PART IV

PHYSICAL NATURE OF ASTEROIDS

1

SIZES AND ALBEDOS OF THE LARGER ASTEROIDS

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The purpose of the present paper is to review all asteroid diameter measurements, current through mid-1976, and to combine them in a consistent way to give the best available estimates for a sample totalling 187 objects. From these diameters it is possible to determine the size-distributions of minor planets down to diameters of 50 km in the inner belt and 100 km in the outer belt. The associated albedos further indicate the distribution of objects of the C, S, and M classes throughout the belt.

A basic datum for the physical study of a minor planet is diameter. In combination with the mass, the diameter yields the density, which is diagnostic of bulk composition. In combination with the photometric brightness, the diameter yields the geometric albedo, which, together with spectrophotometric color, places constraints on surface composition. This paper is an extended summary of the complete work, which is being published in *Icarus* (Morrison 1977b).

Before 1970, diameter estimates, largely based on visual micrometer measurements, were available for only five asteroids: Ceres, Pallas, Juno, Vesta, and Eros (cf. Dollfus 1971). Since the apparent disks were, in all cases, near the limit of resolution, the uncertainties in these measurements were substantial; in the case of Pallas, for instance, different observers obtained diameters that disagreed by a factor of two. When Hertz (1968) measured the first asteroid mass (for Vesta), the standard diameter of 390 km (Barnard 1902) yielded the remarkably high density of ~8 g cm^{-3}, suggesting a metallic composition and possible relationship with the iron-nickel meteorites. However, it was virtually impossible to judge the uncertainty in this density.

In about 1970 two new techniques were introduced for the measurement of asteroid sizes and albedos. The first is based on an empirical relation, initially recognized by Widorn (1967) and KenKnight *et al.* (1967), between the linear polarization of reflected light, observed as a function of phase angle, and the reflectance of a dusty or rough surface. The first derivation of an asteroid albedo by this method was published by Veverka (1971). Once the geometric albedo is found, of course, the diameter can be computed from the photometric brightness. The second new method yields diameter more directly. First developed by Allen (1970) and Matson (1972), it involves the measurement of thermally emitted radiation from an asteroid. Some fraction of the incident sunlight is reflected, and the complementary fraction is absorbed and reradiated in the infrared. If it is assumed that the surface of an asteroid is in equilibrium with the sunlight, or alternatively if a detailed thermal model for the surface is developed, it is possible to derive both albedo and diameter from combined infrared and visual photometry.

The primary sources of radiometric diameters and albedos are Cruikshank and Morrison (1973), Morrison (1974, 1976a, 1977a), Morrison and Chapman (1976), Hansen (1976), Morrison, Gradie, and Rieke (1976), and Cruikshank (1976). All of these observations have been combined and interpreted uniformly on the model of Morrison (1973) and Jones and Morrison (1974), as described in Morrison (1977b). The polarimetric data come primarily from Zellner, Gehrels, and Gradie (1974) and Zellner and Gradie (1976), and include both measurements of polarimetric albedo for 53 and estimates of albedo for 17 other objects not included in the other data sets from their minimum linear polarization (P_{min}). The polarimetric albedos have been transformed to the radiometric scale; for $p_V > 0.05$, the transformation involves a simple 20% decrease, but for darker objects the polarimetric values appear to saturate and a more complicated transformation is required (cf. Morrison 1977b). The final, synthesized and averaged list of 187 measured diameters and albedos is presented in Table I, together with the values of V(1,0) derived from the new listing by Gehrels (1977) and of semi-major axis for each object. The final column gives a quality code (1 = marginal, 2 = secure; 3 = excellent) for the diameter and albedo.

The frequency distribution of measured asteroid albedos is illustrated in Figure 1. The bimodality in albedo has been recognized for several years, but less complete compilations tended to favor bright, high-albedo objects and therefore did not show so clearly the size and shape of the low-albedo peak. Additionally, the higher accuracy in many albedos in Table I, resulting from averaging observations from several sources and the use of the new absolute magnitudes, yields narrower and better defined peaks in the albedo distribution.

The major peak centered at a geometric albedo of about 0.035 represents the dominant C-class asteroids. The probable uncertainty in an individual albedo is about ±20%; thus much of the width of the low-albedo peak may be due to observational dispersion, and in particular there is no compelling evidence for albedos substantially lower than 0.025. 65 Cybele (0.022) and 596 Scheila (0.019) are the only objects with quality code 2 that have lower albedos, and quite plausible errors in either V(1,0) or the radiometric observations could shift these to higher albedos. On the other hand, a real dispersion is indicated between numerous high-quality determinations (*e.g.*, 19 Fortuna, 52 Europa, 324 Bamberga) of albedos near 0.030 and the well established albedos of about 0.050 for such asteroids as 1 Ceres. The probable spread in albedos among the C asteroids is thus at least a factor of two, and perhaps as high as a factor of three. The median value is about 0.035.

There is a real dearth of objects with albedos of 0.06-0.07. The S class of asteroids dominates the distribution toward higher albedo, with a peak at $p_V \simeq 0.15$. Also included in this region of Figure 1 are the M objects, with albedos between 0.08 and 0.15 (Morrison 1977a). At albedos above 0.20, however, several additional groups appear (cf. Chapman *et al*. 1975; Bowell *et al*. 1977). At $p_V = 0.25$ lie 4 Vesta and 349 Dembowska, the only known basaltic asteroid and the type member of the O (for ordinary chondrite) class of objects, respectively (cf. Morrison 1977a; Bowell *et al*. 1977). The highest albedos are those of the three members of class E - 44 Nysa, 64 Angelina, and 434 Hungaria - suggested by Zellner (1975) and Zellner *et al*. (1977) to be similar in composition to the enstatite achondrite meteorites.

The presence of several classes of high-albedo asteroids with spectral and color properties that are distinct from those in the S class is well established (Bowell *et al*. 1977), although very few members of these classes have been identified to date. Because of selection effects that favor the observations of bright asteroids, equally rare classes with very low albedo would probably not be recognized from existing data.

The list of asteroids with measured diameters and albedos is essentially

TABLE I

NAME	A	V	D	PV	WT
1 CERES	2.77	3.76	1003	.054	3
2 PALLAS	2.77	4.53	608	.074	3
3 JUNO	2.67	5.69	247	.151	3
4 VESTA	2.36	3.55	538	.229	3
5 ASTRAEA	2.58	7.40	117	.140	3
6 HEBE	2.43	6.06	201	.164	3
7 IRIS	2.39	6.03	209	.154	3
8 FLORA	2.01	6.83	151	.144	3
9 METIS	2.39	6.88	151	.139	3
10 HYGIEA	3.15	5.80	450	.041	3*
11 PARTHENOPE	2.45	6.97	150	.126	3
12 VICTORIA	2.34	7.48	126	.114	2
13 EGERIA	2.58	7.40	224	.041	3*
14 IRENE	2.59	6.60	158	.162	3
15 EUNOMIA	2.64	5.48	272	.155	2
16 PSYCHE	2.93	6.19	250	.093	3
17 THETIS	2.47	8.23	109	.103	2
18 MELPOMENE	2.30	6.83	150	.144	3
19 FORTUNA	2.44	7.71	215	.032	3
20 MASSALIA	2.41	6.97	131	.164	3
21 LUTETIA	2.43	7.90	115	.093	3
22 KALLIOPE	2.91	6.56	177	.130	2
23 THALIA	2.62	7.34	111	.164	3
24 THEMIS	3.14	7.57	234	.03	1
27 EUTERPE	2.35	7.55	108	.147	3
28 BELLONA	2.78	7.30	126	.132	1
29 AMPHITRITE	2.55	6.29	195	.140	3
30 URANIA	2.37	7.94	91	.144	3
31 EUPHROSYNE	3.16	6.57	370	.03	1
32 POMONA	2.59	7.90	93	.14	1
34 CIRCE	2.69	8.90	111	.039	1
36 ATALANTE	2.75	9.28	118	.024	1
37 FIDES	2.64	7.55	95	.186	2
39 LAETITIA	2.77	6.53	163	.169	3
40 HARMONIA	2.27	7.68	100	.123	3*
41 DAPHNE	2.76	7.18	204	.056	2
42 ISIS	2.44	7.94	97	.125	3
43 ARIADNE	2.20	8.33	85	.113	1
44 NYSA	2.42	7.15	82	.377	2*
45 EUGENIA	2.72	7.63	226	.030	2*
46 HESTIA	2.52	8.86	133	.028	2
47 ALAJA	2.88	6.54	158	.027	1
51 NEMAUSA	2.37	7.98	151	.050	2
52 EUROPA	3.10	6.94	289	.035	2
54 ALEXANDRA	2.71	8.15	180	.030	2
56 MELETE	2.60	8.78	146	.026	3
57 MNEMOSYNE	3.16	7.55	109	.14	1
58 CONCORDIA	2.70	9.21	110	.03	1
60 ECHO	2.39	9.11	51	.154	2
63 AUSONIA	2.39	8.05	91	.128	3
64 ANGELINA	2.68	8.07	56	.342	2
65 CYBELE	3.42	7.29	309	.022	2
66 MAJA	2.65	9.79	85	.029	1
67 ASIA	2.42	8.79	58	.157	1
68 LETO	2.78	7.36	126	.126	2
70 PANOPAEA	2.61	8.23	151	.039	2
71 NIOBE	2.76	7.44	115	.14	1
72 FERONIA	2.27	9.45	96	.032	1
77 FRIGGA	2.67	8.66	67	.113	1
79 EURYNOME	2.44	9.37	76	.137	2
80 SAPPHO	2.30	8.38	83	.113	2
82 ALKMENE	2.76	8.68	65	.138	2
83 BEATRIX	2.43	8.96	123	.03	1
84 KLIO	2.36	9.44	90	.037	2
85 IO	2.65	8.21	147	.042	2
88 THISBE	2.77	7.36	210	.045	2
89 JULIA	2.55	7.36	155	.086	2*
91 AEGINA	2.59	9.28	104	.031	2
93 MINERVA	2.75	8.00	168	.039	2
94 AURORA	3.15	8.06	188	.029	2
95 ARETHUSA	3.07	8.08	230	.019	1
97 KLOTHO	2.67	8.02	95	.121	2
103 HERA	2.70	7.98	96	.122	1
105 ARETEMIS	2.37	8.71	126	.036	1
106 DIONE	3.16	8.09	139	.053	1
107 CAMILLA	3.49	7.57	211	.037	1
109 FELICITAS	2.70	9.43	75	.053	2
113 AMALTHEA	2.38	8.95	47	.208	2
114 KASSANDRA	2.68	8.75	136	.03	1
115 THYRA	2.38	7.99	93	.129	2
116 SIRONA	2.77	8.05	80	.166	2
120 LACHESIS	3.12	8.07	173	.034	2
123 BRUNHILD	2.69	9.28	47	.152	1
124 ALKESTE	2.63	8.55	67	.147	2*
129 ANTIGONE	2.87	7.13	115	.187	2
130 ELEKTRA	3.12	7.68	173	.050	1
131 VALA	2.43	10.20	35	.120	2
135 HERTHA	2.43	8.55	78	.108	2
137 MELIBOEA	3.12	8.41	150	.033	1
139 JUEWA	2.78	8.47	163	.040	2*
140 SIWA	2.73	8.87	103	.047	2
141 LUMEN	2.67	8.87	133	.028	2
144 VIBILIA	2.65	8.44	130	.043	2
145 ADEONA	2.67	7.96	195	.03	1
146 LUCINA	2.72	8.53	141	.034	1
159 AEMILIA	3.11	8.50	140	.035	2
172 BAUCIS	2.38	9.27	67	.082	2
182 ELSA	2.42	9.36	39	.212	1
186 CELUTA	2.36	9.61	49	.104	2
189 PHTHIA	2.45	9.93	41	.109	2
192 NAUSIKAA	2.40	7.71	94	.165	3
194 PROKNE	2.62	8.13	191	.027	2
196 PHILOMELA	3.11	6.88	161	.120	2
204 KALLISTO	2.67	9.23	50	.140	1
208 LACRIMOSA	2.89	9.64	42	.136	2
211 ISOLDA	3.04	8.30	166	.030	2
219 THUSNELDA	2.35	9.89	39	.126	1
224 OCEANA	2.64	9.04	71	.083	1
230 ATHAMANTIS	2.38	7.78	121	.100	3
238 HYPATIA	2.91	8.52	154	.029	2
241 GERMANIA	3.05	7.92	200	.030	1
247 EUKRATE	2.74	8.60	142	.031	3
264 LIBUSSA	2.80	8.83	63	.127	2
270 ANAHITA	2.20	9.16	51	.147	2
306 UNITAS	2.36	9.58	43	.14	1
308 POLYXO	2.75	8.47	138	.038	2
313 CHALDAEA	2.38	9.23	160	.014	1
324 BAMBERGA	2.69	7.38	246	.032	3
326 TAMARA	2.32	9.62	80	.038	1
345 TERCIDINA	2.33	9.44	99	.03	1
349 DEMBOWSKA	2.92	6.28	144	.260	2
354 ELEONORA	2.80	6.75	153	.148	2*
356 LIGURIA	2.76	8.54	150	.030	2
362 CARLOVA	3.00	8.72	130	.034	2
364 ISARA	2.22	10.16	28	.198	1
365 CORDUBA	2.80	9.62	99	.025	2
367 AMICITIA	2.22	11.26	20	.14	1
381 MYRRHA	3.20	6.97	126	.028	2
386 SIEGENA	2.90	7.70	191	.040	2
387 AQUITANIA	2.74	7.61	112	.127	2
389 INDUSTRIA	2.61	8.21	81	.14	1
393 LAMPETIA	2.78	8.44	129	.044	2
397 VIENNA	2.64	9.72	50	.089	2
404 ARSINOE	2.59	9.52	102	.026	1
410 CHLORIS	2.73	8.72	134	.031	2
415 PALATIA	2.79	9.82	93	.024	1
416 VATICANA	2.79	8.34	76	.14	1
433 EROS	1.46	10.76	23	.174	3
434 HUNGARIA	1.94	11.76	11	.300	2
441 BATHILDE	2.81	8.61	66	.146	2
444 GYPTIS	2.77	8.44	165	.027	1
451 PATIENTIA	3.06	7.37	276	.026	2
455 BRUCHSALIA	2.66	9.35	105	.029	1
471 PAPAGENA	2.89	7.02	143	.133	2
476 HEDWIG	2.65	9.07	113	.032	1
497 IVA	2.85	10.00	31	.184	1
498 TOKIO	2.65	9.63	71	.049	2
511 DAVIDA	3.19	6.63	323	.037	3
516 AMHERTIA	2.68	8.63	63	.152	2
532 HERCULINA	2.77	7.20	150	.100	2*
537 PAULY	3.07	9.12	136	.021	1
550 SENTA	2.59	9.68	53	.084	1
554 PERAGA	2.38	9.12	101	.039	1
558 CARMEN	2.91	9.30	64	.082	2
563 SULEIKA	2.71	9.11	51	.156	2
584 SEMIRAMIS	2.37	8.91	55	.159	3
596 SCHEILA	2.93	9.27	134	.019	2
602 MARIANNA	3.09	8.76	137	.029	2
617 PATROCLUS	5.21	8.34	147	.037	1
624 HEKTOR	5.12	7.89	179	.038	1
654 ZELINDA	2.30	8.80	128	.032	1
660 CRESCENTIA	2.54	9.71	51	.086	1
674 RACHELE	2.92	7.70	102	.14	1
679 PAX	2.59	8.37	73	.146	2
694 EKARD	2.67	9.47	101	.028	1
704 INTERAMNIA	3.06	6.60	350	.033	3*
737 AREQUIPA	2.59	9.08	46	.200	1
747 WINCHESTER	2.99	8.11	205	.024	2
782 MONTEFIORE	2.18	11.84	15	.141	1
785 ZWETANA	2.58	9.93	49	.078	2
790 PRETORIA	3.40	8.38	176	.025	2
804 HISPANIA	2.84	8.14	141	.048	1
830 PETROPOLITANA	3.20	9.60	51	.099	1
863 BENKOELA	3.20	9.51	33	.245	1
887 ALINDA	2.52	14.50	4	.166	2*
1011 LAODAMIA	2.39	13.34	7	.156	2
1052 BELGICA	2.24	12.37	12	.14	1
1058 GRUBBA	2.20	12.17	13	.14	1
1172 AENEAS	5.17	8.42	130	.044	1
1173 ANCHISES	5.17	9.47	92	.034	1
1178 IRMELA	2.68	12.28	20	.053	1
1566 ICARUS	1.08	16.82	1	.166	1
1567 1941HN	3.22	10.04	72	.033	2
1620 GEOGRAPHOS	1.24	15.10	3	.181	1
1685 TORO	1.37	15.32	3	.124	1
1976AA	0.98	17.56	1	.166	1

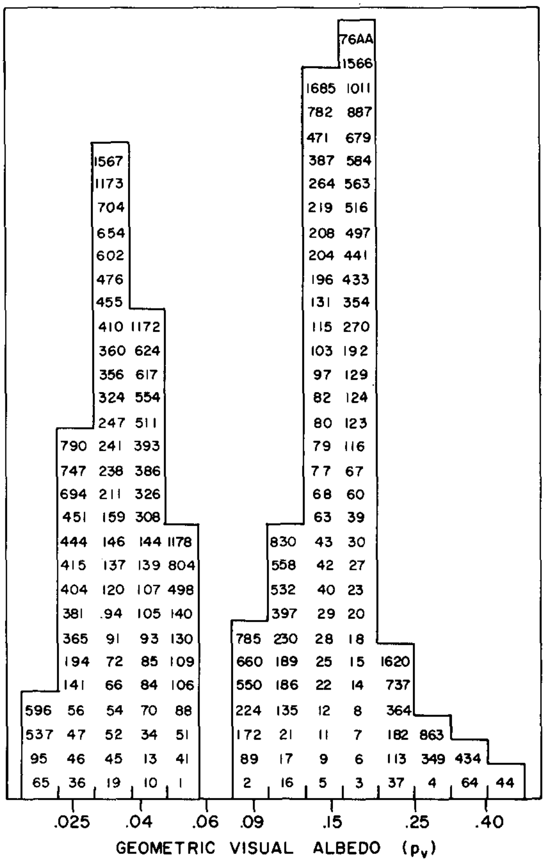

Figure 1. Frequency distribution of measured asteroid albedos.

TABLE II

ALL ASTEROIDS WITH D > 250 KM

NAME	DIAMETER	CLASS	NAME	DIAMETER	CLASS
1 Ceres	1003	C	65 Cybele	309	C
2 Pallas	608	U	52 Europa	289	C
4 Vesta	538	U	451 Patientia	276	C
10 Hygiea	450	C	15 Eunomia	272	S
31 Euphrosyne	370:	C	16 Psyche	250	M
704 Interamnia	350	C pec.	48 Doris	250:	C
511 Davida	323	C	92 Undina	250?	C?

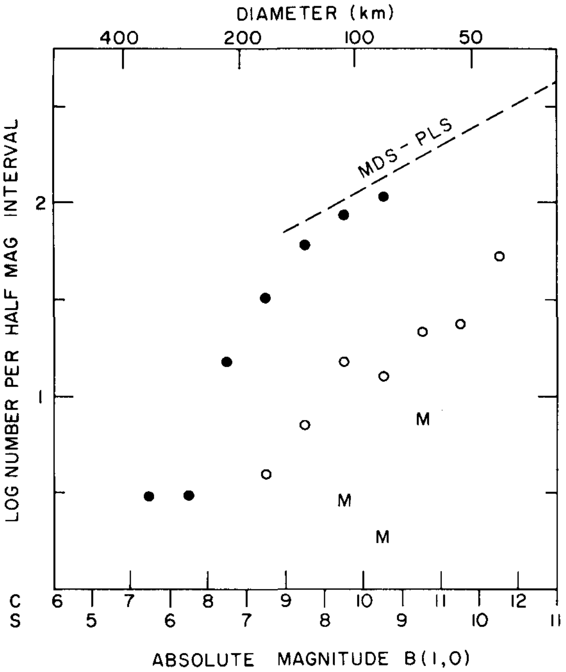

Figure 2. Size-frequency distribution of C and S asteroids.

complete down to a diameter limit of 250 km. Table II lists the 14 largest asteroids in order of size. At smaller sizes, however, corrections must be made for selection effects in the observations that tend to favor objects with high albedo and small semimajor axes. These corrections, which involve a normalization based on the MDS and PLS asteroid surveys (van Houten *et al.* 1970; van Houten 1971), are described in detail in Morrison (1977b). The remainder of this paper discusses the conclusions that can be reached from the corrected sample.

The size-frequency distribution of C and S asteroids for the whole asteroid belt (2.0 - 3.5 AU) is illustrated in Figure 2. This analysis extends to a diameter of 80 km for both populations, and to 40 km for the S objects alone. There are only four S asteroids with diameters above 200 km, an insufficient number for statistical analysis. However, from 170 to 80 km, the total ratio C:S in the belt remains remarkably constant at (7 ± 2):1. In terms of the analysis by Chapman *et al.* (1975), the ratio C / (C+S) is 0.88 ± 0.04, to be compared with a ratio of about 0.7 derived by Chapman *et al.* for a much smaller sample. Thus the present analysis confirms that C objects are much more common than S in the size range from 100 km up, but increases the imbalance in favor of the C objects by about a factor of two. The M population, indicated by the symbol M in Figure 2, is much smaller, amounting to only about 5% of the asteroid population at diameters of 80 km or larger.

Figure 3 illustrates the distribution of C and S asteroids with semimajor axis, down to a cutoff diameter of 100 km. Again, the large preponderance of dark C objects is evident. The fraction of C's increases with increasing *a*, until there are almost no S's beyond 3.0 AU. The total number of asteroids also increases outward; for D > 100 km, half of all the asteroids are at *a* > 3.0 AU.

These were overlooked in the past because of their large distances and low albedos, but they are in fact the main component of the asteroid population.

It is possible to calculate the mass of all asteroids with $D > 80$ km, and to estimate the mass down to $D = 20$ km. If the mean density is 3.0 g cm^{-3}, the mass for $600 < D < 20$ is 3.1×10^{24} g. The measured mass of Ceres, for comparison, is 1.2×10^{24} g (Schubart 1974).

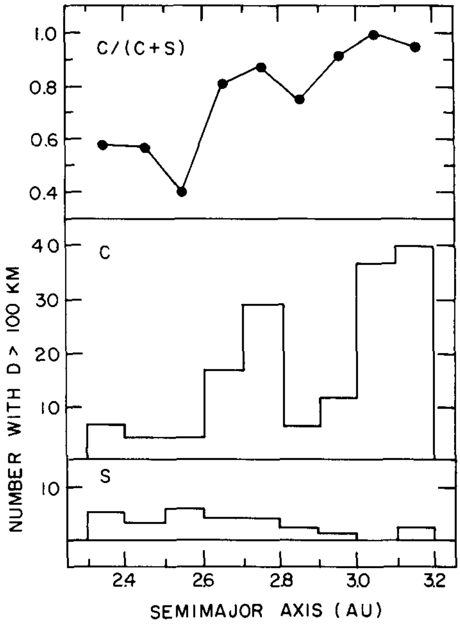

Figure 3. (Top) Fraction of C asteroids with semi-major axis.
(Middle) Distribution of C asteroids with semi-major axis.
(Bottom) Distribution of S asteroids with semi-major axis.

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DISCUSSION

BRECHER: From the various papers we heard this morning, it appears that spectroscopic data indicate only two major classes of asteroids: C and S. On the other hand, Gaffey's and McCord's data show a continuum of surface compositions for asteroids, similar to the meteorite continuum. Are the discrete populations an artifact of an arbitrary cutoff, or do they tell us something about the type (composition) of condensate, as a function of heliocentric distance?

*MORRISON: I have discussed only two taxonomic groups: C and S - because they constitute at least 90% of all asteroids with diameters larger than 50 km. However the present suite of photometric, spectrophotometric, polarimetric, and radiometric data clearly define not only these two classes, but in addition four or five others with smaller populations (see paper by Zellner and Bowell in this volume). In terms of the observed parameters, (*e.g.*, B-V, U-B,* P_{min}*, albedo, etc.) these classes are indeed distinct. Between two classes there are real gaps in (usually) several of these parameters; it is on the basis of these observed discrete groupings that the classes were defined. This is not to say all members of any class are homogeneous, for they certainly are not. McCord and Gaffey (in this volume) have discussed the substantial variety of mineralogical and petrological types that can be identified within the C or S groups. But the observed separation between C and S is real, and they do not simply represent end members of a continuum of surface properties.*

HANSEN: Some readers may be aware of a 20% discrepancy between Morrison's radiometric size scale and that used by Hansen (1976). I have now resolved that discrepancy in favor of Morrison's values by introducing a rough sphere model for interpreting the radiometric data. The details of this model, which differs from the model used by Morrison, can be found in a forthcoming issue of Icarus.

MORRISON: I am pleased that Dr. Hansen's new calibration of radiometrically-

derived diameters and albedos is in such good agreement with my own. However, I think it is worth repeating that there is a basic uncertainty in all of these measurements amounting to about 20% in albedo or 10% in diameter, and that the fact that our two models now are in agreement should not blind us to this fundamental uncertainty or to the differences that still exist between albedos measured from radiometry and those obtained from polarimetry.