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THE NATURE OF ASTEROID SURFACES, FROM OPTICAL POLARIMETRY

A. DOLLFUS, J. E. GEAKE,
J. C. MANDEVILLE and B. ZELLNER

Telescopic observations of the polarization of light by asteroids are interpreted on the basis of a systematic polarimetric analysis of terrestrial, meteoritic and lunar samples. Laboratory measurements were made using samples with different surface textures, and scanning electron microscope pictures were used to investigate the influence of microtexture and crystalline structure.

It is demonstrated that asteroid surfaces do not accumulate thick regolithic layers of micro-fragments, as do the Moon and Mercury. This is because the majority of debris ejected by impacts are lost, due to the low gravitational escape velocity from these bodies. However, asteroids are not bare rocks, but are coated with a thin layer of adhesive debris. This coating apparently has the composition of the body itself. The fact that there is no indication of significant maturation by space weathering suggests that the dust which coats the surface of asteroids is frequently replaced by further impacts.

Asteroids may be classified polarimetrically in several groups: those in group C are made of very dark material and behave like carbonaceous chondrites, or very dark Fe-rich basalts; Those in group S correspond to silicates and stony meteorites. A third group represented by Asteroid 21 Lutetia and 16 Psyche may be metallic.

The purpose of this paper is to deduce the physical nature and texture of the asteroid surfaces; this has been achieved by means of telescopic observations of the way in which these bodies polarize reflected sunlight. The amount of polarization produced and its variation with phase angle are diagnostic of surface texture and albedo. Previous work has already demonstrated that, on terrestrial samples measured at the laboratory as well as on celestial bodies, the shape of the polarization curve clearly discriminates between surface types, such as clean bare rock, rock coated with adhesive debris, pulverized rocks and an impact-generated regolithic layer of fines of the lunar type (*cf*. Dollfus 1971, Dollfus and Geake 1975).

POLARIZATION PARAMETERS

The amount of polarization P is defined as $(I_1 - I_2)/(I_1 + I_2)$, where I_1 is the intensity of the light with the plane of polarization perpendicular to the Sun/asteroid/Earth plane, and I_2 is the intensity of the light polarized at 90^o to this plane. By measuring P (expressed in units of 10^{-3}) at the telescope, night after night, as the orbital motion of the Earth and the asteroid progressively change the phase angle V between Sun, asteroid and Earth, one can build up the curve of polarization which relates P with V. Typically, as V increases from zero, the polarization curve first goes negative, reaching a flat minimum value P_{min}; it then rises, and passes through zero again at a phase angle V_o and then becomes positive with a slope h. Typically, P_{min} has values of between -2×10^{-3} and -20×10^{-3}, depending on the nature of the surface; V_o lies between 6° and 25°, also depending on the texture. h is very precisely related to the geometric albedo p of the surface (see Bowell *et al*. 1973). (For albedo measurements see also Morrison 1977).

All the characteristics of the observed curve are described by the three fundamental parameters: P_{min}, V_o and p. Their mutual interrelations characterize the surface properties.

POLARIMETRIC DATA FROM ASTEROIDS

The polarimetric survey of asteroids, organized under T. Gehrels at the University of Arizona, was conducted by B. Zellner and co-workers, with also contributions from J. Veverka and others (see Zellner and Gradie 1976). To date, 47 asteroids have been measured accurately enough to give values of the three fundamental parameters P_{min}, V_o and p, as listed in Table I (after Zellner and Gradie 1976).

TABLE I

OPTICAL PARAMETERS FOR ASTEROIDS (AFTER B. ZELLNER AND J. GRADIE (1976))

ASTEROID No.	Name	Group	p	$-P_{min}$ 10^{-3}	V_o degrees
1	Ceres	C	.071	7.2	18.2
2	Pallas	(C)	.089	13.8	18.7
3	Juno	S	.183	7.6	19.6
4	Vesta		.282	5.5	21.3
5	Astrae	S	.182	7.0	18.9
6	Hebe	S	.233	8.0	20.5
7	Iris	S	.181	7.5	20.4
8	Flora	S	.200	6.8	19.3
9	Metis	S	.205	7.4	21.1
11	Parthenope	S	.163	7.3	18.4
12	Victoria	S	.149	6.8	21.1
13	Egeria	C	.072	21.0	22.0
14	Irene	S	.171	8.0	20.2
15	Eunomia	S	.145	7.2	20.8
16	Psyche	M	.229	10.0	23.1
17	Thetis	S	.152	7.4	20.5
18	Melpomene	S	.202	8.0	21.3
19	Fortuna	C	.062	17.2	21.4
20	Massalia	S	.218	7.1	18.8
21	Lutetia	M	.102	13.0	24.5
22	Kalliope	M	----	9.5	20.0
23	Thalia	S	.213	7.4	19.6

27	Euterpe	S	.205	6.6	19.9
29	Amphitrite	S	.177	8.8	20.6
30	Urania	S	.192	7.8	19.3
39	Laetitia	S	.213	7.7	20.5
40	Harmonia	S	.190	7.8	20.7
42	Isis	(S)	.153	6.4	17.3
44	Nysa	E	.347	3.1	18.5
51	Nemausa	C	.066	19.6	20.3
55	Alexandra	C	.062	19.5	22.0
56	Melete	C	.055	14.7	20.0
63	Ausonia	S	.174	7.0	19.4
64	Angelina	E	.498	3.2	17.1
84	Klio	C	.062	14.9	20.2
89	Julia	(M)	.148	9.0	22.1
139	Juewa	C	.067	13.1	20.6
141	Lumen	C	.059	17.8	21.3
192	Nausikaa	S	.210	7.5	19.6
230	Athamantis	S	.147	9.4	19.8
324	Bamberga	C	.057	14.6	20.1
410	Chloris	C	.058	19.4	19.9
433	Eros	S	.203	7.0	20.6
511	Davida	C	.062	16.9	19.6
532	Herculina	S	.166	7.8	20.2
563	Suleicka	S	.196	7.0	18.8
654	Zelinda	C	.055	14.6	21.1
887	Alinda	S	.210	7.6	19.4

In Fig. 1, P_{min} is plotted as a function of V_0. The asteroids are represented by circles and their diameter gives a rough indication of the accuracy of measurement. In each case, the fraction of the circle which is blackened represents the albedo as deduced from the slope h. The relationship between the albedo p and P_{min} is shown more directly in Figs. 2 and 3.

In Fig. 1 as well as in Fig. 2, the asteroids are seen to split into several groups. The most clearly defined group is centered at $P_{min} = -7.5 \times 10^{-3}$ and $V_0 = 19.5$ degrees (Fig. 1). The average albedo for this group is 0.19 (Fig. 2); the albedo has been deduced from the slope h of the polarization curve for $\lambda = 5500$ Å and it is calibrated for observation normal to the surface and for illumination at a phase angle of 5°. This group corresponds to the S or silicaceous group in the classification of Chapman *et al.* (1975), Zellner *et al.* (1975), and Zellner and Bowell (1977). It includes all the asteroids labelled S in Table I (not all of which are actually plotted in Fig. 1, because of overlaps).

In addition, 3 asteroids are near to this group and they are indicated by their numbers in Fig. 1 (4-Vesta, 42-Isis and 89-Julia). Two other asteroids are distinctly brighter and less polarized, (44-Nysa and 64-Angelina).

The other main group comprises darker objects with albedos ranging from 0.10 to 0.05 (Fig. 2). P_{min} ranges from -13×10^{-3} to -21×10^{-3}; V_0 has an average of 20° and never exceeds 22°. This category corresponds to the C (carbonaceous) group of Chapman *et al.* (1975) and has polarimetric properties similar to carbonaceous meteorites and dark basaltic glasses (Dollfus and Geake 1975). It also fits with particularly dark lunar basaltic breccia such as

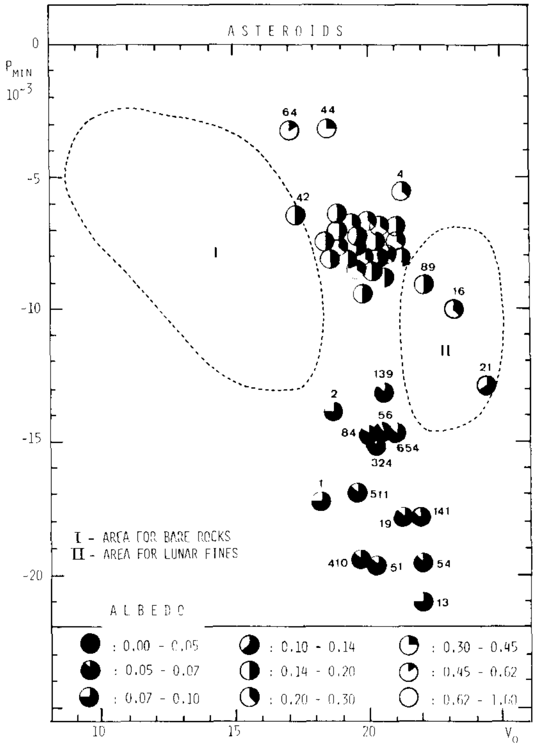

Figure 1. P_{min} as a function of V_o for asteroids.

sample 60015, when coated by their own debris. This group so far includes 14 asteroids among those observed polarimetrically; they are identified by their numbers in Fig. 1 and labelled C in Table I. Deimos, the satellite of Mars also falls in this group (*cf.* Dollfus and Geake 1965).

These two groups, S and C, are completely separated polarimetrically. We note that in Fig. 1 there is a gap, as no asteroids have values of P_{min} between -9.5×10^{-3} and -13×10^{-3}.

Three asteroids 21-Lutetia, 22-Kalliope and 16-Psyche depart from these two categories (perhaps also 89). They correspond to the special category M (metallic) of the classification by Morrison *et al.* Additional polarimetry is needed for their interpretation.

IDENTIFICATION OF THE NATURE OF ASTEROID SURFACES

One implication of these results is that, since asteroids split into several categories with albedos ranging from 0.50 for 64-Angelina to 0.055 for 56-Melete and 654-Zelinda, they cannot all be covered by a layer of cosmic dust accumulating on the surface. A continuing process of dust collection would have tended to make all the optical properties uniform.

To make further deductions, one has to make laboratory measurements of samples. An extensive research program has been developed along these lines at Meudon Observatory, France, at the Laboratory "Physique du Système Solaire." The sample investigated included 60 terrestrial samples selected by A. Cailleux

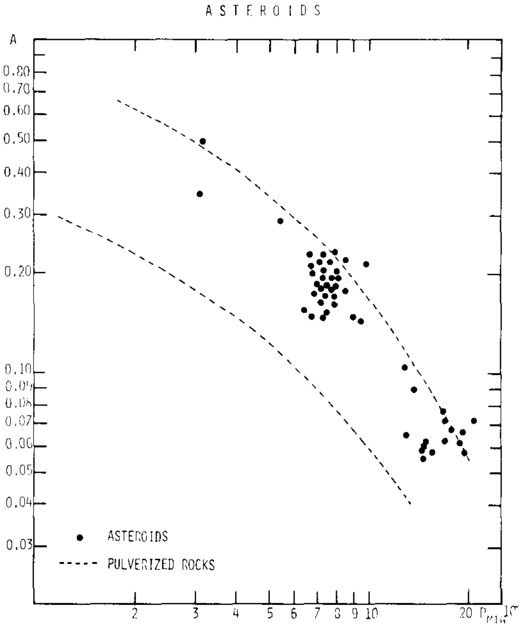

Figure 2. Albedo as a function of P_{min} for asteroids, compared with pulverized rocks.

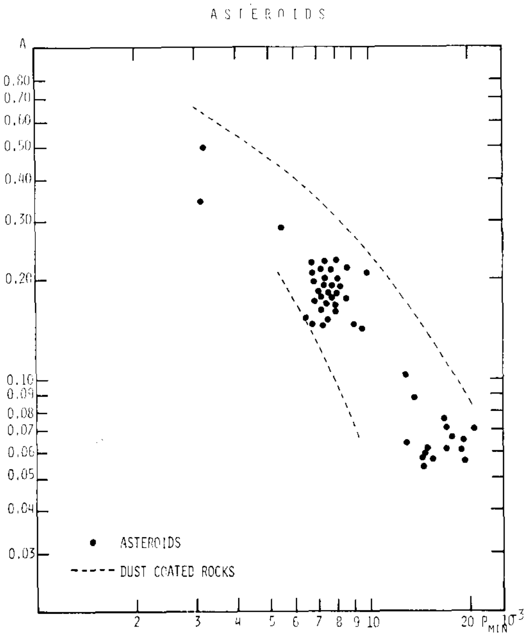

Figure 3. As Fig. 2, but compared with dust-coated lunar rocks.

and analyzed by M. Christophe-Michel-Levy, 18 meteorites from the "Museum National d'Histoire Naturelle" and the Smithsonian Institution Washington, and 35 lunar samples from NASA and the USSR Academy of Sciences (see Dollfus 1971, Dollfus and Geake 1975).

Surface textures were analyzed and classified by the scanning electron microscope and by ordinary microscopic techniques. The optical polarization parameters P_{min}, V_0 and p were measured, and their inter-relations plotted in pairs; finally, models were constructed in which all 3 parameters could be plotted together in 3 dimensions, in order to bring out any relationships more clearly. A report on these laboratory results is in preparation (Dollfus *et al.* 1977).

On the basis of this work we find that freshly chipped silicaceous rocks are a category of surface having a specific polarimetric signature. In the P_{min} versus V_0 plots of Fig. 1 and Fig. 4, the terrestrial rocks measured (24 specimens), and also the lunar rocks and breccia when chipped or cleaned of their coating of adhesive grains by ultrasonic techniques (7 specimens) all lie in domain I (Fig. 1). This category does not appear to correspond to any of the asteroids.

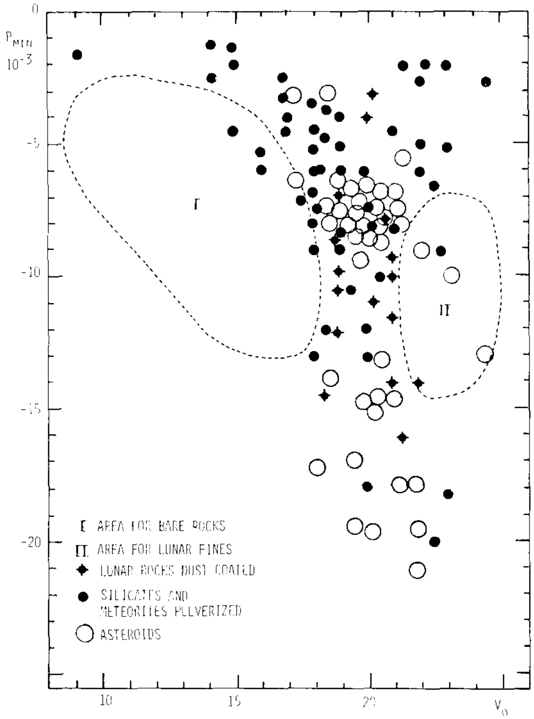

Figure 4. P_{min} as a function of V_0 for asteroids, dust-coated lunar rocks, and pulverized terrestrial and meteoritic rocks.

A second category of surface is that of the lunar regolith of fines: 22 specimens of lunar fines all cluster into domain II. This group is very specific with large values of V_0 due to the effect on polarization of multiple diffraction, shadowing and scattering between the grains of the highly porous "fairy castle" structure that is produced by grain cohesion under the high-vacuum conditions prevailing at the lunar surface. Except for the two exceptional asteroids 21 and 16 of the M group, and perhaps also 89, this structure does not match the optical properties of asteroids.

When terrestrial rocks and meteorites are pulverized to a fine powder, either by natural processes or at the laboratory, they do not produce the grain-adhesion characteristic of the lunar surface. Their polarization parameters P_{min} and V_o do not now fall in domain II as do the lunar fines, but, as shown by the filled dots in Fig 4, they characteristically lie in between domains I and II; the S and C asteroid groups both correspond exactly to this domain, as shown by the open circle in Fig. 4.

However, the identification on this basis is not unique, because another category of samples also has the same P_{min} - V_o characteristics. Because of the adhesive nature of solids in high vacuum, lunar rocks usually have their surfaces coated with small debris and fragments, which strongly stick to the rocks and cover the whole surface with a thin layer of dust. This layer does not construct thick "fairy castle" structures, and the polarization signatures are the same as for the terrestrial powders, as shown in Fig. 4 by the dot-cross symbols.

On the basis of the P_{min} and V_o parameters alone, the asteroids are identified either as being covered by an optically thick powder of silicate grains, or as having a rocky surface coated with a thin layer of adhering debris. If one considers the physical environment, the alternative of a thick powder of small grains is unlikely, because in a vacuum such a dust layer would tend to form "fairy-castle" structures, which is excluded by observations.

This ambiguity may be resolved observationally, by plotting the polarimetric albedo p as a function of P_{min}. In Fig. 2, the asteroids are compared with the pulverized rocks; the agreement is only marginal, as the albedos of the asteroids are systematically too high. In Fig. 3, the comparison with dust-coated lunar rocks and breccias is far better.

We conclude that asteroids of both type S and type C have a solid surface coated with a thin layer of small debris, which covers most of the surface.

As the optical parameters are found to have a wide range of values, the debris coating the surface cannot come predominantly from outside as it would then tend to be always the same, but it must be dominantly debris from the bulk asteroidal rocks themselves; these bodies are therefore covered by their own debris.

DISCUSSION OF RESULTS

The surface texture implied by the polarization measurements suggests that impact ejecta are retained by asteroids. The escape velocity from an asteroid is proportional to the radius and to the square root of the density: *e.g.*, for a silicaceous body with a diameter of 200 km, the escape velocity V_e = 135 m/sec; for the largest asteroid 1-Ceres, with a diameter of 1000 km but a density of only 2.5 gr/cm^3, V_e = 590 m/sec.

Collisions by micrometeorites and other objects are produced within the asteroid belt with an average impact velocity of the order of 5 km/sec (Dohnanyi 1971). Impacts of around this velocity have been produced in the laboratory and a large fraction of the ejecta are found to have velocities of several hundred meters per second (Gault and Heitowit 1963). This suggests that for asteroid-size objects, much of the ejected material will be lost into space. This problem was recently reviewed by Gaffey (1974). Those grains ejected at sub-escape velocities will fall back on to the surface, and, under the ultra-high vacuum conditions prevailing, are subjected to electrostatic and molecular adhesion forces of the kind discussed by Salisbury and more recently by Arrhenius and Asunmaa (1973). Apparently, these forces are responsible for the retention by asteroids of a thin coating of their own debris.

The situation could be different for impacts on a surface that is already covered with a thick regolithic layer of fines; an impacting object then ejects a larger quantity of debris than it would from a rock surface, but the ejection velocities are smaller (Stoeffler *et al.* 1975); therefore, the fraction of the ejecta that is retained by the gravitational field and falls back on to the surface is increased. The resulting mixing has been statistically derived by Monte Carlo methods, such as those developed by Duraud *et al.* (1975). An existing thick unconsolidated soil of the lunar type could then, with certain limits, be more easily maintained. However, the polarization results indicate that this is not the kind of surface that asteroids have.

The optical telescopic techniques at present available for the remote analysis of asteroids only tell us about the superficial coating of these bodies. They give no direct indication of the mineralogy of the underlaying rocks nor of its physical texture, which may be consolidated rock, brecciated structures, gravel packings, or the rock foam produced by melting in vacuum. However, it seems probable that the debris coating the surface of an asteroid has the same composition as the rock forming the underlaying surface. Moreover, polarimetric observations indicate a wide range of albedo with no suggestion of the uniformity that would tend to result from the accumulation of dark agglutinates, or from radiation sputtering and other effects produced by long exposure to space weathering (described generally as "maturation"). Also, maturation would tend to wash out the spectral absorption bands but this effect is not observed (Adams *et al.* 1971). Accordingly, we conclude that the debris coating the asteroid surfaces have to be rather frequently rejuvenated. Successive impacts should blow off a large fraction of the pre-existing fragments and replace them by newly formed debris. Furthermore, Gaffey (1974) argued that impact velocities of the order of 5 km/sec. are not sufficient to produce a significant amount of the dark glassy agglutinate which is a dominant factor of maturation.

Gas-rich meteorites (*e.g.*, the achondrites Kapoeta and Lafayetteville) are brecciated aggregations of grains highly maturated and radiation-exposed. They are traditionally explained as having been formed in a regolithic soild of the lunar type. However, our present results show that thick regolithic layers apparently are not in process of formation in the present state of the asteroid belt. Thus, if gas-rich meteorites were formed in the asteroid belt by impacts on maturated regolithic soils, this suggests that larger size parent bodies were broken up in several successive stages, as suggested, for instance, by H. Urey, and more recently by B. Levin (1977).

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DISCUSSION

KIANG: Is the slope-albedo calibrated with lunar fines, terrestrial rocks or results from IR radiometry of asteroids? Has there been any theoretical derivation of this relation from a model surface texture?

DOLLFUS: The slope-albedo relationship was calibrated empirically by laboratory measurements on rather large varieties of terrestrial, lunar and meteoritic samples. The relationship is almost independent of the nature of the samples and of its physical texture.