightest reddest asteroids approach these high albedos, none of them show the prominent absorption bands typical of these meteorites.

Chapman et al (1973b) have proposed that 1685 Toro is similar to L type chondritic meteorites, particularly those of type L5. Although its absorption band is shallower than those of most L5's, and its albedo somewhat lower, Toro is well within the normal range of variability for L5's. 8 Flora seems intermediate in spectral characteristics between Toro and asteroids 5 and 89, both of which have narrow absorption bands indicating the lack of appreciable olivine (McCord and Chapman, 1975). The albedos of these asteroids, and indeed of all reddish asteroids, are in the range of albedos of most ordinary chondrites -- especially the lower petrologic types -- but are spectrally dissimilar from chondrites. McCord and Gaffey (1974) have proposed that a mixture of chondrite-like minerals with larger quantities of free iron than normally occur in ordinary chondrites may account for the spectral properties of many of the reddish asteroids with 0.95 μm absorption features. The one measurement of a mesosiderite, which is just such a mixture of iron and silicates and has many of the appropriate spectral properties, yields an albedo in the middle of the range of albedos for these reddish asteroids. This fact supports the suggestion of McCord and Gaffey, and suggests a large amount of free iron in the asteroid belt.

For some of the asteroids which lack the 0.95 μm pyroxene absorption feature, enstatite chondrites provide a plausible match and possibly a metal-olivine mixture would match the remaining ones.

In summary, the albedos measured for three dozen asteroids support the proposition that the asteroids are composed of common meteoritic minerals and, therefore, that meteorites may be derived from the asteroid belt. Particularly good matches between spectral albedos of asteroids and meteorites occur for a variety of carbonaceous chondrites and enstatite chondrites, although these meteorites lack truly diagnostic absorption bands. A eucritic composition for Vesta and an L5 composition for Toro, which have been previously suggested, are also compatible with measured albedos. The most common asteroid spectral albedo curves are spectrally incompatible with ordinary chondrites and most other known meteorite types, but may be compatible with metal-rich assemblages of silicaceous minerals such as mesosiderites.

Other Synthesis Studies

I have dwelled in this section on describing the spectral albedo curves obtained by synthesizing the polarimetric, radiometric, and spectrophotometric data. Another major phase of the synthesis studies involves studying correlations between the various photometric parameters obtained by the three techniques, and correlations between them and orbital parameters. I will not describe these analyses in detail in this final report but will outline some of the highlights.

Asteroid spectra (and in particular the average red/blue color) correlates strongly with P_{min} (the minimum polarization as a function of phase angle) and with geometric albedo as determined by the polarimetry and the radiometry. The correlation is in the sense that the darkest surfaces (or those containing most opaques as indicated by large p_{min}'s) are the least red in color.

Diameters have now been measured for many dozens of asteroids by combining the albedos measured by the polarimetric and radiometric techniques with visible photometry. Additionally, we can infer roughly the diameters of most asteroids with known colors by assuming low albedos for neutral-colored asteroids. On this basis, I have calculated for the first time a reliable diameter-frequency relationship for the asteroid belt using actual diameters (as opposed to the traditional plots calculated using identical assumed albedos for all asteroids).

Fig. 1 shows the diameter frequency relation for the asteroid belt. On the left is the relation spanning the entire size range from Ceres down to tiny meteoroids. The meteoroid data have been obtained from a preprint of the Sisyphus experimenters on Pioneer 10 (Soberman, et al). The extrapolation up to small asteroids follows the form of the frequency relation in near-earth space as determined previously (e.g. by Whipple, 1967).

Shown in an expanded section to the right in Fig. 1 is the asteroid size distribution. The Palomar-Leiden and McDonald Survey results have been plotted, along with the juncture between the two surveys as determined by Dohnanyi (1972), using an assumed geometric albedo of 0.07. This is a

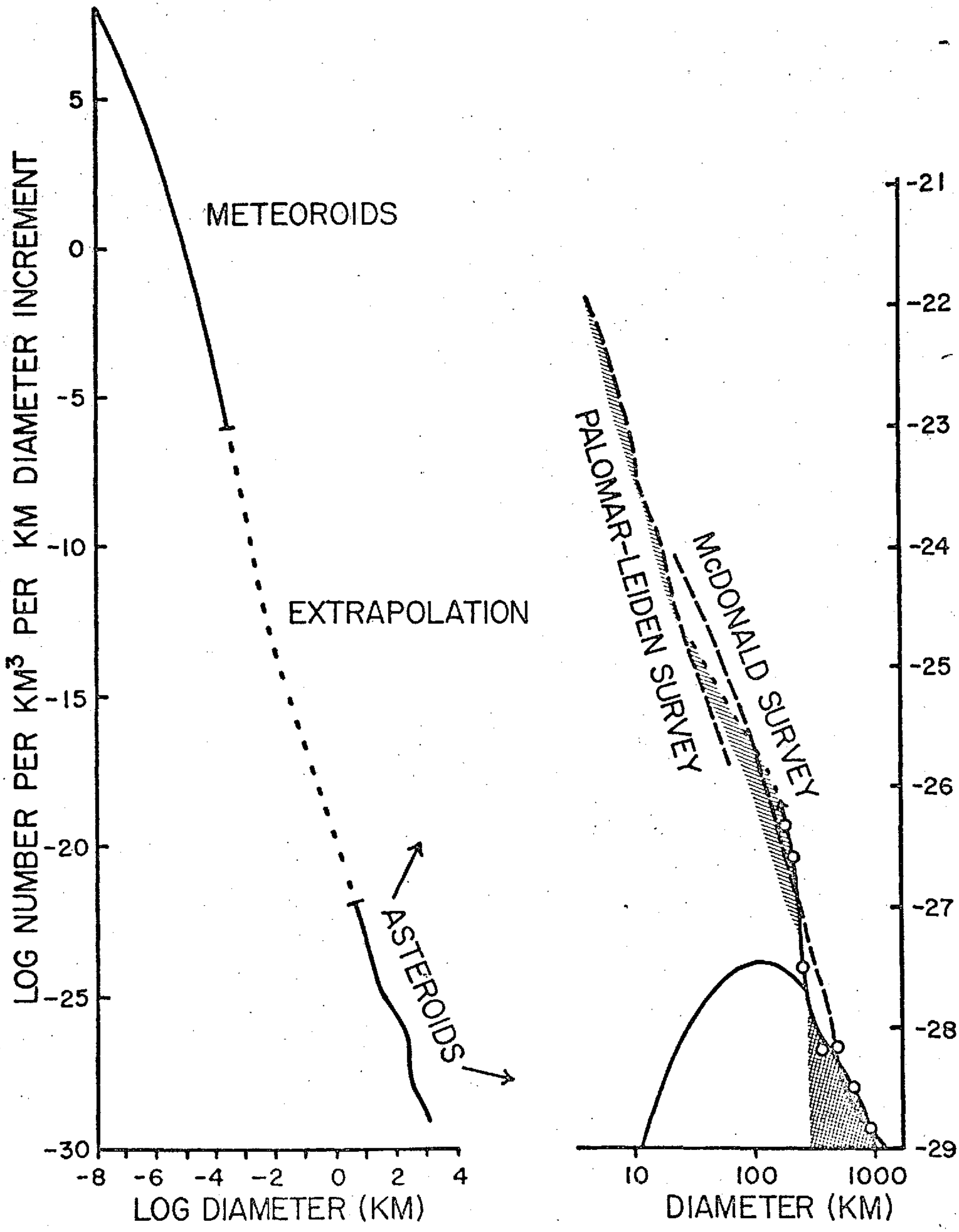
LOG NUMBER PER KM^3 PER KM DIAMETER INCREMENT
5
0
-5
-10
-15
-20
-25
-30
METEOROIDS
EXTRAPOLATION
ASTEROIDS
-8
-6
-4
-2
0
2
4
LOG DIAMETER (KM)
PALOMAR-LEIDEN SURVEY
McDONALD SURVEY
-21
-22
-23
-24
-25
-26
-27
-28
-29
10
100
1000
DIAMETER (KM)

FIGURE 1

lower albedo than has usually been applied in the past but is most reasonable based on the polarimetric and radiometric albedos so far measured.

The circles, joined by a solid line, indicate the size-frequency relation actually calculated from known diameters. It may be seen that, relative to the constant albedo assumption, the diameter-distribution shows an enhanced "bump" or excess of objects near 150 km diameter. I have argued elsewhere (Chapman, 1975; Final Report for NASA Contract NASW 2521) that this bump represents not-easily-fragmented metallic (or stony-metal) cores of highly fragmented originally-differentiated large asteroids (represented by the cross-hatched area in an Anders-type original Gaussian population).

Histograms of albedos, colors, minimum polarizations, etc. all confirm the interpretation that the asteroid belt is composed of two fundamentally different compositions: carbonaceous materials and rocky-metal-silicate materials. Observational selection biases against the low-albedo material; thus the fact that the two groups are about equally represented in our observations so far suggests that the carbonaceous materials in fact dominate in the asteroid belt. Though the asteroid belt is dominantly of carbonaceous composition, reddish stony-metal cores may predominate around 150 km diameter.

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