

RADIOMETRIC DIAMETERS OF 84 ASTEROIDS FROM OBSERVATIONS IN 1974-1976

DAVID MORRISON*†

Institute for Astronomy, University of Hawaii, Honolulu

Received 1976 June 17

ABSTRACT

Diameters and geometric albedos are derived from 10 and 20 μm infrared photometry for 84 asteroids, 68 of them not previously observed in this program of asteroid radiometry. All but three of the 30 brightest asteroids are included in the total sample of 131 objects, and all asteroids with diameters greater than 250 km can now be identified. The albedos are strongly bimodal, with the great majority of asteroids (class C) having visual geometric albedos between 0.025 and 0.050. The albedos of the second most numerous class, the S asteroids, are primarily between 0.10 and 0.16. The third largest class appears to be the M objects, of which seven are now identified. Apparently, the M objects are very rare for $a < 2.4$ AU. The unusual asteroids with albedos greater than 0.20 are also discussed.

Subject headings: asteroids — infrared: general

1. INTRODUCTION

Recent studies of asteroids by multicolor photometry, spectrophotometry, polarimetry, and infrared radiometry have greatly increased the amount of physical information available on these objects. Both radiometry and polarimetry yield data from which diameters and albedos can be computed, and both techniques have been widely applied. A recent summation by Zellner and Gradie (1976) lists polarimetric albedos for 52 asteroids, while radiometric results have been given for 40 by Morrison (1974), for an additional 22 by Morrison and Chapman (1976), and for a partially overlapping set of 84 by Hansen (1976). This paper, a continuation of the series begun by Morrison (1974) and Morrison and Chapman (1976), reports additional observations of 84 asteroids, 68 of them new. Other short publications in this same series deal with individual Earth-approaching asteroids. They are Morrison (1976a), for 433 Eros; and Morrison, Gradie, and Rieke (1976), for 1976AA. All of the data in these papers have been obtained and reduced in a uniform manner and the results interpreted with the same quantitative model.

The radiometric technique of measuring diameters of asteroids has been discussed recently by Morrison (1973, 1976b), Jones and Morrison (1974), Hansen (1976), and Chapman, Morrison, and Zellner (1975), as well as in the previous papers of this series. These discussions will not be repeated here, except to note that the most direct result of the method is the determination of the effective diameter of the asteroid. The geometric albedo can also be found, but such a

calculation requires knowledge of the visual magnitude at the time of observation, a quantity that is often poorly known because of both ill-determined average magnitudes and possible departures from the average caused by the irregular shape of the asteroid. In a few cases near-simultaneous photoelectric photometry is available, but generally the magnitudes at the time the radiometric observations were made are uncertain by several tenths. These uncertainties can introduce errors of tens of percent in derived albedos for single observations, but where radiometric magnitudes obtained on several nights yield the same results, it can be presumed that the light curve of the asteroid has small amplitude and the albedo value is more secure.

The radiometric observations reported here cannot be considered in isolation. Much of the interpretation requires information from other physical observations, such as *UBV* photometry (primarily Zellner *et al.* 1975; Zellner, Andersson, and Gradie 1977; and Bowell 1977), visible polarimetry (primarily Zellner and Gradie 1976), and 0.3 to 1.1 μm spectrophotometry (primarily Chapman, McCord, and Johnson 1973; McCord and Chapman 1975a, b). In particular, the physical classification of asteroids requires a synthesis of such data. Such a synthesis was published for about 100 asteroids by Chapman, Morrison, and Zellner (1975), who were the first to define the major classes: C (dark, carbonaceous) and S (light, siliceous). Most recently, the classification has been expanded to include M (possible metallic), E (possibly enstatite), and O (possibly like the ordinary chondrite) types, and many additional asteroids have been examined as well. For a definition of these broad classes, the reader is referred to Bowell *et al.* (1977). The interpretation of these classes in terms of mineralogy, such as that of Chapman and Salisbury (1973), Johnson and Fanale (1973), McCord and Gaffey (1974), Chapman, Morrison, and Zellner (1975), and Gaffey (1976), is not further developed in the present paper.

* Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

† Part of this work was done while the author was at the Lunar and Planetary Laboratory, University of Arizona, Tucson.

II. OBSERVATIONS

a) Radiometric (10 and 20 μm) Magnitudes

The observations presented in this paper were obtained with three infrared photometers at three different observatories between 1974 March and 1976 June. At Mauna Kea in Hawaii, broad-band filters centered near both 10 and 20 μm were used on the 2.2 m telescope; the photometer and photometric system are described in the first paper of this series (Morrison 1974). Additional broad-band 10 μm observations of many asteroids were made with the 1.3 m telescope at Kitt Peak National Observatory; this system is described by Morrison and Chapman (1976). Finally, a few 10 μm observations were made in the winter of 1975/1976 with the 70 cm and 1.5 m telescopes of Mount Lemmon Observatory at the University of Arizona, with the photometric system described by Low and Rieke (1974).

All infrared reductions were made with reference to the stellar standard magnitudes listed in Table 1. The broad-band 10 μm and 20 μm magnitudes are labeled N and Q , respectively. The flux densities corresponding to zero magnitude are taken to be $1.2 \times 10^{-16} \text{ W cm}^{-2} \mu\text{m}^{-1}$ at 10.0 μm and 7.3×10^{-18} at 20.0 μm , the same values adopted in the calibration of the radiometric technique (Jones and Morrison 1974). The good agreement in asteroid diameters derived from simultaneous N and Q measurements demonstrates the consistency of these flux scales with each other if the asteroids have similar emissivities in both wavelength bands. The absolute flux calibration is uncertain by 10 to 20%, however, and this uncertainty introduces a 5 to 10% uncertainty in the derived diameters. All N -magnitudes were reduced to their zenith values with a nominal extinction coefficient of 0.15 mag per air mass, while the Q -magnitudes were reduced with values of the extinction coefficient derived from observations of standard stars on each individual night.

A listing of the observations is given in Table 2. Shown for each object is a log of nightly average magnitudes, expressed on the instrumental system by direct comparison with two or more of the standards listed in Table 1. The uncertainties quoted are internal standard deviations estimated from the consistency of the observations, the proximity of the standard stars, and the general photometric quality of the night. Table 2 includes, in addition to the new observations, re-reductions of some pre-1974 data for the bright asteroids 1 Ceres, 2 Pallas, 4 Vesta, 10 Hygiea, 13 Egeria, 16 Psyche, and 19 Fortuna (Cruikshank and Morrison 1973; Morrison 1974). The number of observations (n) listed for each magnitude entry in Table 2 refers to independent sets of integrations. Occasionally these observations may be consecutive, but generally they are separated by between 30 and 120 minutes.

In order to derive diameters and albedos, we require the monochromatic radiometric magnitudes. For the standard N and Q filters at Mauna Kea, correction factors for blackbodies at various temperatures needed

TABLE 1
INFRARED CALIBRATION STANDARDS

Star	N	Q
α Tau.....	-3.08	-3.23
α Aur.....	...	-2.05
α Ori.....	-5.17	-5.74
β Gem.....	-1.30	...
α Leo.....	+1.55	...
α Boo.....	-3.20	-3.32
α Her.....	-3.97	-4.26
α Lyr.....	-0.05	...
β Peg.....	-2.53	-2.74

to convert to monochromatic values at 10 μm (m_{10}) and 20 μm (m_{20}) have been derived (cf. Morrison 1973). At 10 μm , the corrections range from +0.05 inside the orbit of Mars to +0.20 in the outer part of the belt, while at 20 μm the correction throughout the belt is about -0.10. However, the corrections are a sensitive function of the effective band shape of the filters, and the values appropriate to the Kitt Peak and Mount Lemmon photometers might be significantly different. To determine these differences, I observed several bright standard objects (1 Ceres, 19 Fortuna, 192 Nausikaa, 324 Bamberga, 511 Davida) at both Mauna Kea and the Arizona observatories and established whether a systematic shift in one wavelength scale relative to the other was required to reconcile the observations. No such shift was required, at least to a precision of ± 0.1 mag, as demonstrated by the excellent agreement in results from all three observatories. Therefore the same corrections were applied to the Kitt Peak and Mount Lemmon N -magnitudes as at Mauna Kea for conversion to monochromatic m_{10} values.

Both radiometric and visual magnitudes of asteroids are expected to vary with phase angle. In V , a standard phase coefficient of 0.023 mag degree $^{-1}$ is usually adopted (cf. Gehrels 1970), although recent photometry suggests that the average coefficient may be at least as high as 0.030 (E. Bowell, private communication 1976). At N and Q , the variations are expected to be smaller, at least for phase angles less than 30°. Both model calculations (T. Jones, private communication 1976) and observations of Eros (Morrison 1976a) indicate that the variation is not linear, but a coefficient near 0.01 mag degree $^{-1}$ is a reasonable average for phase angles out to about 30°. In order to retain consistency with the previous publications in this series, I adopt a linear phase coefficient at N and Q of 0.01 mag degree $^{-1}$ for reduction of these data to zero phase.

b) V -Magnitudes

Although a well-determined radiometric observation defines the effective diameter of an asteroid quite well, a value for the corresponding brightness in reflected light is also required if the albedo is to be determined. For the standard reduction technique (Jones and Morrison 1974) the photometric quantity used is $V(1, 0)$, the visual magnitude at unit distance

TABLE 2
LOG OF OBSERVATIONS*

Object	Source	N	Q	Object	Source	N	Q
1 Ceres	MK 04/12/71	2	-3.08 .15	21 Lutetia	KP 12/03/76	2	1.73 .10
	MK 05/12/71	2	-2.97 .10		KP 13/03/76	2	1.75 .10
	MK 06/01/72	1	-3.46 .15		KP 14/03/76	2	1.72 .10
	MK 08/04/72			25 Phocaea	KP 06/06/76	5	0.38 .10
	MK 11/06/74	2	-1.97 .15				
	MK 31/07/74			30 Urania	MK 31/07/74		1 -1.46 .20
	MK 22/09/74						
	MK 15/11/74	2	-1.78 .10	41 Daphne	KP 06/06/76	8	-1.50 .10
	MK 16/11/74	1	-1.95 .15				
	KP 14/09/75	1	-2.28 .10	42 Isis	MK 11/06/74	3	1.61 .15
	KP 15/09/75	2	-2.46 .05				
	KP 16/09/75	3	-2.33 .05	44 Nysa	MK 11/06/74	2	2.47 .15
	ML 12/12/75	2	-3.10 .10		KP 14/09/75	1	3.30 .25
	ML 26/01/76	2	-2.70 .10		KP 16/09/75	2	3.07 .15
	KP 14/02/76	7	-2.45 .05	45 Eugenia	KP 15/09/75	4	1.40 .15
	KP 12/03/76	6	-2.20 .05				
	KP 13/03/76	8	-2.10 .05	46 Hestia	MK 16/11/74	4	-0.21 .10
	KP 14/03/76	7	-2.14 .05		KP 12/03/76	2	1.62 .10
2 Pallas	MK 08/09/71	1	-1.81 .20		KP 13/03/76	1	1.65 .15
	MK 13/09/71	1	-1.96 .15		KP 14/03/76	2	1.68 .10
	MK 05/10/71	1	-2.68 .20	52 Europa	KP 15/09/75	1	0.71 .15
	MK 04/12/71	2	-2.59 .20		KP 16/09/75	2	0.84 .10
	MK 05/12/71	1	-2.61 .25				
	MK 09/05/74	1	0.17 .15	54 Alexandra	MK 31/07/74		2 -3.10 .15
	MK 01/08/74				MK 01/08/74		3 -3.30 .10
	MK 02/08/74	2	-0.52 .15				
	MK 22/09/74			56 Melete	MK 31/07/74		2 -3.25 .25
					MK 01/08/74		1 -3.00 .20
4 Vesta	MK 06/10/71	1	-1.92 .20				
	MK 08/10/71	1	-1.65 .15	60 Echo	KP 16/09/75	5	2.43 .05
	MK 17/10/72	2	-1.59 .10				
	MK 18/10/72	1	-1.45 .15	63 Ausonia	KP 13/03/76	2	1.25 .10
	MK 23/10/72	1	-1.60 .15		KP 14/03/76	4	1.25 .10
	MK 17/01/74	1	-1.89 .15				
	MK 18/01/74	3	-1.81 .10	66 Maja	KP 14/09/75	1	1.41 .15
	MK 09/05/74	3	-2.58 .05				
	MK 11/06/74	2	-2.14 .10	68 Leto	MK 15/11/74	2	1.12 .20
	MK 31/07/74				MK 16/11/74	3	0.99 .10
	MK 01/08/74				KP 12/03/76	2	2.80 .10
	MK 02/08/74	2	-1.49 .15		KP 13/03/76	1	2.59 .15
9 Metis	KP 16/09/75	2	-0.03 .10				
10 Hygiea	MK 23/06/73	2	-0.59 .05	77 Frigga	KP 14/09/75	1	2.65 .20
	MK 24/06/73	1	-0.64 .10				
	MK 25/06/73	1	-0.98 .15	79 Eurynome	MK 15/11/74	3	-0.07 .10
	MK 16/09/73	2	-0.68 .05		MK 16/11/74	2	-0.12 .10
	MK 21/09/74				KP 12/03/76	1	2.70 .15
	MK 22/09/74				KP 13/03/76	2	2.70 .10
	MK 16/11/74	5	0.10 .10		KP 14/03/76	2	2.78 .10
12 Victoria	KP 14/09/75	1	-0.10 .15	82 Alkmene	KP 12/03/76	1	1.77 .15
	KP 15/09/75	2	-0.28 .10		KP 13/03/76	2	1.84 .10
	KP 16/09/75	1	-0.31 .15		KP 14/03/76	2	1.73 .10
13 Egeria	MK 21/09/74			84 Klío	MK 22/09/74		2 -2.82 .15
	MK 22/09/74						
	MK 15/11/74	2	-0.39 .10	85 Io	KP 12/03/76	2	1.42 .10
	MK 16/11/74	2	-0.35 .10		KP 13/03/76	2	1.73 .10
16 Psyche	MK 18/04/73	2	0.96 .15		KP 14/03/76	2	1.67 .10
	MK 14/05/73			91 Aegina	ML 26/01/76	2	0.70 .15
	MK 22/06/73	2	0.98 .10		KP 14/02/76	2	0.87 .15
	MK 31/07/74			94 Aurora	KP 12/03/76	3	1.72 .05
	MK 01/08/74						
	MK 01/09/74			97 Klotho	KP 14/09/75	1	0.64 .15
	KP 14/09/75	4	0.23 .05		KP 15/09/75	1	0.50 .15
	KP 15/09/75	2	0.10 .10		KP 16/09/75	1	0.63 .15
	KP 16/09/75	3	0.21 .05	106 Dione	KP 13/09/75	1	1.25 .20
	ML 12/12/75	2	-0.20 .10		KP 16/09/75	2	1.45 .20
	ML 26/01/76	3	0.40 .10	109 Felicitas	KP 14/09/75	1	1.58 .20
	KP 14/02/76	9	0.78 .05		KP 16/09/75	4	1.65 .10
	KP 12/03/76	7	1.35 .05	113 Amalthea	KP 14/09/75	2	3.45 .20
	KP 13/03/76	11	1.35 .10		KP 16/09/75	4	3.45 .10
	KP 14/03/76	14	1.39 .05	115 Thyra	KP 14/03/76	5	1.76 .10
19 Fortuna	MK 16/03/73	2	-0.16 .10				
	MK 17/04/73	2	0.26 .10	120 Lachesis	KP 14/03/76	7	1.70 .05
	MK 18/04/73	2	0.26 .15				
	MK 11/06/74	1	-0.26 .15	123 Brunhild	ML 26/01/76	2	2.80 .30
	MK 31/07/74						
	MK 01/08/74			124 Alkeste	KP 16/09/75	4	3.30 .20
	MK 22/09/74						
	KP 14/02/76	1	-0.48 .15	129 Antigone	KP 06/06/76	6	0.40 .15
	KP 14/03/76	11	-0.08 .05				
20 Massalia	MK 11/06/74	3	1.17 .10	130 Elektra	KP 16/09/75	1	0.12 .15
				135 Hertha	KP 14/02/76	1	3.10 .20
					KP 12/03/76	1	3.05 .15
					KP 13/03/76	1	2.38 .15

TABLE 3
UBV PHOTOMETRY* BY C. R. CHAPMAN ON 1975 SEPTEMBER 14 AND 15

Object	Date/Time (LST)	<i>n</i>	<i>V</i>	<i>V</i> (1, 0)	<i>B</i> - <i>V</i>	<i>U</i> - <i>B</i>
16 Psyche.....	14/04:01	4	10.64	6.26	0.72	0.26
44 Nysa†.....	14/02:01	2	10.26	6.92	0.70	...
45 Eugenia.....	15/04:08	2	12.48	8.24	0.65	...
66 Maja.....	14/03:01	2	12.59	8.85	0.71	0.36
97 Klotho.....	14/02:18	2	10.15	7.80	0.70	0.26
270 Anahita.....	14/02:30	1	10.90	9.12	0.87	0.51
365 Corduba.....	15/03:82	2	12.88	9.78	0.69	0.29

* *V*-magnitudes should be accurate to ± 0.05 and colors to ± 0.02 .

† These data were taken at large air mass and are therefore more uncertain.

difference is greater than 0.2 mag (for 44 Nysa, 45 Eugenia, 66 Maja, and 97 Klotho), I use the instantaneous $V(1, 0)$ value to compute the albedo and then combine this albedo with the average $V(1, 0)$ value to compute an average diameter as well as the instantaneous diameter obtained directly from the radiometry. For all other asteroids, the data are reduced on the basis of the average $V(1, 0)$ value listed by Gehrels and Gehrels (1977), who incorporate part of the recent photometry of Bowell (1977) and Zellner, Andersson, and Gradie (1977). If improved magnitudes become available at a later time, the albedos can be recomputed to a good first approximation from the radiometric diameters.

III. COMPUTATION OF DIAMETERS AND ALBEDOS

All of the radiometric data have been reduced on the basis of the model of Jones and Morrison (1974). The blackbody brightness temperature at 1 AU (T_0 in the notation of that paper) is assumed to be 408 K, and no additional adjustments are made in the infrared emissivity which is taken to be 1.0. For all objects, I assume the phase integral $q = 0.6$ and values of the ratio of bolometric to visual albedo $p/p_V = 1.0$. These two numbers enter the calculations only weakly (cf. Jones and Morrison 1974); for most objects, a variation of 20% in their product has an effect of less than 1% on the derived diameters.

All of the reductions are summarized in Table 4. For each asteroid listed in Table 2, the data taken during a single observing run are averaged, and the run is identified by month and year. For comparison, Table 4 also includes reductions for the same objects from previous observations (Morrison 1974; Morrison and Chapman 1976), where such data exist. When both 10 and 20 μm observations exist, they are given equal weight in computing the final diameter and albedo. For the four cases from Table 3 where values of $V(1, 0)$ from Chapman's observations are used instead of average values, the average diameter is listed below the instantaneous diameter.

The weighting system indicated in the last column of Table 4 can be described as follows: Weight 1 is assigned to single observations or to data with large internal uncertainties; these values are not necessarily reliable and should be used with caution. Weight 2 is assigned in a broad range of situations, including at the minimum two independent measurements on a

good photometric night; this weight indicates basically secure, believable results. Weight 3 is assigned to excellent, multiply verified data—either four or more independent and highly repeatable measurements on a single night or, more commonly, several observations on two or more nights that are in good agreement.

The calibration adopted in this and other papers of the same series differs in important respects from that of other workers. On the one hand, it has been apparent for some time that the polarimetric technique gives higher albedos than the radiometric by some 20–30% (cf. Chapman, Morrison, and Zellner 1975). On the other, the independent radiometric model developed by Hansen (1976) gives much lower albedos.

Differences between the radiometry presented here and the polarimetry as presented by Zellner and Gradie (1976) are not serious for albedos $p_V > 0.06$, where they amount to 10% in the diameters and 20% in the albedos. Such differences can be explained by modest calibration uncertainties in either method, e.g., by a shift of 0.2 mag in the radiometric flux scale. For the darker objects, however, the discrepancy is much larger. Most C-type asteroids have polarimetric albedos between 0.05 and 0.06, while the radiometric albedos for these same objects range from 0.02 to 0.05. For the present discussion I will assume that, apart from a possible 20% scale shift, the radiometric albedo scale is accurate. Possible reconciliation of these two scales will be discussed in a later paper (Morrison 1977).

Hansen (1976) published systematically lower radiometric albedos than those given in Table 4. This difference is due in part to a small shift in the infrared flux scales at 10 μm , such that Hansen obtains values of m_{10} that are ~ 0.2 mag brighter than mine. As a consequence, he tends to derive emissivities much less than unity from his 10 μm /20 μm color temperatures. However, most of the difference results from the models used to interpret the data. The Hansen model does not include a peaking of the infrared emissivity to values greater than 1.0 for small phase angles, while the Jones and Morrison model does, in agreement with measured infrared brightness temperatures near the center of the full Moon, which exceed the equilibrium kinetic temperatures there. This model difference explains most of the discrepancy between Hansen's results and those presented here.

TABLE 4
COMPUTED DIAMETERS AND GEOMETRIC ALBEDOS

NAME	SOURCE	V(1,0)	M10	M20	R	ALPH	D	PV	WT	NAME	SOURCE	V(1,0)	M10	M20	R	ALPH	D	PV	WT
1 CERES	MK 12/71	3.76	-4.46	-7.25	2.50	-23	1052.	.049	2	16 PSYCHE	KP 9/75	6.19	-1.54	-3.88	2.82	-14	234.	.076	3
1 CERES	MK 1/72	3.76	-4.49	-7.43	2.56	-15	1094.	.046	1	16 PSYCHE	ML 12/75	6.19	-1.34	-3.95	2.67	3	246.	.096	1
1 CERES	MK 4/72	3.76	-7.10	-7.10	2.83	-14	1089.	.046	2	16 PSYCHE	ML 1/76	6.19	-1.08	-4.30	2.73	18	243.	.099	2
1 CERES	MK 6/74	3.76	-3.93	-6.79	2.18	-20	1020.	.053	1	16 PSYCHE	KP 2/76	6.19	-.96	-4.30	2.75	20	235.	.105	3
1 CERES	MK 8/74	3.76	-6.95	-6.95	2.98	-12	1054.	.049	1	16 PSYCHE	KP 3/76	6.19	-.73	-3.80	2.79	21	220.	.121	3
1 CERES	MK 9/74	3.76	-6.90	-6.90	2.98	9	1016.	.053	2	19 FORTUNA	MK 3/73	7.71	-.91	-3.88	2.82	-14	234.	.026	2
1 CERES	MK 11/74	3.76	-3.80	-6.60	2.97	19	943.	.062	2	19 FORTUNA	MK 4/73	7.71	-1.00	-3.95	2.83	1	250.	.027	3
1 CERES	KP 9/75	3.76	-4.19	-7.29	2.79	-21	1041.	.050	3	19 FORTUNA	MK 6/74	7.71	-1.36	-4.30	2.41	-21	226.	.028	1
1 CERES	ML 12/75	3.76	-4.33	2.73	2.73	5	999.	.055	1	19 FORTUNA	MK 8/74	7.71	-.96	-4.30	2.32	3	241.	.035	1
1 CERES	ML 1/76	3.76	-4.22	2.69	2.69	19	990.	.056	2	19 FORTUNA	MK 9/74	7.71	-.96	-3.80	2.23	20	201.	.035	2
1 CERES	KP 2/76	3.76	-4.19	2.68	2.68	22	984.	.056	3	19 FORTUNA	KP 2/76	7.71	-1.25	-3.88	2.45	11	208.	.033	1
1 CERES	KP 3/76	3.76	-4.20	2.67	2.67	23	988.	.056	3	19 FORTUNA	KP 3/76	7.71	-1.18	-3.95	2.50	18	215.	.031	3
2 PALLAS	MK 9/71	4.53	-3.38	-5.95	2.51	-23	615.	.071	2	20 MASSALIA	MK 6/74	6.97	-.04	-2.55	2.60	15	133.	.161	2
2 PALLAS	MK 10/71	4.53	-3.87	2.46	2.46	-21	739.	.049	1	21 LUTETIA	MK 6/73	7.90	-.20	-2.65	2.14	8	109.	.102	3
2 PALLAS	MK 12/71	4.53	-3.45	-5.90	2.32	20	560.	.086	2	21 LUTETIA	KP 3/76	7.90	.58	-2.75	2.75	-5	108.	.103	3
2 PALLAS	MK 5/74	4.53	-2.15	3.37	3.37	-17	559.	.086	1	25 PHOAEA	KP 6/76	8.15	.47	-1.85	1.85	-24	72.	.184	2
2 PALLAS	MK 8/74	4.53	-2.42	-5.41	3.41	11	605.	.074	2	30 URANIA	MK 4/73	7.94	1.02	-1.92	2.65	7	90.	.133	2
2 PALLAS	MK 9/74	4.53	-5.24	3.42	3.42	16	558.	.086	1	30 URANIA	MK 8/74	7.94	1.02	-2.17	2.33	4	94.	.133	1
4 VESTA	MK 10/71	3.55	-2.90	-5.96	2.33	24	546.	.222	1	41 DAPHNE	KP 6/76	7.18	-1.67	-2.07	2.07	15	204.	.056	2
4 VESTA	MK 10/72	3.55	-2.70	-5.65	2.55	-19	527.	.239	3	42 ISIS	MK 6/74	7.94	.60	-2.38	2.38	21	94.	.133	2
4 VESTA	MK 1/72	3.55	-2.70	-5.71	2.55	-17	530.	.236	1	44 NYSA	MK 6/74	7.15	1.46	-1.31	2.65	7	79.	.388	2
4 VESTA	MK 1/74	3.55	-3.05	-5.85	2.32	-24	545.	.224	3	44 NYSA	KP 9/75	6.92	2.06	-1.31	2.64	6	71.	.592	2
4 VESTA	MK 5/74	3.55	-3.15	-5.80	2.22	18	501.	.264	2	44 NYSA	KP 9/75	7.15	-.15	-2.90	2.90	14	65.	.592	2
4 VESTA	MK 6/74	3.55	-3.23	-5.80	2.20	26	533.	.233	2	45 EUGENIA	KP 9/75	8.24	-.15	-3.40	1.99	12	148.	.025	1
4 VESTA	MK 8/74	3.55	-2.15	-5.80	2.17	28	540.	.227	2	45 EUGENIA	KP 9/75	7.63	-.65	-3.04	2.27	-3	134.	.028	3
9 METIS	MK 4/73	6.88	-1.08	-3.85	2.49	11	209.	.070	3	46 HESTIA	MK 11/74	8.66	-.28	-3.04	2.27	-3	134.	.028	3
9 METIS	MK 8/74	6.88	-1.35	-3.10	2.60	9	158.	.123	3	46 HESTIA	KP 3/76	8.66	.28	-3.04	2.27	-3	134.	.028	3
9 METIS	KP 9/75	6.88	-1.17	-4.75	2.12	-28	181.	.094	3	52 EUROPA	KP 9/75	6.94	-.92	-3.70	2.19	-4	176.	.031	2
10 HYGIEA	MK 6/73	5.80	-1.85	-4.75	2.96	-16	385.	.056	3	54 ALEXANDRA	MK 8/74	8.78	-.65	-3.40	1.99	12	148.	.025	1
10 HYGIEA	MK 9/73	5.80	-2.15	-5.40	3.06	12	488.	.035	2	56 MELETE	MK 8/74	8.78	-.65	-3.40	1.99	12	148.	.025	1
10 HYGIEA	MK 9/74	5.80	-1.77	-4.92	3.42	-11	464.	.039	2	61 ECHO	KP 9/75	9.11	1.79	-2.32	2.32	13	51.	.154	2
10 HYGIEA	MK 11/74	5.80	-1.77	-4.92	3.46	7	457.	.040	2	63 AUSONIA	MK 6/73	8.05	-.20	-2.55	2.10	12	106.	.094	2
12 VICTORIA	KP 9/75	7.48	-7.74	-4.08	2.10	-21	142.	.089	2	63 AUSONIA	KP 3/76	8.05	.59	-2.55	2.41	1	88.	.137	3
13 EGERTIA	MK 9/74	7.40	-1.38	-4.03	2.61	-12	250.	.031	2	66 MAJA	KP 9/75	6.85	.06	-2.70	2.70	12	133.	.029	1
13 EGERTIA	MK 11/74	7.40	-1.38	-4.03	2.56	12	239.	.034	3	66 MAJA	KP 9/75	6.85	.06	-2.70	2.70	12	133.	.029	1
16 PSYCHE	MK 4/73	6.19	-.62	-3.72	3.28	-7	254.	.090	2	68 LETO	MK 11/74	7.36	.05	-2.57	2.57	-5	126.	.126	2
16 PSYCHE	MK 5/73	6.19	-7.75	-3.73	3.26	3	252.	.092	2	68 LETO	KP 3/76	7.36	.92	-3.28	3.28	9	126.	.126	2
16 PSYCHE	MK 6/73	6.19	-7.75	-3.81	3.23	15	271.	.080	2	77 FRIGGA	KP 9/75	8.66	1.56	-2.63	2.63	-12	67.	.113	1
16 PSYCHE	MK 8/74	6.19	-3.50	-3.50	2.72	1	195.	.154	1	79 EURYNOME	MK 11/74	8.37	-.02	-2.03	1.97	-3	81.	.120	3
16 PSYCHE	MK 9/74	6.19	-3.50	-3.50	2.65	18	205.	.139	1	79 EURYNOME	KP 3/76	8.37	1.47	-2.78	2.78	-9	76.	.137	3

673

In the following section of this paper the new radiometric diameters and albedos given in Table 4 will be discussed in combination with those published previously by Morrison (1974, 1976a), Morrison and Chapman (1976), and Morrison, Gradie, and Rieke (1976). In a later publication (Morrison 1977) an analysis of asteroid sizes and size distributions will be given, based on radiometric observations by Hansen (1976) and polarimetric observations by Zellner and Gradie (1976) as well as the radiometry discussed here.

IV. ALBEDO AND SIZE DISTRIBUTIONS

Now available for discussion are 131 objects with known radiometric diameters and albedos. With the exception of two or three faint Earth-approaching objects, all of the asteroids observed were selected purely on the basis of apparent brightness. There is therefore a strong selection in favor of objects that have large diameters, high albedos, and small semi-major axes. However, no other criteria, such as color or spectrum or orbital peculiarity, were used in the selection of objects to be observed. Consequently, the 131 observed objects with computed diameters and albedos constitute a reasonably sound statistical sample from which to derive average properties for all of the larger asteroids.

In terms of absolute, rather than apparent, magnitude, the sample includes all 13 asteroids with $B(1, 0) \leq 7.28$. As one proceeds to fainter absolute magnitudes, the first objects *not* included are 31 Euphrosyne, 39 Laetitia, 48 Doris, and 92 Undina, all with $7.28 < B(1, 0) < 8.00$, and all but Laetitia in the outer belt ($a > 3.10$ AU). As will be seen below, asteroids with such large values of a are almost certainly of low albedo. Laetitia is known to be an S object, and if an albedo appropriate to a typical C asteroid is assumed for objects 31, 48, and 92, the sample can be considered complete for the 35 objects with $B(1, 0) < 8.10$. This magnitude limit corresponds to a diameter of 110 km for a typical S-class object and 240 km for a typical C-class object.

The distribution of observed geometric albedos, shown in Figure 1, is strongly bimodal, with most objects having albedos near either 0.033 or 0.14. The former value corresponds to the typical C object, the latter to the typical S. The probable uncertainty, corresponding to a 0.1 mag error in the radiometric and a 0.2 mag error in the photometric data, is $\sim 20\%$, approximately the width of one bar of the histogram. Thus, much of the apparent width of both peaks of the histogram can be ascribed to observational uncertainties, and Figure 1 is consistent with the hypothesis that the geometric albedos of most asteroids fall into two narrow ranges, one from 0.025 to 0.050, the other from 0.10 to 0.16. In particular, there appear to be no well-authenticated cases of albedos significantly less than 0.025, and the few apparently lower values are probably the result of observational scatter. Of course, if the polarimetric calibration for the brighter objects is correct, each of these numbers should be increased by 20%, and the lowest real albedo is 0.030.

The "tail" of albedos greater than about 0.18

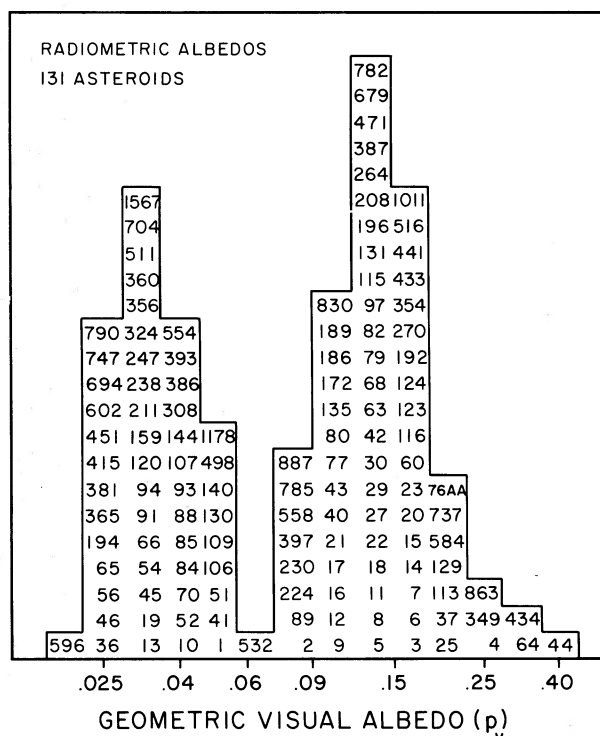


FIG. 1.—Distribution of geometric visual albedos for 131 radiometrically measured asteroids from this paper and previous papers in this series. The width of each bar in the histogram is 0.1 in log albedo, approximately equal to the probable error in an average determination.

cannot be explained by observational scatter. Among the objects of high albedo are 4 Vesta, the only known asteroid with a basaltic surface; 349 Dembowska, the only large asteroid spectrally similar to the ordinary chondrites; and 44 Nysa, 64 Angelina, and 434 Hungaria, the three known members of class E, which may be related to the enstatite achondrite meteorites. For discussion of the spectral basis of these identifications, see McCord, Johnson, and Adams (1970); McCord and Gaffey (1974); Chapman, Morrison, and Zellner (1975); Zellner (1975); Zellner, Morrison, and Leake (1977); and Bowell *et al.* (1977). It is clear, however, that the very great majority of asteroids have albedos between 0.025 and 0.18.

The ratio of the typical C and S albedos is ~ 4.0 . If both populations were well mixed and the objects were selected on the basis of apparent brightness only, the C objects would be underrepresented by the same amount, and the true number of C asteroids would exceed the number of S asteroids by about a factor of 3. However, the actual distributions of the classes in space are not the same, and in consequence the true proportion of C objects is larger than indicated above.

A complete correction for the bias introduced by the dependence of spectral class on semimajor axis for the asteroids will be given in a separate paper (Morrison 1977). The result of that analysis is that, among the approximately 300 asteroids 100 km or larger in diameter, the C group is about seven times more

numerous than the S group. Since the C's are strongly concentrated toward large semimajor axes, the total number of asteroids per radial increment increases from the inner to the outer edge of the belt. Nearly half of all asteroids larger than 100 km in diameter are farther than 3.0 AU from the Sun. Since a 100 km C asteroid at 3.0 AU has a magnitude of $B = 14$, these objects are almost unsampled by radiometry or other physical observations.

For the S asteroids, which have high albedos and are concentrated inside the 2/5 Kirkwood gap at $a \approx 2.9$ AU, the sample for which radiometric observation is complete extends to much smaller sizes than for the C asteroids. Down to a diameter of 100 km, there are about 20 S asteroids, and only two objects with $a < 3.0$ AU have not been observed radiometrically: 57 Mnemosyne, which has been classified polarimetrically as S; and 216 Kleopatra, which has recently been found to be in class M (C. Chapman, private communication 1977). Also included in the completely sampled range of magnitudes are a substantial number of less common objects. In addition to 4 Vesta, 44 Nysa, and 349 Dembowska, all mentioned above, these include the M objects 16 Psyche and 22 Kalliope and the unclassified objects 2 Pallas, 129 Antigone, 130 Elektra, and 68 Leto, which will be discussed along with other interesting special objects below.

V. INDIVIDUAL ASTEROIDS OF INTEREST

a) High-Albedo Asteroids

When Chapman, Morrison, and Zellner (1975) reviewed all existing physical observations, the asteroid of highest albedo was 4 Vesta, with its unique surface of pigeonitic basalt (McCord, Johnson, and Adams 1970). These authors concluded that no other asteroid with an equally high albedo was likely to exist with a diameter greater than 80 km. Subsequently, two higher-albedo asteroids, 44 Nysa (70 km) and 64 Angelina (60 km), were identified polarimetrically by Zellner (1975) and Zellner and Gradie (1976), who suggested that these objects were of enstatite composition and could be considered the prototype of the E class of asteroids. A third and smaller member of

this class, 434 Hungaria, was recently identified from combined *UBV* photometry, radiometry, and polarimetry (Zellner, Morrison, and Leake 1977). As seen in Figure 1, the three members of the E class are the highest-albedo asteroids in the sample.

Morrison and Chapman (1976) obtained an albedo of 0.25 (diameter 143 km) for 349 Dembowska and suggested that this object, which spectrally resembles the ordinary chondrites, serve as the prototype of the O class of asteroids. This albedo is essentially the same as that of 4 Vesta. The only other asteroid with a comparably high albedo is 863 Benkoela, observed by Morrison and Chapman (1976). However, the radiometric observation of Benkoela was of low weight and was not repeated, and in the absence of other physical data on the asteroid, it is premature to accept even the high albedo value, quite aside from assigning it to a given class. Thus, only 349 Dembowska and the three E-class objects are known to have albedos as high as or higher than that of Vesta.

b) M-Class Asteroids

Three asteroids have previously been assigned to class M: 16 Psyche, 21 Lutetia, and 22 Kalliope. A weight-3 radiometric albedo has now been computed for object 16, and weight-2 values for 21 and 22. As a result of the present study, together with recent *UBV* photometry, spectrophotometry, and polarimetry, three additional asteroids can be definitely assigned to this class: 97 Klotho, 135 Hertha, and 516 Amherstia (cf. Bowell *et al.* 1977). In addition, if the weight-1 albedo for 224 Oceana can be trusted, it in combination with *UBV* colors places this object in the M class. The data on these seven asteroids are summarized in Table 5. Their albedos, ranging from 0.08 to 0.15, completely overlap the lower half of the domain of albedos for S asteroids. Thus, measurement of albedo alone cannot be used to distinguish between the M and S classes.

The data in Table 5 indicate not only that these seven objects are similar in their observational parameters, but also that all fall in the central part of the asteroid belt, with semimajor axes measuring between 2.43 and 2.92 AU. Indeed, there is a tendency

TABLE 5
M-CLASS ASTEROIDS

Object	a	$B - V^*$	$U - B^*$	Bend †	$R/B^\dagger$	Depth †	$P_{\min}^\ddagger$	p_V (pol) ‡	p_V (rad) §
16 Psyche.....	2.92	0.70	0.25	0.04	1.21	1.00	1.00	...	0.09
21 Lutetia.....	2.43	0.71	0.19	0.09	1.14	1.00	1.30	0.10	0.10
22 Kalliope.....	2.91	0.72	0.28	0.07	1.24	0.91	0.98	...	0.13
97 Klotho.....	2.67	0.73	0.22	0.06	1.12	...	...	...	0.12
135 Hertha.....	2.43	0.69	0.27	...	...	...	1.06	...	0.11
224 Oceana.....	2.64	0.75	0.21	...	...	...	...	...	0.08
516 Amherstia.....	2.68	0.74	0.27	...	...	...	...	...	0.15
Average.....	2.66	0.72	0.24	0.07	1.18	0.97	1.09	0.10	0.11

* From Zellner *et al.* 1975 or Bowell 1977.

† From McCord and Chapman 1975a, b.

‡ From Zellner and Gradie 1976.

§ This paper.

for these objects, insofar as can be judged from the small number in the sample, to have values of a that put them near the centers of the major Kirkwood gaps at 2.48 and 2.85 AU; the M asteroids do not appear to avoid these gaps, in any case. As proposed by Chapman (1974, 1976), in a fragmentation regime objects with little cohesive strength might be preferentially eliminated from these gaps by collisions, while the intrinsically strongest would be less affected. It has already been noted (Chapman, Morrison, and Zellner 1975) that the C asteroids avoid the gaps more strongly than do the S asteroids, as one would expect from the suggested carbonaceous and stony-iron compositions of the two groups, respectively. If, as these data suggest, the M asteroids are not affected by the gaps, this result would be consistent with a metallic composition for these objects and would lend further support to the suggestion of early evolution of the asteroids made by Chapman (1974, 1976) and Chapman and Davis (1975). However, identification of a larger sample of M asteroids is required to test this hypothesis.

Based on their average semimajor axes of $a = 2.66$ and their average albedos of $p_v = 0.11$, an estimate of the true frequency of M asteroids can be made from the available observations. The seven identified objects have values of $B(1, 0)$ from 6.9 (16 Psyche) to 9.8 (224 Oceana). There are approximately 100 asteroids brighter than $B(1, 0) = 9.8$ for $2.4 < a < 3.0$, and for about 30% of them both albedo and color have been measured. Thus, the true number of M's must be about 20, or about 20% of the total to this magnitude limit. The M objects are less numerous for $a < 2.4$ AU, however, where the physically observed sample is nearly complete down to diameters of ~ 75 km for an albedo of 0.11. On the other hand, there could be as many M as S asteroids beyond 3.0 AU without their having been identified.

c) Anomalous Asteroids

In one case—that of 532 Herculina—the radiometric albedo appears anomalous (cf. Fig. 1). The colors of Herculina are those of an S asteroid; but two sets of radiometry, while not in particularly close agreement, both place Herculina below the S range of albedos ($p_v = 0.043$ and $p_v = 0.067$). Hansen (1976) also obtained 10 and 20 μ m magnitudes that, when interpreted with my methods and the average $V(1, 0)$, give a low albedo. However, Hansen reports a value of V at the time of his observation that is a full magnitude brighter than the average, and his V , in combination with either his or my radiometry, places Herculina in the S group, in agreement with all the other observations (polarimetry, photometry, spectrophotometry). It therefore seems most likely that the visible photometry is primarily responsible for the contradictions that have arisen regarding this asteroid and that Herculina is in fact a normal S object.

While most asteroids are adequately characterized by classification into broad taxonomic groups (Bowell *et al.* 1977), there are several of these minor planets that resist such simple classification. The most prominent of these from the present sample is 129

Antigone. That this asteroid has a well-established high ($p_v = 0.19$) radiometric albedo has been confirmed by a measurement of the minimum linear polarization (Zellner and Gradie 1976) characteristic of an S-class object. However, its UBV colors (Zellner *et al.* 1975; Bowell 1977) are those of a C object. The origin of this contradiction is not known, but clearly Antigone should be considered a prime object for additional study.

Several asteroids have low albedos ($p_v \approx 0.03$) characteristic of C objects but have unusual colors according to the UBV photometry of Zellner *et al.* (1975) and Bowell (1977). These include 94 Aurora, 694 Ekard, and 704 Interamnia. Another group, also with contradictory colors, has albedos of 0.05 to 0.12, in the range appropriate for M objects. These are 2 Pallas, 68 Leto, 80 Sappho, and 130 Elektra. Finally, the one other significant anomaly occurs for the Mars-crossing asteroid 887 Alinda, where the radiometric albedo is only 0.08 while the polarimetric albedo (Zellner and Gradie 1976) is 0.20. Since in other respects Alinda, like most other Mars-crossing asteroids, appears to be a high-albedo S object, the polarimetric value for the albedo seems preferable to the radiometric value.

d) Asteroids beyond 3.0 AU

Nineteen asteroids with $a \geq 3.0$ AU are included in the sample, 13 with weights of 2 or greater for their radiometric albedos. Of these 13, one—196 Philomela—appears to be an S object, while the others are all of too low albedo to qualify as S's. The range in albedo values for these 12 is from 0.024 to 0.040, with an average of 0.031, slightly lower than the average for C objects nearer the Sun (see Fig. 1). Perhaps coincidentally, the two darkest, 65 Cybele (0.025) and 790 Pretoria (0.024), are also the two with the largest semimajor axes (3.43 and 3.39 AU, respectively). There is, thus, a suggestion that the C asteroids tend to be darker at larger distances from the Sun, although this effect is certainly not yet demonstrated.

There are no measurements of radiometric albedo for main-belt asteroids beyond 3.5 AU, such as members of the Hilda group. However, if these bodies are very dark, as suggested by their UBV colors (Zellner, Andersson, and Gradie 1977), they could constitute a substantial fraction of all asteroids. Radiometry of four Trojans by Cruikshank (1977) does indicate very low albedos for this latter group ($a \approx 5.2$ AU). It seems likely that many large asteroids populate the outer belt and that these are underrepresented in most lists because of their dark surfaces and great distances, not because of small size.

VI. CONCLUSIONS

This paper completes the program of radiometric observations of a statistically significant sample of main-belt asteroids begun in 1971. The observations of 68 new objects reported in this paper bring the total number of asteroids for which I have reported radiometric diameters and albedos to 131.

The present study, in combination with parallel physical observations carried out for similar numbers of asteroids by photometry, spectrophotometry, and polarimetry, has revealed a number of broad groups or classes of asteroids with widely differing surface properties. While detailed spectrophotometry is required to investigate the mineralogical significance of these classes, a simple property such as albedo is often diagnostic for purposes of classification. In particular, the C class of asteroids, defined by their low albedos ($p_v < 0.06$), is revealed as by far the most numerous type of asteroid, constituting more than 80% of the population of at least the larger asteroids in the outer part of the belt. The C albedos are clearly distinguished from those of the S class, the second most important group. The M asteroids, which have albedos overlapping those of the S objects, constitute the third largest class; albedo measurements alone are not sufficient to distinguish between these two groups. Of highest albedo ($p_v \geq 0.25$) are the very rare objects with surfaces apparently similar to the ordinary chondrite, basaltic achondrite, and enstatite achondrite meteorites.

The sizes of the asteroids provide important input to any discussion of collisional frequency and past evolution of the belt. These sizes are much larger, on the average, than had been thought a few years ago;

there are, for instance, about 15 asteroids with diameters ≥ 250 km and many hundreds larger than 100 km in diameter. The sizes and size distributions will be pursued in detail in a subsequent discussion (Morrison 1977).

This research could not have been carried out without the aid and participation of many persons. C. R. Chapman assisted in the 1975 September observing and kindly made available, in addition, his unpublished *UBV* photometry. E. T. Bowell provided ephemerides for many objects in addition to making available his *UBV* photometric results in advance of publication. The values of $B(1, 0)$ for all numbered asteroids were generously provided by T. Gehrels in advance of publication. T. J. Jones assisted in computer programming and data reduction, and J. C. Gradie helped during three observing runs. Instrumentation assistance was given at Mauna Kea by H. M. Dyck, at Kitt Peak by R. Joyce and R. Capps, and at Mount Lemmon by G. H. Rieke. M. Lebofsky kindly made for me an important observation of Ceres and Psyche near their 1975 opposition. Finally, many stimulating conversations with E. T. Bowell, C. R. Chapman, and B. Zellner are gratefully acknowledged. This research was supported in part by NASA grant NGL 12-001-057 to the University of Hawaii.

REFERENCES

- Bowell, E. T. 1977, in preparation.
 Bowell, E. T., Chapman, C. R., Gradie, J. C., Morrison, D., and Zellner, B. 1977, in preparation.
 Chapman, C. R. 1974, *Geophys. Res. Letters*, **1**, 341.
 ———. 1976, *Geochim. Cosmochim. Acta*, **40**, 701.
 Chapman, C. R., and Davis, D. R. 1975, *Science*, **190**, 553.
 Chapman, C. R., McCord, T. B., and Johnson, T. V. 1973, *A.J.*, **78**, 126.
 Chapman, C. R., Morrison, D., and Zellner, B. 1975, *Icarus*, **25**, 104.
 Chapman, C. R., and Salisbury, J. W. 1973, *Icarus*, **19**, 507.
 Cruikshank, D. P. 1977, *Icarus*, **30**, 224.
 Cruikshank, D. P., and Morrison, D. 1973, *Icarus*, **20**, 477.
 Gaffey, M. J. 1976, *J. Geophys. Res.*, **81**, 905.
 Gehrels, T. 1970, in *Surfaces and Interiors of Planets and Satellites*, ed. A. Dollfus (London: Academic Press), p. 319.
 Gehrels, T., and Gehrels, N. 1977, in preparation.
 Hansen, O. L. 1976, *A.J.*, **81**, 74.
 Johnson, T. V., and Fanale, F. P. 1973, *J. Geophys. Res.*, **78**, 8507.
 Jones, T. J., and Morrison, D. 1974, *A.J.*, **79**, 892.
 Low, F. J., and Rieke, G. H. 1974, in *Methods of Experimental Physics*, Vol. 12, Part A, ed. N. Carleton (New York: Academic Press), p. 415.
 McCord, T. B., and Chapman, C. R. 1975a, *Ap. J.*, **195**, 553.
 ———. 1975b, *Ap. J.*, **197**, 781.
 McCord, T. B., and Gaffey, M. J. 1974, *Science*, **186**, 352.
 McCord, T. B., Johnson, T. V., and Adams, J. B. 1970, *Science*, **168**, 1445.
 Morrison, D. 1973, *Icarus*, **19**, 1.
 ———. 1974, *Ap. J.*, **194**, 203.
 ———. 1976a, *Icarus*, **28**, 125.
 ———. 1976b, in *Planetary Satellites*, ed. J. A. Burns (Tucson: University of Arizona Press).
 ———. 1977, *Icarus*, in press.
 Morrison, D., and Chapman, C. R. 1976, *Ap. J.*, **204**, 934.
 Morrison, D., Gradie, J. C., and Rieke, G. H. 1976, *Nature*, **260**, 691.
 Zellner, B. 1975, *Ap. J.*, **198**, L45.
 Zellner, B., Andersson, L., and Gradie, J. C. 1977, *Icarus*, in press.
 Zellner, B., and Gradie, J. 1976, *A.J.*, **81**, 262.
 Zellner, B., Morrison, D., and Leake, M. 1977, in preparation.
 Zellner, B., Wisniewski, W. Z., Andersson, L., and Bowell, E. 1975, *A.J.*, **80**, 986.

DAVID MORRISON: Code SL, Office of Space Science, NASA Headquarters, Washington, DC 20546