

Minor planets and related objects. XVI. Polarimetric diameters

B. Zellner, T. Gehrels, and J. Gradie

Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

(Received 3 June 1974)

Polarimetric observations of 43 asteroids are presented. All objects show a well-developed negative polarization branch as an indicator of unconsolidated surface regoliths. The empirical slope-albedo law for diffusely reflecting solid surfaces is reexamined and used to compute polarimetric albedos and diameters for 30 asteroids. In many cases the results are in good agreement with infrared-radiometric diameters; the older visual diameter measurements were systematically too small. Radiometric albedos below 5%, however, are not confirmed by the polarimetry. Bimodal frequency distributions are noted for asteroid color, albedo, and the depth of the negative polarization branch. Correlations between $B - V$ color and polarimetric parameters suggest that most of the asteroid population can be divided into siliceous and carbonaceous opacity classes.

INTRODUCTION

AN intensive survey of asteroid polarization-phase relationships was begun in April 1973. New observations of 36 objects are here presented along with previously unpublished measurements made since 1958. We also make use of observations of 1566 Icarus reported by Gehrels *et al.* (1970), of six objects by Veverka (1970, 1971, 1973), of 1685 Toro reported by Dunlap *et al.* (1973), and of 1620 Geographos by Dunlap (1974). The photographic polarimetry of asteroids by Lyot (1934) and the early photoelectric

work by Provin (1955; see also Dollfus 1961) were not of a precision comparable with more modern data.

Continuing polarimetric work is stimulated by the fruition of infrared-radiometric surveys in which asteroid diameters are inferred from the ratio of thermal emission to solar irradiation (e.g., Matson 1971; Jones and Morrison 1974; Morrison 1974), and spectrophotometric work in which surface mineral assemblages may be identified (Chapman *et al.* 1973; McCord and Chapman 1975). An analysis of combined radiometric, polarimetric, and spectrophotometric results for asteroids is provided by Chapman *et al.* (1975).

The more fundamental photopolarimetric parameters available from existing data are presented in the first section below. In Sec. II the slope-albedo law as a polarimetric discriminant of geometric albedo is reexamined. In the third section this law is used to derive preliminary polarimetric albedos and diameters for 30 objects, and the observed photopolarimetric properties are discussed in terms of asteroid surface structures and compositions.

I. OBSERVATIONAL PARAMETERS

As few as four or five asteroid observations at optimally selected solar phase angles would suffice to delineate the polarization-phase curve. Due to the vagaries of telescope scheduling, weather, and orbital eccentricity and inclination, perhaps twice this number of observations spread over two apparitions is generally necessary for adequate coverage. The program described here is therefore somewhat less than half completed.

In Tables I, II, and III are listed the observations made over a time span of 15 yr. Beginning in 1973 we use a computerized, photon-counting version (Serkowski 1974, pp. 161-164) of our Wollaston polarimeter. The observed asteroids are generally brighter than 12.5 mag and are usually observed in both the blue and green filters. A total of 10-30 one-minute integrations gives a probable error not worse than $\pm 0.1\%$. The corrections for instrumental polarization, derived from observations of unpolarized standard stars, are $\leq 0.05\%$

TABLE I. Polarization measurements made at the McDonald 2.1- and 0.9-m reflectors, using a Polaroid, V filter, and 1P21 photometer.

Ast. No.	Date (UT)	Tel.	Phase	P %	θ_r	P_r %
1	59 02 17.44	M0.9	21.85	0.95	2.0	0.95
2	58 12 07.52	M0.9	23.06	1.31	-2.0	1.31
2	59 02 04.46	M0.9	23.41	1.14	1.0	1.14
2	59 02 17.51	M0.9	20.94	0.48	1.0	0.48
4	58 11 04.50	M2.1	22.58	0.26	88.0	-0.26
4	58 12 07.29	M0.9	19.41	0.18	60.0	-0.09
4	58 12 15.25	M0.9	17.75	0.26	84.0	-0.25
4	59 02 04.38	M0.9	5.13	0.55	89.0	-0.55
4	59 02 17.36	M0.9	11.07	0.59	84.0	-0.58
4	59 02 18.33	M0.9	11.42	0.53	91.0	-0.53
6	59 02 04.43	M0.9	5.74	0.89	98.0	-0.86
6	59 02 15.45	M0.9	1.32	0.27	73.0	-0.22
7	58 10 22.42	M2.1	5.13	0.68	91.0	-0.68
7	58 12 03.10	M2.1	22.41	0.16	9.0	0.15
7	59 02 04.21	M0.9	35.16	1.58	-3.0	1.57
7	59 02 05.10	M0.9	35.24	1.17	1.0	1.17
8	58 12 03.20	M2.1	10.75	0.55	77.0	-0.49
8	58 12 15.19	M0.9	16.70	0.43	63.0	-0.25
10	58 12 03.27	M2.1	2.13	0.84	76.0	-0.74
10	58 12 07.40	M0.9	0.92	0.52	93.0	-0.52
10	58 12 15.24	M0.9	2.23	0.69	69.0	-0.51
13	59 02 04.33	M0.9	19.34	0.59	94.0	-0.58
14	59 02 15.49	M0.9	23.58	0.09	7.0	0.09
29	58 12 03.31	M2.1	9.22	0.75	91.0	-0.75
51	58 12 03.16	M2.1	12.42	1.58	91.0	-1.58
532	59 02 17.39	M0.9	7.98	0.80	98.0	-0.77
532	59 02 20.47	M0.9	9.09	0.82	89.0	-0.82

TABLE II. Observations with the current-integrating Wollaston polarimeter described by Gehrels and Teska (1960).

Ast. No.	Date (UT)	Tel. ^a	Filt. ^b	Phase	P %	ϵ_p %	θ_r °	P_r %	Ast. No.	Date (UT)	Tel. ^a	Filt. ^b	Phase	P %	ϵ_p %	θ_r °	P_r %
1	59 04 17.42	M2.1	I	11.07	1.49		92.0	-1.49	3	72 04 03.18	C1.5	B	2.48	0.55	0.03	88.0	-0.55
1	59 04 17.42	M2.1	V	11.07	1.58		95.0	-1.56	3	72 04 27.29	C1.5	B	9.88	0.76	0.05	90.0	-0.76
1	59 04 17.42	M2.1	U	11.07	1.58		94.0	-1.56	3	72 04 27.31	C1.5	G	9.89	0.77	0.06	87.0	-0.77
1	59 08 02.22	M2.1	V	21.23	0.86		-6.0	0.84	3	72 05 05.24	C1.5	B	12.15	0.66	0.05	92.0	-0.66
1	66 10 13.39	C1.5	B	20.92	0.68	0.04	5.9	0.67	4	59 04 25.13	M2.1	I	24.83	0.33		38.0	0.08
1	66 10 13.42	C1.5	U	20.91	0.60	0.16	16.2	0.51	4	59 04 25.13	M2.1	U	24.83	0.48		13.0	0.43
1	66 10 13.46	C1.5	I	20.91	0.81	0.14	-3.4	0.80	4	59 04 28.19	M2.1	I	24.82	0.22		24.0	0.15
1	66 10 13.47	C1.5	R2	20.91	0.51	0.16	0.5	0.51	4	59 04 28.19	M2.1	V	24.82	0.10		11.0	0.09
1	66 10 13.48	C1.5	O	20.91	0.40	0.17	-1.3	0.40	4	59 04 28.19	M2.1	U	24.82	0.31		8.0	0.30
1	66 12 13.29	C1.5	N	4.25	1.39	0.17	91.7	-1.39	4	67 04 18.41	C1.5	I	14.76	0.51	0.08	91.2	-0.51
1	66 12 13.30	C1.5	B	4.25	1.67	0.02	82.6	-1.61	4	67 04 18.40	C1.5	R2	14.76	0.43		86.2	-0.43
1	66 12 13.31	C1.5	G	4.24	1.58	0.02	84.9	-1.56	4	67 04 18.39	C1.5	O	14.76	0.54	0.05	88.2	-0.54
1	66 12 13.33	C1.5	U	4.23	1.64	0.05	85.1	-1.62	4	67 04 18.33	C1.5	G	14.78	0.59	0.03	90.2	-0.59
1	66 12 13.35	C1.5	R2	4.22	1.47	0.13	86.3	-1.46	4	67 04 18.35	C1.5	B	14.77	0.41	0.07	95.0	-0.40
1	66 12 13.35	C1.5	O	4.22	1.45	0.09	89.1	-1.45	4	67 04 18.34	C1.5	U	14.78	0.69	0.07	86.2	-0.68
1	66 12 13.36	C1.5	I	4.22	1.28	0.10	91.5	-1.28	4	67 04 18.37	C1.5	N	14.77	0.77	0.10	94.0	-0.76
1	71 11 28.37	S2.3	B	21.73	0.92	0.02	1.2	0.92	4	67 06 09.29	C1.5	I	13.51	0.62	0.07	81.0	-0.59
1	71 12 30.41	C1.5	B	15.86	0.56	0.04		-0.56	4	67 06 09.30	C1.5	R2	13.51	0.74	0.05	84.0	-0.72
1	72 01 02.40	C1.5	B	14.99	0.72	0.05		-0.72	4	67 06 09.28	C1.5	O	13.50	0.62	0.03	93.0	-0.62
1	72 02 06.42	C1.5	B	05.44	1.68	0.02	89.5	-1.68	4	67 06 09.34	C1.5	G	13.52	0.55	0.02	82.0	-0.53
1	72 04 03.14	C1.5	B	20.71	0.71	0.03	0.2	0.71	4	67 06 09.37	C1.5	B	13.54	0.58	0.02	82.0	-0.56
1	72 04 27.14	C1.5	B	23.08	1.42	0.02	1.3	1.42	4	67 06 09.35	C1.5	U	13.53	0.43	0.06	80.0	-0.40
1	72 04 27.22	C1.5	U	23.08	1.40	0.07	5.0	1.38	4	67 06 09.33	C1.5	N	13.52	0.30	0.14	82.0	-0.29
1	72 04 27.24	C1.5	G	23.08	1.30	0.03	1.3	1.30	4	71 11 28.08	C1.5	B	23.32	0.15	0.08		0.15
									4	72 08 31.53	H2.2	G	23.32	0.11	0.05		0.11
									4	72 09 06.55	H0.6	G	23.29	0.12	0.10		0.12
2	59 04 17.35	M2.1	I	11.43	1.28		90.0	-1.28	192	59 08 04.42	M2.1	R1	31.80	1.23		13.0	1.11
2	59 04 17.35	M2.1	V	11.43	1.30		86.0	-1.29	192	59 08 04.42	M2.1	V	31.80	1.15		2.0	1.15
2	59 04 17.35	M2.1	U	11.43	0.82		89.0	-0.82	192	59 08 04.42	M2.1	B	31.80	1.20		7.0	1.16
2	59 04 19.28	M2.1	U	11.82	0.58		100.0	-0.54	192	59 08 04.42	M2.1	U	31.80	1.22		-14.0	1.08
2	59 08 01.19	M2.1	V	20.43	0.57		23.0	0.40	192	59 08 05.33	M2.1	V	31.71	1.01		4.0	1.00
2	59 08 03.21	M2.1	V	20.24	0.57		-2.0	0.57	192	59 08 07.43	M2.1	V	31.45	0.97		1.0	0.90
2	66 10 19.23	C1.5	I	9.48	1.23		88.9	-1.23	192	59 08 08.44	M2.1	R1	31.32	0.90		6.0	0.95
2	66 10 19.28	C1.5	R2	9.50	0.88		89.8	-0.88	192	59 08 07.43	M2.1	V	31.45	0.90		1.0	0.90
2	66 10 19.36	C1.5	G	9.52	1.35		96.6	-1.31									
2	66 10 19.31	C1.5	B	9.51	1.36		93.8	-1.35									
2	66 10 19.39	C1.5	U	9.53	0.66		79.6	-0.62									
2	66 11 15.21	C1.5	B	17.14	0.35		104.0	-0.30									
2	66 12 13.10	C1.5	I	21.45	0.66		8.0	0.63	324	72 04 17.29	C1.5	B	4.16	0.87	0.06	91.0	-0.87
2	66 12 13.13	C1.5	O	21.46	0.48		-14.0	0.42	324	72 05 05.18	C1.5	B	8.57	1.47	0.06	91.5	-1.47
2	66 12 13.14	C1.5	R2	21.46	0.42		-4.0	0.42	324	72 05 11.18	C1.5	B	10.07	1.41	0.11	88.0	-1.41
2	66 12 13.18	C1.5	U	21.47	0.57		2.0	0.57	324	72 06 11.21	C1.5	B	15.62	1.09	0.14	92.0	-1.09
2	66 12 13.22	C1.5	G	21.48	0.22		-3.0	0.22	324	72 06 22.21	S2.3	B	16.55	1.00	0.18	92.0	-1.00
2	66 12 13.23	C1.5	B	21.49	0.47		0.0	0.47									
2	71 11 28.30	S2.3	B	19.60	0.19	0.09	-41.0	0.03	433	68 01 05.35	C1.5	G	53.20	3.53	0.13	-2.4	3.52
2	72 04 01.14	C1.5	B	25.92	1.62	0.08	1.0	1.62	433	68 01 05.38	C1.5	B	53.20	3.88	0.17	2.4	3.88
									433	68 01 05.42	C1.5	U	53.20	8.17	0.74	14.5	7.91
3	66 09 26.48	C1.5	B	27.48	0.75		3.5	0.74	433	68 01 05.52	C1.5	R2	53.20	3.49	0.24	2.0	3.48
3	66 10 18.44	C1.5	B	28.70	0.79		4.0	0.78	433	68 01 05.55	C1.5	O	53.20	2.68	0.23	0.7	2.68
3	66 10 18.46	C1.5	U	28.70	0.91	0.17	11.6	0.84	433	68 01 06.36	C1.5	R2	53.10	2.52	0.28	0.2	2.52
3	66 10 18.50	C1.5	G	28.70	0.69	0.11	14.6	0.60	433	68 01 06.38	C1.5	O	53.10	3.30	0.42	0.8	3.30
3	66 10 19.42	C1.5	B	28.71	0.84	0.06	7.0	0.82	433	68 01 06.44	C1.5	U	53.10	5.43	0.36	-1.6	5.43
3	66 10 19.46	C1.5	I	28.71	0.85	0.22	-20.0	0.65	433	68 01 06.47	C1.5	B	53.10	3.75	0.10	-1.1	3.75
3	66 10 19.48	C1.5	O	28.71	0.90	0.23	8.0	0.87	433	68 01 06.50	C1.5	G	53.10	3.10	0.12	-2.4	3.09
3	66 10 19.50	C1.5	R2	28.71	0.65	0.12	7.0	0.63	433	68 01 06.53	C1.5	U	53.10	5.53	0.34	-3.0	5.53
3	66 11 16.39	C1.5	O	27.24	0.60	0.17	-3.0	0.60	433	72 06 20.46	S2.3	B	32.92	1.08	0.16		1.08
3	66 11 16.41	C1.5	R2	27.24	0.40	0.18	4.0	0.40	433	72 07 08.58	H2.2	B	28.94	1.10	0.08	-8.0	1.09
3	66 11 16.43	C1.5	I	27.24	1.11	0.20	8.0	1.07	433	72 07 25.51	H2.2	B	22.59	0.07	0.09	-3.9	0.07
3	66 11 16.46	C1.5	G	27.23	0.85	0.08	-2.0	0.85	433	72 08 03.55	H2.2	G	17.82	0.17	0.12	106.1	-0.14
3	66 11 16.48	C1.5	B	27.23	0.71	0.08	-4.0	0.70	433	72 08 03.55	H2.2	G	17.81	0.39	0.17	103.2	-0.34
3	66 12 14.50	C1.5	G	21.47	0.37	0.09	10.0	0.35	433	72 08 09.35	H2.2	B	14.36	0.23	0.08	93.0	-0.23
3	67 01 01.48	C1.5	B	15.09	0.49	0.04	82.0	-0.47	433	72 08 09.34	H2.2	B	14.36	0.16	0.06	72.7	-0.15
3	67 01 30.30	C1.5	I	6.83	0.69	0.19	94.0	-0.68	433	72 08 20.43	H2.2	B	8.45	0.75	0.06	91.9	-0.75
3	67 01 30.33	C1.5	R2	6.83	0.84	0.09	97.0	-0.81	433	72 08 31.39	H2.2	B	8.94	0.66	0.31		-0.66
3	67 01 30.35	C1.5	O	6.84	0.57	0.12	101.0	-0.53									
3	67 01 30.39	C1.5	G	6.84	0.73	0.07	98.0	-0.70	511	72 08 09.31	H2.2	B	4.73	1.06	0.05	93.3	-1.06
3	67 01 30.42	C1.5	N	6.85	1.07	0.40	109.0	-0.84									
3	67 01 30.44	C1.5	B	6.85	0.77	0.15	94.0	-0.76	877	69 11 05.29	C1.5	B	21.22	0.08	0.02	0.0	0.08
3	67 02 08.42	C1.5	B	8.86	1.16	0.09	94.0	-1.15	877	69 12 08.27	S2.3	B	36.77	2.24	0.17	-0.3	2.24
3	69 03 13.51	C1.5	B	17.09	0.41	0.11	102.9	-0.37	877	70 01 21.27	C1.5	B	43.30	3.17	0.11	-5.7	3.11
3	69 04 13.37	C1.5	B	17.99	0.10	0.28	90.8	-0.10									
3	71 11 28.53	S2.3	B	17.81	0.21	0.07	81.0	-0.20	1036	72 08 20.60	H2.2	B	42.04	3.92	0.04	-1.2	3.92
3	72 04 01.18	C1.5	B	2.33	0.56	0.07	88.0	-0.56									

^a Telescopes are indicated by the aperture in meters preceded by one of the following symbols: C, Catalina Station, Lunar and Planetary Laboratory, University of Arizona; H, Mauna Kea Observatory, University of Hawaii; M, McDonald Observatory; P, Palomar Mt., Hale Observatories (observations by K. Serkowski); S, Steward Observatory, University of Arizona.

^b Approximate effective wavenumbers in μm^{-1} are as follows: I, 1.05; R2, 1.20; R1, 1.46; O, 1.55; V, 1.79; G, 1.93; B, 2.30; U, 2.76; and N, 3.00.

^c The internal errors where computed refer to the mean deviation from a $\cos 2\theta$ curve, and are not directly comparable with the error quantities listed in Table III.

^d A blank indicates that the Wollaston prism was oriented at the precomputed angle of maximum polarization.

for the 1.5-m Catalina reflector and $\leq 0.02\%$ for the 2.3-m reflector of Steward Observatory.

The absolute calibration of polarization position angles at any telescope is provided by a precisely fabricated rotatable reticle, also used as an offset guider

TABLE III. Observations with the new photon-counting Wollaston polarimeter, in which the polarization modulation is provided by a rapidly spinning achromatic half-wave plate. Symbols are as in Table II.

Ast. No.	Date (UT)	Tel.	Filt.	Phase	P %	ϵ_p^a %	ϵ_r	P_r %
1	73 04 06.45	C1.5	B	18.67	0.12	0.03	0.5	0.12
1	73 04 06.46	C1.5	G	18.67	0.15	0.05	8.1	0.14
1	73 04 13.44	S2.3	B	17.31	0.23	0.01	91.1	-0.23
1	73 04 13.44	S2.3	G	17.31	0.20	0.02	88.9	-0.20
1	73 04 22.37	C1.5	B	15.11	0.80	0.04	89.9	-0.80
1	73 04 22.38	C1.5	G	15.11	0.74	0.03	89.7	-0.74
1	73 05 02.39	C1.5	G	12.05	1.22	0.06	90.0	-1.22
1	73 05 02.39	C1.5	B	12.05	1.29	0.04	90.1	-1.29
1	73 05 02.39	C1.5	U	12.05	1.18	0.12	89.7	-1.18
1	73 05 08.39	S2.3	U	9.95	1.84	0.07	90.5	-1.84
1	73 05 08.39	S2.3	G	9.95	1.60	0.04	90.5	-1.60
1	73 05 08.40	S2.3	B	9.95	1.66	0.03	91.0	-1.66
1	73 05 11.28	S2.3	G	8.88	1.62	0.02	92.2	-1.62
1	73 05 11.29	S2.3	B	8.88	1.62	0.04	91.8	-1.62
1	73 05 13.38	C1.5	B	8.08	1.67	0.04	89.5	-1.67
1	73 05 13.38	C1.5	G	8.08	1.64	0.04	89.2	-1.64
1	73 05 14.36	C1.5	B	7.69	1.72	0.04	88.9	-1.72
1	73 05 14.37	C1.5	G	7.69	1.66	0.05	89.6	-1.66
1	73 06 02.37	C1.5	B	1.11	0.56	0.03	90.5	-0.56
1	73 06 02.38	C1.5	G	1.11	0.63	0.04	91.6	-0.63
1	73 06 03.36	C1.5	B	1.30	0.69	0.03	91.9	-0.69
1	73 06 03.36	C1.5	G	1.30	0.67	0.02	90.0	-0.67
1	73 06 11.34	S0.5	G	4.33	1.44	0.07	90.0	-1.44
1	73 06 11.35	S0.5	B	4.33	1.50	0.13	89.2	-1.50
1	73 06 26.17	C1.5	B	9.96	1.53	0.06	89.8	-1.53
1	73 06 26.17	C1.5	G	9.96	1.58	0.04	89.9	-1.58
1	73 06 26.18	C1.5	U	9.97	1.51	0.15	89.9	-1.51
1	73 08 22.14	C1.5	G	20.60	0.64	0.05	2.2	0.64
2	73 04 06.40	C1.5	B	14.79	0.71	0.03	94.7	-0.70
2	73 04 13.17	S2.3	G	13.97	0.82	0.03	92.2	-0.82
2	73 04 13.18	S2.3	B	13.97	0.83	0.02	91.4	-0.83
2	73 04 22.34	C1.5	B	13.48	0.89	0.03	94.5	-0.88
2	73 06 03.32	C1.5	B	17.59	0.15	0.04	92.7	-0.15
2	73 06 14.38	C1.5	B	18.82	0.10	0.03	1.4	0.10
2	73 08 07.23	S2.3	G	19.85	0.42	0.07	-0.1	0.42
2	73 08 22.21	S2.3	G	18.88	0.16	0.09	11.5	0.15
2	73 08 26.22	C1.5	G	18.55	0.13	0.08	-10.9	0.12
2	74 04 22.48	C1.5	G	17.35	0.17	0.12	84.8	-0.17
3	73 04 06.44	C1.5	B	15.97	0.37	0.10	121.3	-0.17
3	73 04 13.22	S2.3	B	15.12	0.51	0.13	90.9	-0.51
3	73 05 15.39	C1.5	G	8.79	0.74	0.16	88.5	-0.74
3	73 07 31.29	S2.3	G	16.13	0.38	0.17	82.0	-0.37
3	73 08 08.24	S2.3	G	17.09	0.29	0.11	92.6	-0.29
4	73 04 06.14	C1.5	G	20.12	0.06	0.07	90.8	-0.06
4	73 04 06.15	C1.5	B	20.12	0.03	0.03	89.6	-0.03
4	73 04 13.16	S2.3	G	19.24	0.21	0.04	91.1	-0.21
4	73 10 25.51	C1.5	B	17.77	0.26	0.04	87.8	-0.26
4	73 10 25.53	C1.5	G	17.77	0.24	0.07	86.1	-0.23
4	73 10 27.52	S0.5	G	18.29	0.26	0.13	89.9	-0.26
4	73 12 10.54	S2.3	B	23.83	0.16	0.02	0.2	0.16
4	73 12 10.55	S2.3	G	23.83	0.13	0.02	0.1	0.13
4	73 12 28.56	C1.5	B	24.84	0.21	0.03	0.2	0.21
4	73 12 28.57	C1.5	G	24.84	0.18	0.06	0.2	0.18
4	73 12 28.58	C1.5	U	24.84	0.26	0.06	0.3	0.26
4	73 12 30.49	C1.5	G	24.84	0.21	0.05	0.2	0.21
4	73 12 30.50	C1.5	B	24.84	0.23	0.05	0.2	0.23
4	73 12 30.52	C1.5	U	24.84	0.26	0.14	0.3	0.26
4	73 12 30.53	C1.5	F	24.84	0.23	0.06	0.2	0.23
4	73 12 30.53	C1.5	G	24.84	0.19	0.05	0.2	0.19
4	74 02 22.35	C1.5	G	17.81	0.28	0.02	91.2	-0.28
4	74 02 22.36	C1.5	B	17.80	0.22	0.01	95.1	-0.22
4	74 02 22.38	C1.5	U	17.80	0.28	0.02	94.6	-0.28
4	74 04 01.38	C1.5	U	5.58	0.56	0.01	93.4	-0.56
4	74 04 01.39	C1.5	R2	5.58	0.70	0.08	93.7	-0.69
4	74 04 05.38	C1.5	U	5.91	0.68	0.02	84.0	-0.67
4	74 04 05.40	C1.5	I	5.95	0.74	0.05	86.5	-0.73
4	74 04 05.42	C1.5	R2	5.05	0.80	0.01	84.8	-0.79
4	74 04 05.44	C1.5	O	5.95	0.79	0.02	86.1	-0.78
4	74 04 10.22	S2.3	U	7.55	0.66	0.05	91.9	-0.66
4	74 04 10.20	S2.3	R2	7.55	0.71	0.07	90.6	-0.71
5	73 08 08.39	S2.3	B	21.81	0.33	0.15	-21.4	0.24
5	73 08 08.41	S2.3	G	21.81	0.27	0.20	-17.0	0.22
5	73 08 22.42	S2.3	B	21.22	0.21	0.14	3.2	0.21
5	73 09 19.45	C1.5	B	16.88	0.21	0.14	84.2	-0.21
5	73 09 19.48	C1.5	G	16.87	0.20	0.14	94.0	-0.20
5	73 10 07.30	S2.3	G	11.42	0.60	0.11	90.4	-0.60
5	73 10 07.31	S2.3	B	11.42	0.63	0.12	91.5	-0.63
5	73 12 07.24	S2.3	B	15.89	0.36	0.08	85.2	-0.36
5	73 12 07.25	S2.3	G	15.89	0.32	0.10	87.5	-0.32
5	73 12 28.26	C1.5	B	21.39	0.23	0.15	0.2	0.23
5	73 12 29.23	C1.5	G	21.57	0.27	0.16	-0.4	0.27
5	73 12 29.25	C1.5	B	21.57	0.33	0.15	-1.4	0.32
5	74 01 29.14	C1.5	B	24.44	0.48	0.15	-0.8	0.48
5	74 01 29.14	C1.5	G	24.44	0.46	0.18	-0.9	0.46
6	73 10 25.49	C1.5	G	24.07	0.30	0.15	-3.5	0.30
6	73 12 28.50	C1.5	B	16.42	0.37	0.08	94.8	-0.37
6	73 12 28.53	C1.5	G	16.41	0.39	0.08	85.6	-0.39
6	74 01 19.42	C1.5	G	8.44	0.80	0.07	88.7	-0.80
6	74 01 19.43	C1.5	B	8.43	0.82	0.06	90.6	-0.82
6	74 02 22.31	C1.5	B	7.76	0.75	0.02	92.4	-0.75
6	74 02 22.33	C1.5	G	7.77	0.75	0.02	92.5	-0.75
6	74 04 01.20	C1.5	B	19.28	0.06	0.17	92.4	-0.06
6	74 04 01.22	C1.5	G	19.28	0.13	0.04	91.9	-0.13
6	74 04 22.20	C1.5	B	21.42	0.03	0.12	17.8	0.02
6	74 04 22.22	C1.5	G	21.42	0.02	0.17	-4.8	0.02
6	74 04 26.25	C1.5	B	21.56	0.11	0.11	13.5	0.10
7	73 09 12.44	C1.5	B	32.72	1.54	0.06	0.0	1.54
7	73 09 12.46	C1.5	G	32.72	1.37	0.05	0.0	1.37
7	73 09 12.48	C1.5	U	32.72	1.98	0.21	0.8	1.98
7	73 10 06.51	S2.3	G	32.23	1.22	0.06	-1.2	1.22
7	73 10 06.52	S2.3	U	32.23	1.93	0.31	-1.4	1.93
7	73 10 07.45	S2.3	U	32.15	1.75	0.10	0.6	1.75
7	73 10 07.45	S2.3	B	32.15	1.30	0.05	0.9	1.30
7	73 10 07.47	S2.3	G	32.15	1.20	0.06	1.2	1.20
7	73 10 07.52	S2.3	R2	32.14	1.18	0.26	2.9	1.18
7	73 10 27.45	S0.5	G	29.32	0.87	0.16	0.7	0.87
7	73 10 31.25	S0.5	G	28.46	0.85	0.24	-0.3	0.85
7	73 11 04.39	S2.3	G	27.33	0.56	0.08	3.4	0.56
7	73 11 04.40	S2.3	B	27.33	0.72	0.05	-1.5	0.72
7	73 12 07.28	S2.3	G	13.42	0.62	0.02	91.3	-0.62
7	73 12 07.29	S2.3	R	13.41	0.58	0.02	94.4	-0.58
7	73 12 07.30	S2.3	U	13.41	0.48	0.08	91.1	-0.48
7	73 12 28.33	C1.5	B	1.64	0.38	0.04	89.0	-0.38
7	73 12 28.34	C1.5	G	1.64	0.36	0.04	88.5	-0.36
7	73 12 28.34	C1.5	U	1.64	0.36	0.08	86.8	-0.36
7	74 01 16.40	C1.5	G	11.03	0.68	0.07	90.7	-0.68
7	74 01 16.41	C1.5	U	11.04	0.80	0.10	89.4	-0.80
7	74 01 16.42	C1.5	B	11.04	0.68	0.05	90.7	-0.68
7	74 01 29.20	C1.5	G	17.00	0.37	0.04	90.8	-0.37
7	74 01 29.20	C1.5	B	17.00	0.36	0.02	87.1	-0.36
7	74 01 30.30	C1.5	B	17.44	0.31	0.04	91.9	-0.31
7	74 01 30.31	C1.5	G	17.44	0.30	0.06	87.6	-0.30
7	74 02 02.25	C1.5	U	18.57	0.13	0.15	100.2	-0.12
7	74 02 02.27	C1.5	G	18.58	0.25	0.05	91.9	-0.25
7	74 02 22.27	C1.5	U	24.11	0.85	0.10	-7.9	0.82
7	74 02 22.29	C1.5	B	24.11	0.41	0.02	0.1	0.41
7	74 02 22.30	C1.5	G	24.12	0.31	0.03	-0.6	0.31
7	74 04 01.14	C1.5	U	26.90	1.04	0.28	5.4	1.02
7	74 04 01.16	C1.5	G	26.90	0.64	0.04	0.9	0.64
8	73 04 06.38	C1.5	B	4.58	0.54	0.10	90.2	-0.54
8	73 04 06.39	C1.5	G	4.58	0.66	0.05	86.0	-0.65
8	73 04 13.36	S2.3	G	3.93	0.54	0.03	89.5	-0.54
8	73 04 13.36	S2.3	B	3.93	0.57	0.05	91.8	-0.57
8	73 05 02.35	C1.5	G	10.37	0.57	0.14	90.4	-0.57
8	73 05 02.35	C1.5	B	10.37	0.54	0.10	91.0	-0.54
8	73 06 04.21	C1.5	B	20.29	0.04	0.12	-40.0	0.01
8	73 06 04.21	C1.5	G	20.29	0.03	0.10	10.8	0.03
8	73 07 22.23	P1.5	B	23.29	0.42	0.25	9.7	0.40
8	73 07 23.19	P1.5	B	23.24	0.40	0.13	-7.8	0.39
8	73 07 23.20	P1.5	G	23.				

MINOR PLANETS. XVI.

1103

TABLE III (continued)

Ast. No.	Date (UT)	Tel.	Filt.	Phase	P %	ϵ_p^a %	θ_r	P_r %	Ast. No.	Date (UT)	Tel.	Filt.	Phase	P %	ϵ_p^a %	θ_r	P_r %
20	74 04 22.36	C1.5	G	6.21	0.63	0.10	88.8	-0.63	63	73 08 26.25	C1.5	B	19.99	0.05	0.11	6.2	0.05
20	74 04 22.38	C1.5	B	6.20	0.72	0.10	88.8	-0.72	63	73 08 26.27	C1.5	G	20.00	0.01	0.16	0.0	0.01
21	73 05 02.45	C1.5	B	24.69	0.07	0.14	6.1	0.07	63	73 10 07.13	S2.3	G	26.98	0.89	0.11	-1.2	0.89
21	73 05 08.44	S2.3	B	23.81	0.16	0.11	85.3	-0.16	63	73 10 07.15	S2.3	G	26.98	0.76	0.12	-1.7	0.76
21	73 05 14.41	C1.5	G	22.69	0.30	0.24	94.7	-0.30	63	73 10 08.19	S2.3	G	27.02	0.68	0.13	-1.2	0.68
21	73 05 15.42	C1.5	G	22.47	0.28	0.20	78.0	-0.26	85	73 08 26.42	C1.5	B	16.94	0.41	0.10	88.5	-0.41
21	73 05 15.44	C1.5	B	22.46	0.41	0.24	88.9	-0.41	85	73 09 19.38	C1.5	G	6.00	1.21	0.06	91.2	-1.21
21	73 06 27.40	C1.5	R	5.95	1.09	0.08	89.9	-1.09	89	73 12 31.29	C1.5	G	7.32	0.84	0.16	90.2	-0.84
21	73 06 27.40	C1.5	G	5.95	1.16	0.08	89.6	-1.16	89	73 12 31.45	C1.5	B	7.25	0.87	0.14	89.1	-0.87
21	73 08 08.30	S2.3	B	16.46	1.04	0.08	89.5	-1.04	89	74 01 16.44	C1.5	G	2.89	0.52	0.09	90.8	-0.52
21	73 08 08.31	S2.3	G	16.47	0.99	0.07	90.1	-0.99	139	74 04 05.32	C1.5	G	3.77	0.81	0.05	96.3	-0.79
21	73 08 22.24	S2.3	B	21.76	0.40	0.08	88.6	-0.40	139	74 04 05.35	C1.5	B	3.78	0.82	0.07	90.8	-0.82
21	73 09 19.18	C1.5	B	27.78	0.51	0.12	1.1	0.51	139	74 04 10.25	S2.3	B	6.23	1.11	0.10	90.4	-1.11
21	73 09 19.21	C1.5	G	27.79	0.64	0.20	2.2	0.64	139	74 04 22.26	C1.5	B	15.62	1.26	0.14	88.7	-1.26
21	73 09 24.15	C1.5	G	28.32	0.69	0.13	3.0	0.69	139	74 04 22.28	C1.5	G	11.84	1.18	0.14	90.9	-1.18
21	73 09 24.18	C1.5	B	28.32	0.71	0.20	-0.4	0.71	141	73 08 23.34	C1.5	B	15.75	1.38	0.09	93.1	-1.37
21	73 10 08.13	S2.3	B	29.12	0.79	0.14	-0.6	0.79	141	73 08 26.39	C1.5	B	14.58	1.51	0.16	90.5	-1.51
21	73 10 08.15	S2.3	G	29.12	0.75	0.12	0.8	0.75	141	73 09 12.30	C1.5	B	8.17	1.66	0.12	89.0	-1.66
22	74 04 22.41	C1.5	B	10.27	0.91	0.17	90.6	-0.91	141	73 09 19.28	C1.5	B	6.84	1.43	0.09	90.1	-1.43
23	73 04 13.34	S2.3	B	7.37	0.70	0.03	90.6	-0.70	141	73 10 08.23	S2.3	G	11.56	1.78	0.10	89.2	-1.78
23	73 04 13.35	S2.3	G	7.37	0.76	0.07	91.0	-0.76	141	73 10 08.25	S2.3	G	11.57	1.72	0.10	89.2	-1.72
23	73 04 22.29	C1.5	B	10.32	0.64	0.08	87.0	-0.64	141	73 10 08.27	S2.3	U	11.57	1.44	0.32	90.2	-1.44
23	73 05 08.30	S2.3	B	15.91	0.35	0.11	88.0	-0.35	141	73 10 08.31	S2.3	R2	11.59	1.76	0.38	86.5	-1.75
23	73 05 11.25	S2.3	B	16.82	0.26	0.07	99.5	-0.25	141	73 10 24.19	C1.5	G	17.82	0.89	0.20	86.0	-0.88
23	73 05 11.26	S2.3	G	16.82	0.34	0.09	87.4	-0.34	141	73 10 24.19	C1.5	B	17.82	0.94	0.12	91.5	-0.94
23	73 05 13.27	C1.5	B	17.40	0.23	0.13	90.1	-0.23	141	73 10 25.09	C1.5	B	18.22	0.82	0.09	88.0	-0.82
23	73 06 04.17	C1.5	G	22.04	0.20	0.15	5.9	0.20	141	73 10 26.21	C1.5	G	18.30	0.73	0.17	88.5	-0.73
23	73 06 04.19	C1.5	B	22.04	0.26	0.16	3.2	0.26	141	73 11 04.31	S2.3	B	21.41	0.07	0.10	-29.8	0.04
23	73 06 27.21	C1.5	B	23.84	0.38	0.19	0.6	0.38	141	73 11 16.18	C1.5	B	24.28	0.95	0.16	-1.4	0.95
27	73 04 13.30	S2.3	B	27.53	0.76	0.19	1.0	0.76	141	73 12 07.18	S2.3	B	27.11	2.14	0.16	2.1	2.13
27	73 04 22.22	C1.5	B	27.95	0.79	0.14	-0.9	0.79	141	73 12 07.21	S2.3	G	27.12	2.15	0.21	2.1	2.14
27	73 05 08.16	S2.3	B	27.93	0.74	0.06	0.6	0.74	141	73 12 29.12	C1.5	B	27.64	2.15	0.32	1.0	2.15
31	74 04 10.44	S2.3	B	9.41	1.28	0.25	89.0	-1.28	141	73 12 29.16	C1.5	G	27.64	2.23	0.27	-1.0	2.13
31	74 04 10.46	S2.3	G	9.41	1.24	0.26	90.4	-1.24	324	73 04 06.50	C1.5	G	20.24	0.15	0.03	-7.5	0.14
39	73 06 14.42	C1.5	G	22.63	0.15	0.20	9.0	0.14	324	73 04 06.51	C1.5	B	20.24	0.10	0.17	1.6	0.10
39	73 06 14.44	C1.5	B	22.63	0.26	0.14	-7.0	0.25	324	73 04 22.45	C1.5	B	19.08	0.41	0.35	103.7	-0.36
39	73 06 26.44	C1.5	B	21.29	0.03	0.13	-6.0	0.03	324	73 08 08.18	S2.3	B	20.53	0.02	0.15	80.6	-0.02
39	73 06 26.44	C1.5	G	21.29	0.06	0.18	-43.0	0.00	324	73 08 08.20	S2.3	G	20.53	0.05	0.10	39.1	0.01
39	73 07 23.43	P1.5	B	14.93	0.47	0.05	87.3	-0.47	324	73 08 22.16	S2.3	B	23.75	1.19	0.14	0.4	1.19
39	73 07 23.44	P1.5	G	14.93	0.47	0.08	90.6	-0.47	324	73 08 22.18	S2.3	G	23.75	1.12	0.15	2.3	1.12
39	73 08 08.32	S2.3	G	8.88	0.76	0.06	89.6	-0.76	324	73 08 26.19	C1.5	B	24.46	1.83	0.23	-0.9	1.53
39	73 08 08.33	S2.3	B	8.87	0.74	0.05	90.5	-0.74	324	73 08 27.19	C1.5	B	24.62	1.47	0.27	-0.5	1.47
39	73 08 26.29	C1.5	B	0.69	0.29	0.05	84.3	-0.28	324	73 08 28.14	C1.5	B	24.76	1.68	0.37	-16.8	1.40
39	73 08 26.33	C1.5	G	0.68	0.27	0.07	89.4	-0.27	349	74 03 26.30	C1.5	B	9.56	0.37	0.18	94.4	-0.37
39	73 09 12.25	C1.5	B	7.48	0.57	0.08	88.9	-0.57	349	74 03 26.31	C1.5	B	9.56	0.32	0.13	92.2	-0.32
39	73 09 12.26	C1.5	G	7.49	0.68	0.06	89.1	-0.68	349	74 04 01.27	C1.5	B	11.33	0.40	0.04	93.9	-0.40
39	73 10 24.15	C1.5	G	20.96	0.04	0.11	52.0	-0.01	349	74 04 01.29	C1.5	G	11.33	0.38	0.06	95.9	-0.37
39	73 10 24.14	C1.5	B	20.96	0.06	0.09	10.2	0.06	511	73 07 31.44	S2.3	B	19.33	0.11	0.08	95.6	-0.09
39	73 10 25.15	C1.5	B	21.17	0.10	0.08	4.5	0.10	511	73 07 31.45	S2.3	G	19.33	0.10	0.17	32.0	0.04
39	73 10 25.17	C1.5	G	21.17	0.08	0.09	35.4	0.03	511	73 08 06.42	S2.3	B	18.96	0.13	0.08	91.2	-0.13
39	73 10 31.32	S0.5	G	22.08	0.22	0.34	5.8	0.22	511	73 08 06.45	S2.3	G	18.95	0.19	0.09	87.2	-0.19
39	73 11 16.11	C1.5	G	23.47	0.24	0.09	-5.2	0.24	511	73 08 22.36	S2.3	B	17.22	0.55	0.15	89.6	-0.55
39	73 11 16.13	C1.5	B	23.47	0.30	0.08	0.2	0.30	511	73 08 22.38	S2.3	G	17.22	0.61	0.13	90.2	-0.61
40	73 06 14.46	C1.5	B	26.36	0.73	0.26	-10.5	0.68	511	73 08 23.39	C1.5	G	17.07	0.70	0.14	96.5	-0.68
40	73 06 14.47	C1.5	G	26.36	0.60	0.34	-16.5	0.50	511	73 08 23.41	C1.5	B	17.07	0.57	0.16	88.4	-0.57
40	73 06 26.47	C1.5	G	24.76	0.50	0.23	-1.4	0.50	511	73 08 27.40	C1.5	B	16.45	0.78	0.17	91.1	-0.78
40	73 06 27.43	C1.5	B	24.59	0.42	0.11	3.1	0.42	511	73 08 27.44	C1.5	G	16.44	0.70	0.20	90.1	-0.70
40	73 06 27.44	C1.5	G	24.59	0.39	0.19	1.6	0.39	511	73 09 27.38	C1.5	B	13.39	1.23	0.17	91.6	-1.23
40	73 07 23.47	P1.5	B	17.43	0.32	0.09	89.0	-0.32	511	73 09 19.41	C1.5	B	11.83	1.48	0.12	90.4	-1.48
40	73 07 23.48	P1.5	G	17.42	0.33	0.08	92.3	-0.33	511	73 10 07.27	S2.3	B	8.47	1.66	0.09	83.7	-1.66
40	73 07 31.36	S2.3	B	14.22	0.55	0.07	90.4	-0.55	511	73 10 24.28	C1.5	B	8.91	1.67	0.09	86.1	-1.65
40	73 07 31.38	S2.3	G	14.22	0.59	0.07	87.1	-0.59	511	73 10 30.09	S0.5	G	9.98	1.41	0.57	90.9	-1.41
40	73 08 08.37	S2.3	B	10.58	0.74	0.06	91.2	-0.74	511	73 12 28.23	C1.5	B	20.57	0.20	0.13	9.2	0.20
40	73 08 08.35	S2.3	G	10.59	0.74	0.07	89.7	-0.74	511	73 12 29.22	C1.5	G	20.52	0.24	0.19	9.0	0.24
40	73 08 22.30	S2.3	B	4.13	0.63	0.06	89.7	-0.63	511	74 01 16.14	C1.5	B	20.38	0.16	0.25	-20.6	0.12
40	73 08 22.31	S2.3	G	4.13	0.65	0.06	90.2	-0.65	532	73 04 13.32	S2.3	B	19.89	0.02	0.03	98.0	-0.02
40	73 10 07.21	S2.3	G	19.79	0.10	0.05	111.3	-0.07	532	73 04 22.33	C1.5	B	21.98	0.18	0.08	4.9	0.18
40	73 10 07.23	S2.3	B	19.80	0.14	0.09	83.3	-0.14	532	73 05 08.22	S2.3	B	24.63	0.48	0.05	-0.4	0.48
42	74 03 26.40	C1.5	G	11.92	0.47	0.05	89.9	-0.47	532	73 05 11.15	S2.3	B	24.97	0.59	0.09	-2.1	0.59
42	74 03 26.41	C1.5	B	11.90	0.41	0.23	90.5	-0.41	532	73 05 13.17	C1.5	B	25.19	0.64	0.09	0.2	0.64
42	74 04 22.32	C1.5	G	4.63	0.62	0.17	91.9	-0.62	532	73 06 03.15	C1.5	B	26.33	0.70	0.10	1.4	0.70
42	74 04 22.32	C1.5	B	4.63	0.63	0.1											

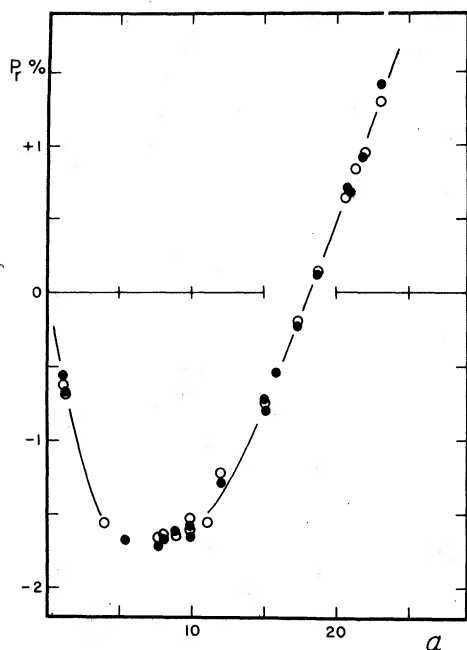


FIG. 1. Polarization as a function of solar phase angle for 1 Ceres. Filled circles represent observations in blue light; open circles in the green or visual.

polarized solar system objects. The two calibration methods are found to agree within $\pm 0.1^\circ$.

In all asteroid data we find the polarization to be either "positive" or "negative" within our error limits; that is, the dominant electric vector is, respectively, either perpendicular to or contained in the Sun-asteroid-Earth plane. When the measured polarization is comparable to or smaller than the photon noise level, its magnitude is inflated and its position angle becomes untrustworthy. In the data listed here this effect is corrected statistically and the polarization sign is defined by the reduction $P_r = P_{\text{obs}} \cos 2\theta_r$, where θ_r is the angle between the observed position angle and the normal to the plane of scattering.

Figure 1 illustrates the polarization-phase curve for (1) Ceres, one of the best-observed asteroids to date. While no two objects have been found to exhibit identical curves, the Ceres data are typical in showing a rapid drop to negative polarizations at small phase angles and a rather flat minimum followed by a nearly linear ascending branch. The observations tend to be remarkably smooth and reproducible from night to night and from year to year. Apparently genuine scatter on the order of $\pm 0.1\%$ was found for a few objects with large-amplitude lightcurves, notably (7) Iris, (39) Laetitia, and (433) Eros, but possible rotation and aspect effects are not specifically identified in the data reported here.

The polarimetric parameters of primary interest are the depth P_{min} of the negative branch (thought of as a positive quantity), the inversion angle α_0 where the polarization changes sign, and the slope h , usually

measured in percent per degree of the ascending branch at the inversion angle. In this survey the quantities h and α_0 are found by a least-squares fit to data points at phase angles larger than 15° , using either a straight line or a parabola as seems appropriate. The curvature invariably is found to be small. P_{min} is estimated by inspection from observations between 5° and 11° phase.

The polarimetric results are summarized in Tables IV-VII. In many cases the listed parameters are provisional and based on data that still are incomplete. Especially well-determined quantities are given with an exclamation mark (!), while noisy or discordant data are indicated by a colon (:), and results from fragmentary data are given with a question mark (?).

The determination of asteroid diameters from polarimetric and radiometric data (Sec. III) requires accurate absolute magnitudes and colors. Table VIII was constructed for this purpose and includes all objects for which B , V photometry could be found and for which radiometric or polarimetric data are known to exist.

A distinctly bimodal character of the asteroid $B-V$ distribution is revealed in Fig. 2. As shown in Sec. III, a similar bimodality is seen in polarimetric quantities.

TABLE IV. Asteroid polarimetric parameters measured in the blue filter.

Object	$P_{\text{min}}\%$	Ascending branch ^a				Blue albedo
		N	$\epsilon\%$	α_0	Slope	
1 Ceres	1.70!	9	0.04	18.3!	0.255!	0.065
2 Pallas	1.40?	9	0.06	18.8	0.191	0.087
3 Juno	0.75!	9	0.05	20.1!	0.096!	0.173
4 Vesta	...	8	0.02	21.2!	0.064!	0.258
5 Astraea	0.70?	7	0.04	19.2:	0.099:	0.168
6 Hebe	0.80	4	0.04	20.6	0.083	0.199
7 Iris	0.70	6	0.05	20.6!	0.102!	0.163
8 Flora	0.60!	...	...	...	...	...
9 Metis	0.75?	6	0.03	21.0	0.099	0.168
11 Parthenope	0.70!	4	0.03	20.3	0.166	0.100
12 Victoria	0.65	...	...	...	...	...
15 Eunomia	0.70?	...	...	...	...	...
17 Thetis	0.70?	6	0.06	20.4	0.127	0.131
19 Fortuna	1.65	2	...	21.9?	0.26 ?	0.064
20 Massalia	0.70	3	...	18.9	0.088	0.188
21 Lutetia	1.30?	7	0.05	24.5!	0.171!	0.097
23 Thalia	0.65?	5	0.02	19.6	0.094	0.176
31 Euphrosyne	1.25?	...	...	...	...	...
39 Laetitia	0.70:	6	0.03	20.5	0.098	0.169
40 Harmonia	0.75	5	0.02	20.8	0.104	0.160
42 Isis	0.55:	...	...	...	...	...
51 Nemausa	1.90?	...	...	...	...	...
63 Ausonia	0.60?	7	0.02	19.3!	0.120!	0.138
89 Julia	0.90?	...	...	...	...	...
139 Juewa	1.30	...	...	...	...	...
141 Lumen	1.75	8	0.07	21.4!	0.297!	0.056
324 Bamberga	1.45	9	0.09	20.6!	0.308!	0.054
349 Dembowska	0.35	...	...	...	...	...
433 Eros	0.70	5	0.16	22 :	0.121:	0.137
511 Davida	1.65	7	0.04	19.7	0.261	0.064
532 Herculina	...	6	0.03	20.2	0.118	0.141
654 Zelinda	...	3	...	21.1	0.318	0.052
887 Alinda	0.75?	4	0.12	19.1	0.127	0.131
1566 Icarus	...	5	0.16	26 ?	0.107?	0.155
1620 Geographos	...	4	0.10	20 ?	0.108?	0.154
1685 Toro	...	8	0.16	22 ?	0.130?	0.128

^a N is the number of data points fitted by a straight line or parabola for the determination of α_0 and h ; ϵ is the rms deviation from the fitted line.

TABLE V. Asteroid polarimetric parameters measured in the green filter.

Object	$P_{\min}\%$	Ascending branch				Green albedo
		N	$\epsilon\%$	α_0	Slope	
1 Ceres	1.65!	7 ^a	0.02	18.1!	0.253!	0.066
2 Pallas	1.35	10 ^a	0.09	18.2	0.213	0.078
3 Juno	0.75	5	0.15	19.5:	0.089:	0.186
4 Vesta	...	10	0.03	21.8!	0.065!	0.254
5 Astraea	0.70?	5	0.03	19.1:	0.090:	0.183
6 Hebe	0.75	4	0.02	20.8	0.087	0.190
7 Iris	0.70	11	0.04	21.1!	0.094!	0.176
8 Flora	0.60!	...	...	...	...	...
9 Metis	...	6	0.05	21.7	0.104	0.160
11 Parthenope	0.70?	...	...	...	...	...
12 Victoria	0.65?	...	...	...	...	...
15 Eunomia	0.70?	...	...	...	...	...
17 Thetis	0.60?	...	...	...	...	...
19 Fortuna	1.65	...	...	...	...	...
20 Massalia	0.65?	2	...	19.9?	0.088?	0.188
21 Lutetia	1.30?	5	0.04	24.2	0.165	0.101
23 Thalia	...	2	...	20.1?	0.103?	0.161
31 Euphrosyne	1.25?	...	...	...	...	...
39 Laetitia	0.75	7	0.04	20.9	0.094	0.177
40 Harmonia	0.75	6	0.05	20.9	0.099	0.168
42 Isis	0.55:	...	...	...	...	...
44 Nysa	...	...	...	18.1	...	...
51 Nemausa	1.95	...	...	...	...	...
63 Ausonia	0.70?	4	0.03	19.8	0.100	0.166
89 Julia	0.85?	...	...	...	...	...
139 Juewa	1.25?	...	...	...	...	...
141 Lumen	1.70?	4	0.04	20.7	0.325	0.051
324 Bamberga	...	2	...	20.2?	0.317?	0.052
349 Dembowska	0.35	...	...	...	...	...
433 Eros	...	3	0.17	20 ?	0.100?	0.166
511 Davida	1.80?	7	0.08	19.7	0.216	0.077
654 Zelinda	...	3	...	20.6	0.273	0.061
887 Alinda	0.75	...	...	...	...	...
1566 Icarus	...	4	0.13	22 ?	0.082?	0.202

^a Some data taken in the V filter are incorporated in the slope determination.

II. THE SLOPE-ALBEDO LAW

The theory of Wolff (1974), which models the polarization from intricate surfaces according to multiple Fresnel reflection within a random cloud of opaque crystal surfaces, seems very promising for interpretation of asteroid polarimetry. Until this theory is more fully developed, we depend primarily upon laboratory results and observations of astronomical objects with known properties for the calibration of empirical relationships. Experimentally, the form of the polarization-phase curve is controlled by the surface structure and opacity, fundamental parameters which are not easily measured and controlled; they combine to determine the readily measurable bulk albedo. The *Umov principle* states that for surfaces of similar structure the polarization is inversely correlated with geometric albedo. It is equivalent to the statement that all surfaces reflect the same amount of polarized light, so that differences in albedo are only differences in the unpolarized flux. This is a natural result if the polarized component comes from pure surface reflections while the unpolarized component is produced by internal turbidity and random diffraction from very fine dust particles.

TABLE VI. Asteroid polarimetric parameters measured in the V filter.

Object	$P_{\min}\%$	Ascending branch				Albedo
		N	$\epsilon\%$	α_0	Slope	
4 Vesta	0.55	...	...	...	...	...
29 Amphitrite	0.75?	...	...	...	...	...
532 Herculina	0.80	...	...	...	...	...
1620 Geographos	...	4	0.25	18?	0.074?	0.224

An empirical law of the form $\log a = -c_1 \log h + c_2$, where a is the geometric albedo of a diffusely reflecting surface and h is the polarimetric slope defined above, was first noted by Widorn (1967) and independently by KenKnight *et al.* (1967). The constants have been established by Veverka and Noland (1973), Bowell and Zellner (1974), and most recently by Bowell *et al.* (1973), from a large body of astronomical and laboratory data. The law seems to be a very general property of diffuse reflection. While genuine deviations apparently exist, *systematic* differences in its numerical form for measurements made at various optical wavelengths or for samples of different opacity, mineralogy, composition, origin, or surface structure have not been detected.

The slope-albedo law for solar-system bodies is reexamined in Table IX. The data differ from those used by Bowell *et al.* (1973) in that (1) Mercury in the ultraviolet is omitted due to its poorly known albedo; (2) for Deimos the new photometry and polarimetry by Zellner and Capen (1974) is used; and (3) revised albedos of Europa and Ganymede, from Morrison and Cruikshank (1974), are used along with improved polarization data from unpublished observations at the University of Arizona.

Table X is adapted from Bowell *et al.* but with the new parameters for solar-system objects. The mean derived value for c_1 is unity, in accordance with the strict form of the Umov law, $dP/P = -da/a$. The last two columns of Table X give the expected albedos, using the four independent sets of calibration data, for polarization slopes characteristic of the lightest and darkest asteroids yet observed. The scatter is no greater than $\pm 6\%$ of the derived albedo, i.e., no greater than $\pm 3\%$ in the implied radius. Few asteroids have absolute magnitudes known to better precision.

TABLE VII. Asteroid polarimetric parameters from the data by J. Veverka (1970), taken in white light.

Object	$P_{\min}\%$	Ascending branch				Albedo
		N	$\epsilon\%$	α_0	Slope	
4 Vesta	0.50	7	0.09	21.9	0.062	0.268
8 Flora	0.65	4	0.01	18.8	0.115	0.144
9 Metis	0.80	4	0.06	20.3	0.093	0.178
15 Eunomia	0.65	8	0.10	20.8	0.120	0.138
20 Massalia	0.6	...	...	...	...	...
89 Julia	0.9:	8	0.13	22.1:	0.119:	0.140

TABLE VIII. Adopted^a asteroid magnitudes and colors.

Asteroid No.	$B-V$	ϵ_{B-V}	$U-B$	$B(1,0)$	$V(1,0)$	Asteroid No.	$B-V$	ϵ_{B-V}	$U-B$	$B(1,0)$	$V(1,0)$
1	0.69	0.05	0.42	4.11	3.42	108	(0.94)	...	...	9.31	8.37
2	0.65	0.03	0.26	5.18	4.53	110	0.71	...	0.30	8.80	8.09
3	0.80	0.01	0.39	6.43	5.64	115	(0.82)	...	...	9.12:	8.30:
4	0.76	0.02	0.46	4.31	3.55	122	0.68	...	0.41	9.08	8.40
5	0.83	0.07	0.36	8.00	7.17	130	(0.77)	...	...	7.95:	7.18:
6	0.83	0.01	0.41	6.70	5.87	140	...	...	...	9.47:	...
7	0.81	0.02	0.45	6.84	6.03	141	(0.64)	...	...	9.65	...
8	0.87	0.06	0.45	7.54	6.67	181	(0.80)	...	...	9.05	8.25
9	0.85	0.01	0.50	7.30	6.45	192	(0.87)	...	...	8.40:	7.53:
10	0.70	0.01	0.40	6.57	5.87	196	(0.92)	...	...	7.68	6.76
11	0.80	0.06	0.38	7.78	6.98	200	(0.69)	...	...	9.44	8.75
12	(0.83)	...	...	8.81	7.98	230	(0.84)	...	...	8.61:	7.77:
13	(0.64)	...	...	7.97	7.33	268	0.69	...	0.29	9.55	8.86
14	0.81	0.00	0.38	7.41	6.60	321	0.81	...	0.44	11.38	10.57
15	0.81	0.04	0.42	6.29	5.48	324	(0.73)	...	...	8.14	7.41
16	0.70	0.01	0.24	6.89	6.19	326	(0.72)	...	...	10.13	9.41
17	0.83	0.02	0.42	8.69	7.86	335	(0.66)	...	...	10.00	9.34
18	0.82	0.03	0.35	7.79	6.97	337	(0.82)	...	...	10.05	9.23
19	(0.72:)	...	...	8.35	7.63:	341	0.92	...	...	12.64	11.72
20	0.81	...	0.43	7.48	6.67	349	0.96	...	0.55	7.29	6.33
21	(0.68:)	...	...	8.68	8.00:	354	0.93	0.00	0.54	7.56	6.63
22	0.72	0.03	0.28	7.48	6.76	356	(0.76)	...	...	9.11	8.35
23	0.87	0.04	...	8.34	7.47	380	0.72	...	...	10.61	9.89
25	0.92	0.01	0.51	9.07	8.15	402	(0.84)	...	...	9.99	9.15
27	(0.90)	...	...	8.56	7.66	409	(0.72)	...	...	8.63	7.91
29	0.84:	0.08	...	7.26:	6.42:	433	0.88	0.06	0.46	12.40	11.52
30	0.88	0.01	0.45	8.78	7.90	471	...	...	...	7.86	...
32	(0.84)	...	...	8.74	7.90	498	0.77	...	0.36	9.99	9.22
37	0.89	...	...	8.49	7.60	510	0.73	...	0.25	11.04	10.31
39	0.88	0.02	0.49	7.41	6.53	511	0.70	0.02	0.36	7.13:	6.43:
40	0.82	0.02	0.42	8.45	7.63	532	0.84	0.02	0.44	7.98:	7.14:
42	...	...	...	8.84	...	540	0.90	...	0.48	12.22	11.32
43	(0.96)	...	...	9.18	8.22	554	(0.75)	...	...	9.49	8.74
44	0.67	...	0.22	8.02	7.35	563	(0.70:)	...	...	9.57	8.87:
51	0.80	0.02	...	8.66	7.86	584	(0.90)	...	...	10.05	9.15
52	0.69	0.00	...	7.63:	6.94:	624	0.78	...	0.24	8.67	7.89
53	(0.77:)	...	...	9.81	9.04:	654	...	...	...	9.88	...
60	0.86	0.02	0.44	10.05	9.19	658	0.87	...	0.36	11.72	10.85
61	0.85	...	0.43	8.77	7.92	704	(0.70)	...	...	7.60:	6.90:
62	0.76	...	0.40	9.83:	9.07	739	(0.67:)	...	...	10.10:	9.43:
63	(0.95)	...	...	8.20	7.25	747	...	...	...	8.83	...
68	(0.84)	...	...	8.29	7.45	887	0.89	...	0.36	15.4	14.5
79	(0.90)	...	...	9.28	8.38	911	0.80	...	...	8.92	8.12
82	(0.89)	...	...	9.42	8.53	976	0.74	...	0.25	10.55	9.81
84	(0.80)	...	...	10.27	9.47	1036	...	...	...	10.86	...
85	...	...	...	8.91	...	1043	0.90	...	0.45	11.02	10.12
88	(0.68)	...	...	8.22	7.54	1212	0.69	...	0.23	8.0	7.3
89	0.83	0.03	0.43	7.84:	7.0:	1287	0.85	...	0.36	12.13	11.28
93	(0.69)	...	...	8.75	8.06	1291	0.83	...	0.39	11.46	10.63
97	(0.72)	...	...	8.67	7.95	1362	0.72	...	0.36	12.3	11.6
						1437	0.72	...	0.20	9.23	8.51
						1566	0.80	...	0.66	17.55	16.75
						1620	0.87	...	0.50	16.67	15.80
						1685	0.82	...	...	14.6:	13.8:

^a Sources include the compilations by Gehrels (1970) and Taylor (1971), the work of Veverka (1970), and published and unpublished observations at the University of Arizona. Parentheses indicate objects not observed on the UBV system; approximate $B-V$ colors were provided by C. R. Chapman from his narrow-band spectrophotometry.

We adopt for the asteroids

$$\log a = -\log h - 1.78.$$

With $V = -26.77$ and $B - V = +0.63$ for the Sun from Gehrels *et al.* (1964), asteroid radii are computed from the following equations:

$$2 \log r = 5.642 - 0.4V(1,0) - \log a_V,$$

$$2 \log r = 5.894 - 0.4B(1,0) - \log a_B,$$

$$2 \log r = 5.718 - 0.4B(1,0) + 0.28(B - V) - \log a_G,$$

where B and V are the standard filters and G indicates our polarimetric green filter.

Thus, we have a useful tool for remote determination of asteroid albedos and radii. Unlike the radiometric method, the polarimetric technique is free of modeling assumptions. It gives the geometric albedo directly, independently of any photometry of the object in question, and is not misled by rotation for nonspherical bodies of uniform albedo. Several limitations should be kept in mind, however. First, the law is an average relationship from which individual objects might deviate substantially. Also, few good laboratory measurements have been made for materials with albedos below 5%; the possibility remains that the law could saturate or become degenerate for very dark surfaces. Finally, the method is applicable only to objects that can be observed at phase angles beyond the inversion angle, which ranges from 18° to 24° for asteroids (Fig. 4). Most of the main-belt asteroids are within reach, at least at perihelic apparitions, but the method fails for Earth-based observations of the Trojans and satellites of the outer planets.

III. SURFACE STRUCTURE, ALBEDO, AND COMPOSITION

Wavelength dependencies: It may be noted in Fig. 1 and in the tables that the parameter $P_{\min}$ shows only small and irregular variations with wavelength, while especially for the redder asteroids the slopes are generally smaller at longer wavelengths. The slope effect is clearly a consequence of the Umov principle, and the rigor with which it holds may be judged by the agreement of diameters computed at two wavelengths in Table XI. Presumably the intrinsic negative-branch effect is also strongest at wavelengths where the surface is darkest. The positive-polarization effect is felt, however, even at phase angles smaller than 5° ; the two wavelength dependencies are opposite in sign and tend to cancel near 10° phase at visible wavelengths.

Surface structure: Frequency distributions of $P_{\min}$ and α_0 are plotted in Figs. 3 and 4. For all objects a well-developed negative branch is observed. The negative branch is known experimentally to result from microscopically intricate or particulate surfaces of sufficient opacity so that little light is transmitted internally across a characteristic scattering length, and has been explained by Wolff (1974) as an effect of double

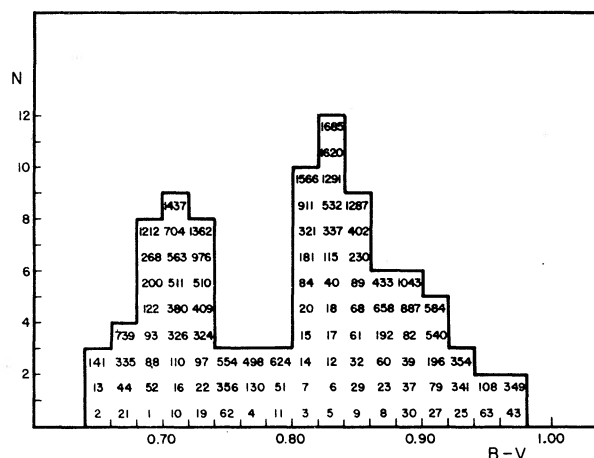


FIG. 2. The distribution of asteroid $B-V$ colors. For many objects, $B-V$ colors were synthesized from narrow-band spectrophotometry by C. R. Chapman (personal communication).

reflection in a random cloud of opaque crystal surfaces. Negative polarizations overlapping the asteroid range have been found for certain fine-grained lunar breccias (Bowell *et al.* 1972) and for some highly-opaque clean surfaces such as chips of coal (Zellner unpublished), but are not characteristic of well-consolidated surfaces. $P_{\min}$ greater than 1.4%, as seen for many asteroids, has never been found for dust-free laboratory samples. Thus we suspect, but cannot prove categorically on polarimetric grounds, that unconsolidated surface regoliths are characteristic of the asteroid population.

Albedos and Diameters: Table XI lists asteroid diameters derived from the polarimetric albedos in the last column of Tables IV–VII and the magnitudes in Table VIII. Results from data in different spectral regions are generally in good agreement. The last two columns of Table XI give visual-wavelength geometric albedos derived from the adopted diameters. The polarimetric diameters are often in good agreement with results from the radiometric method (Matson 1971; Cruikshank and Morrison 1973; Morrison 1974). However for some objects, notably (324) Bamberga and (511) Davida, the extremely low radiometric albedos are not confirmed by the polarimetry. This discrepancy is further examined by Chapman *et al.* (1975); it is a serious one and is likely to be resolved only by the

TABLE IX. The slope-albedo law for solar-system bodies.

Object	Filter	a	Slope h	$\log a$	$\log h$
Moon	U	0.072	0.230	-1.143	-0.638
	B	0.095	0.175	-1.022	-0.757
	V	0.120	0.148	-0.921	-0.830
Mercury	B	0.085	0.172	-1.071	-0.764
	V	0.104	0.147	-0.983	-0.833
Deimos	B	0.064	0.263	-1.195	-0.580
Europa	G	0.68	0.020	-0.167	-1.699
Ganymede	G	0.44	0.031	-0.357	-1.509

TABLE X. The slope-albedo law $\log a = -c_1 \log h + c_2$ for four independent sets of calibration data.

Material	Number of slopes (all wavelengths)	Albedo limits	Least squares		$c_1 = 1$ assumed		
			c_1	c_2	c_2	$a, h=0.065$	$a, h=0.30$
35 Lunar rocks and fines	135	0.05–0.50	1.05	–1.79	–1.780	0.255	0.055
72 Terrestrial samples	81	0.03–1.00	0.99	–1.66	–1.756	0.270	0.058
37 Telescopically-observed lunar regions	139	0.04–0.25	1.03	–1.80	–1.760	0.267	0.058
5 Solar-system bodies	8	0.07–0.68	0.917	–1.729	–1.809	0.239	0.052
		Straight average	1.00	–1.74	–1.78	0.258	0.056
			± 0.06		± 0.02	± 0.014	± 0.003

laboratory identification of materials that violate the known slope-albedo law, or by a third, independent means of asteroid diameter measurement.

Our diameters and those from the radiometric method are systematically about $1\frac{1}{2}$ times larger than those measured by Barnard and others (see Dollfus 1971). Following Dollfus' paper there is a lively debate on this topic. In apparent size the asteroids are close to the limit of 0.5 arcsec set by atmospheric turbulence and not by diffraction for a 1-m telescope. We believe that for the poorly defined limbs of asteroids Barnard was led to place his micrometer wires too close together, an error that would not occur for the double-star work at which he was highly skilled.

Compositional classes: Chapman *et al.* (1975) present radiometric, polarimetric, and spectrophotometric evidence for the existence of two distinct asteroid compositional classes, tentatively identified as the analogues of carbonaceous chondrites and the more refined silicate meteoritic types. The dichotomy can be seen in the

bimodalities of Figs. 2, 3, and 5, and is here demonstrated, for polarimetric parameters and for $B-V$ colors only, in Figs. 6 and 7. If we may assume that details of surface structure such as particle size do not vary greatly from asteroid to asteroid, the general trend upward to the right in both diagrams represents decreasing mineral opacity, i.e., increasing transmission through individual grains. However, we should emphasize that the wide-band photopolarimetric properties are sensitive only to broadly defined opacity classes and not to detailed mineralogical or petrological types.

A marked clustering of at least 16 objects with reddish $B-V$ near +0.85, shallow $P_{\min}$ near 0.7, and polarimetric albedo in the range 0.14–0.21 is noted. Such colors and polarizations are characteristic of many moderate-opacity silicates in powdered form (e.g., Hapke 1971; Dollfus *et al.* 1971), and some of these asteroids are known to have reflection spectra similar to those of specific siliceous meteoritic types (Chapman and Salisbury 1973). A second opacity class,

TABLE XI. Asteroid polarimetric albedos and diameters.

Object	Diameter km				Polarimetric albedo	
	Blue	Green	Other	Adopted	av	$-\log av$
1 Ceres	1043!	1058!	...	1050 —	0.068	1.17
2 Pallas	553	587	...	570 —	0.084	1.08
3 Juno	220!	225!	...	222	0.197	0.70
4 Vesta	478!	504!	490	490	0.278	0.56
5 Astraea	109:	111:	...	110	0.196	0.71
6 Hebe	181	198	...	190	0.218	0.66
7 Iris	188!	192!	...	190	0.188	0.72
8 Flora	...	...	156	156	0.155	0.81
9 Metis	150	165	156	157	0.187	0.73
11 Parthenope	156	...	...	156 —	0.116	0.93
15 Eunomia	...	...	279	279	0.145	0.84
17 Thetis	90	...	...	90	0.155	0.81
19 Fortuna	150?	...	...	150? —	0.069	1.16
20 Massalia	130	138?	...	133	0.213	0.67
21 Lutetia	104!	104	...	104 —	0.102	0.99
23 Thalia	91	102?	...	95	0.200	0.70
39 Laetitia	142	151	...	146	0.201	0.70
40 Harmonia	90	94	...	92	0.184	0.74
63 Ausonia	109!	110	...	109	0.186	0.73
89 Julia	...	...	137:	137:	0.148	0.83
141 Lumen	88!	94	...	90 ~	0.057	1.24
324 Bamberga	180!	188?	...	182 ~	0.058	1.24
433 Eros	15.8:	15.6?	...	15.7:	0.175	0.76
511 Davida	262	245	...	253 ~	0.073	1.13
532 Herculina	120	...	...	120	0.170	0.77
654 Zelinda	82	78	...	80 —	0.058	1.23
887 Alinda	4.1	...	...	4.1	0.165	0.78
1566 Icarus	1.4?	1.3?	...	1.4?	0.179	0.75
1620 Geographos	2.1?	...	1.9?	2.0?	0.210	0.68
1685 Toro	6.0?	...	...	6.0?	0.147	0.83

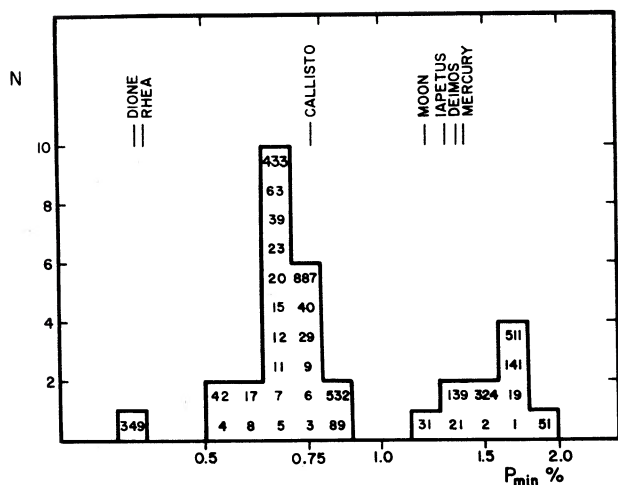


FIG. 3. The frequency distribution of the depth $P_{\min}$ of the negative branch for asteroids and other objects.

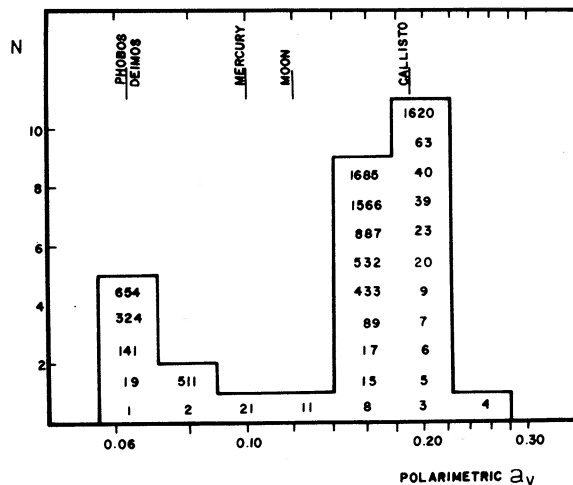


FIG. 5. The frequency distribution of polarimetric albedos for asteroids.

comprising at least six objects (1, 2, 19, 141, 324, and 511) is seen with $B-V$ near $+0.7$, $P_{\min}$ near 1.6%, and albedos below 0.09, and includes objects reported to resemble certain carbonaceous chondrites spectroscopically (Johnson and Fanale 1973). $P_{\min}$ greater than about 1.6% is outside the measured range for silicates and has been reliably demonstrated only for C1 chondrites and carbonaceous substances such as coal dust and candle soot.

The shallow negative branch observed for (349) Dembowska indicates either a well-consolidated surface or else an exceptionally translucent regolith material. Also in classes by themselves are (4) Vesta, (51) Nemausa, (63) Ausonia, and (21) Lutetia because of its large inversion angle. We note that all five small objects in Mars-crossing orbits (433, 887, 1566, 1620, and 1685) fall in the lower-opacity group but are otherwise unremarkable in their optical properties.

Deimos and the darker side of Iapetus are similar to

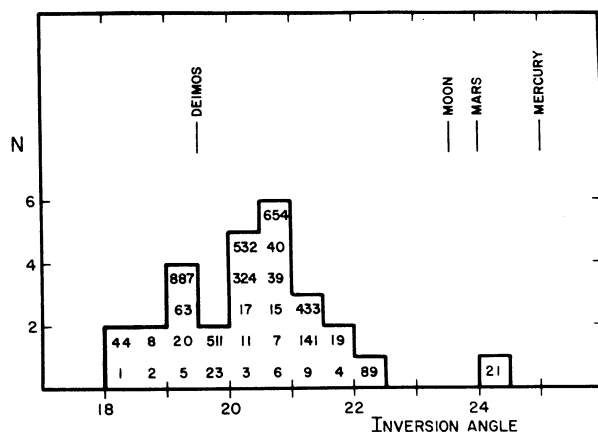


FIG. 4. The frequency distribution of the inversion angle α_o for asteroids and other objects.

the darker asteroids in Figs. 6 and 7, and Callisto to the lighter ones, but no asteroids exhibit the reddish color and relatively low polarimetric albedo of the Moon and Mercury. Darkening mechanisms believed to operate on the lunar surface (e.g., Hapke 1973) are apparently less effective for the asteroids. This may result from the reduced solar particle and photon flux in the asteroid belt, or, as pointed out by Chapman and Salisbury (1973), it may be a consequence of the fact that asteroid regoliths are lost to space and replenished from subsurface material with a relatively short time scale.

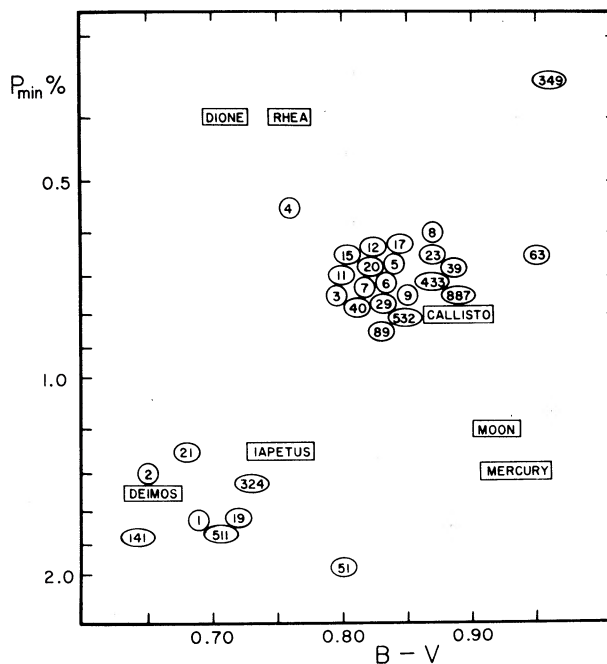


FIG. 6. Depth $P_{\min}$ of the negative polarization branch vs $B-V$ color for asteroids and other objects.

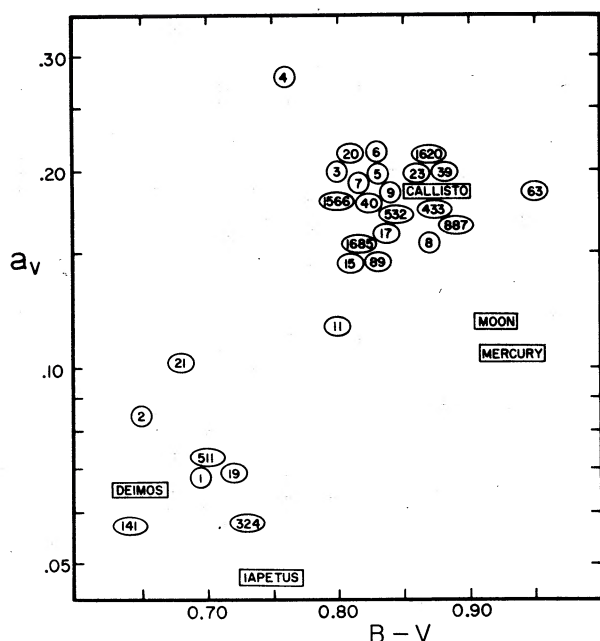


FIG. 7. Polarimetric albedo vs $B-V$ color for asteroids and other objects.

IV. FUTURE WORK

The precision of polarimetric parameters listed here will be substantially improved, and the number of well-observed objects increased to perhaps 50, after another year's work. We hope to extend the wavelength range from the ultraviolet into the near infrared at least for a few of the brighter objects. In some cases, particularly for 433 Eros, we expect to identify rotation and aspect effects in the polarization.

A major new program of high-quality *UBV* photometry of asteroids is needed for interpretation of results from the more sophisticated techniques. Support from laboratory and theoretical work is also needed. The Wolff theory should permit direct computation of photometric as well as polarimetric quantities in terms of fundamental optical properties. Few laboratory measurements have been made with sufficient precision to investigate deviations from the slope-albedo law, or to delineate wavelength dependencies in parameters such as $P_{\min}$ and α_0 ; polarimetry free of systematic errors at the $\pm 0.01\%$ level, a commonplace in astronomical work, has yet to be approached in the laboratory. We especially feel the need for precision laboratory polarimetry of super-dark materials of all kinds, since asteroid albedos may range as low as 2% . New techniques such as radar backscattering and interferometric diameter measurements will prove invaluable.

ACKNOWLEDGMENTS

We are indebted to Dr. Paul Herget, Director of the Minor Planet Center, for furnishing accurate ephemerides

and to the Directors of the McDonald, Mauna Kea, and Steward Observatories and of the Lunar and Planetary Laboratory for generous allotments of telescope time. Some of the observations were made by G. V. Coyne, L. Dunlap, M. Howes, K. Serkowski and others. This work is supported by the National Aeronautics and Space Administration.

REFERENCES

- Bowell, E., Dollfus, A., and Geake, J. E. (1972). In *Proceedings of the Third Lunar Science Conference*, edited by D. R. Criswell (MIT Press, Cambridge), Vol. 3, p. 3103.
- Bowell, E., Dollfus, A., Zellner, B., and Geake, J. E. (1973). In *Proceedings of the Fourth Lunar Science Conference*, edited by J. Chamberlain and C. Watkins (Lunar Science Inst., Houston), Vol. 3, p. 3167.
- Bowell, E., and Zellner, B. H. (1974). In *Planets, Stars, and Nebulae Studies with Photopolarimetry*, edited by T. Gehrels (U. Ariz. Press, Tucson), p. 381.
- Chapman, C. R., McCord, T. B., and Johnson, T. V. (1973). *Astron. J.* **78**, 126.
- Chapman, C. R., and Salisbury, J. W. (1973). *Icarus* **19**, 507.
- Chapman, C. R., Morrison, D., and Zellner, B. H. (1975). *Icarus*. To be published.
- Cruikshank, D. P., and Morrison, D. (1973). *Icarus* **20**, 477.
- Dollfus, A. (1961). In *Planets and Satellites*, edited by G. P. Kuiper and B. M. Middlehurst (U. Chicago Press, Chicago), p. 343.
- Dollfus, A. (1971). In *Physical Studies of Minor Planets*, edited by T. Gehrels, NASA SP-267, p. 25.
- Dollfus, A., Bowell, E., and Titulaer, C. (1971). *Astron. Astrophys.* **10**, 450.
- Dunlap, J. L. (1974). *Astron. J.* **79**, 324.
- Dunlap, J. L., Gehrels, T., and Howes, M. L. (1973). *Astron. J.* **78**, 491.
- Gehrels, T., and Teska, T. M. (1960). *Publ. Astron. Soc. Pac.* **72**, 115.
- Gehrels, T. (1970). In *Surfaces and Interiors of Planets and Satellites*, edited by A. Dollfus (Academic Press, London), p. 317.
- Gehrels, T., Coffeen, T., and Owings, D. (1964). *Astron. J.* **69**, 826.
- Gehrels, T., Roemer, E., Taylor, R., and Zellner, B. H. (1970). *Astron. J.* **75**, 186.
- Hapke, B. (1971). In *Physical Studies of Minor Planets*, edited by T. Gehrels, NASA SP-267, p. 67.
- Hapke, B. (1973). *The Moon* **7**, 342.
- Johnson, T. V., and Fanale, F. P. (1973). *J. Geophys. Res.* **78**, 8507.
- Jones, T. J., and Morrison, D. (1974). *Astron. J.* To be published.
- Ken Knight, C. E., Rosenberg, D. L., and Wehner, G. K. (1967). *J. Geophys. Res.* **72**, 3105.
- Lyot, B. (1934). *C. R. Acad. Sci. Paris* **199**, 774.
- Matson, D. L. (1971). In *Physical Studies of Minor Planets*, edited by T. Gehrels, NASA SP-267, p. 45.
- McCord, T. B., and Chapman, C. R. (1975). *Astrophys. J.* To be published.
- Morrison, D. (1974). *Astrophys. J.* To be published.
- Morrison, D., and Cruikshank, D. P. (1974). *Space Sci. Rev.* **15**, 641.
- Provin, S. (1955). *Publ. Astron. Soc. Pac.* **67**, 115.
- Serkowski, K. (1974). In *Planets, Stars, and Nebulae Studied with Photopolarimetry*, edited by T. Gehrels (U. Arizona Press, Tucson), p. 135.
- Taylor, R. C. (1971). In *Physical Studies of Minor Planets*, edited by T. Gehrels, NASA SP-267, p. 117.
- Veverka, J. (1970). Ph.D. thesis, Harvard University.
- Veverka, J. (1971). *Icarus* **15**, 11.
- Veverka, J. (1973). *Icarus* **19**, 114.
- Veverka, J., and Noland, M. (1973). *Icarus* **19**, 130.
- Widorn, T. (1967). *Ann. Univ. Sternw. Wien* **27**, 112.
- Wolff, M. (1974). Privately circulated manuscript, The Aerospace Corporation, El Segundo, California 90009.
- Zellner, B. H., and Capen, R. C. (1974). *Icarus*. To be published.