Earth Planets Space, **57**, 71–76, 2005

Quantification of porosity and surface roughness in laboratory measurements of the bidirectional reflectance of asteroid surface analogues

Tatsuya Sakai and Akiko M. Nakamura

Graduate School of Science and Technology, Kobe University, 1-1 Rokkodai, Nada, Kobe, Japan

(Received March 14, 2004; Revised December 1, 2004; Accepted December 2, 2004)

We studied the effects of the surface roughness and porosity of a sample layer on its light-scattering properties in laboratory experiments using fly ash, iron, graphite, and olivine powders. Three types of surface structure were prepared: compacted, knocked, and fluffy surfaces. The surface roughness is represented by the mean slope angle of small facets on the surface. We found a positive correlation between the surface roughness and the porosity of the layer. The bidirectional reflectance of the surface at the wavelength of a He-Ne laser (633 nm) was measured to illustrate the influence of surface structure on scattering properties, with the incidence angle fixed at 0°, while varying the phase angle from 2 to 80°. The reflectance of a relatively rough surface was lower than that of a relatively smooth one for all of the materials measured. The reflectance measured at 30° in phase angle decreased by between ∼25 and ∼60%. This effect may explain the discrepancy between the absolute reflectance in previous laboratory results and the observed results for C class asteroids (Kamei and Nakamura, 2002; Nakamura *et al.*, 2002).

Key words: Asteroids, surface, bidirectional, reflectance, porosity.

1. Introduction

Laboratory photometric phase curves of meteorite powders place constraints on meteorite-asteroid connections and the surface structure of asteroids. In previous studies of the bidirectional reflectance of meteorite powders, the sample surfaces were smoothed using a spatula (Kamei and Nakamura, 2002; Tomita *et al.*, 2003). These studies found that (1) the surfaces of meteorite powders had shallower phase curves than those of most asteroids and (2) the surfaces made of carbonaceous-chondrite powders were up to 200% as bright as asteroid 253 Mathilde (Kamei and Nakamura, 2002; Nakamura *et al.*, 2002).

The discrepancies in the slope and absolute value of the phase curve between laboratory surfaces and asteroids may arise from differences in the particle size, surface roughness, and packing as well as material composition. Asteroid surfaces are excavated by impact bombardment. Any ejecta with a velocity less than the escape velocity fall back onto the surface and form a powdery structure. Laboratory impact experiments show that the minimum ejection velocity from weak surfaces is 1 m/s or less (Housen, 1991; Michikami, 2001). Therefore, asteroid surfaces with escape velocities beyond tens of cm/s can have a regolith layer made from such fallen ejecta. Moreover, data from spacecraft observations interpreted using Hapke's (1993) model indicate that the surface of asteroid 433 Eros has a porosity exceeding 70% (Domingue *et al.*, 2002). Therefore, the surface is probably rougher and more porous than laboratory surfaces smoothed using a spatula.

The effect of surface roughness and porosity on the phase curve has been studied in a number of laboratory experiments. Adams and Filice (1967), French and Veverka (1983), Capaccioni *et al.* (1990), and Shkuratov *et al.* (2002) compared the reflectance curves of surfaces with different degrees of roughness. Buratti and Veverka (1985) demonstrated that the macroscopic roughness lowers the reflectance. These studies mention the importance of the surface condition of the powdery layer on the reflectance; however, quantitative examinations of surface structure are still lacking. Quantitative research into the relationship between the layer structure and its optical properties should generate more information about asteroid surfaces. Therefore, this study quantified the surface structure of simulated asteroid surfaces. We report on the relationship between porosity and surface roughness, and the effect on the bidirectional reflectance.

2. Experiments

2.1 Instrumentation

We used a goniometric apparatus at Kobe University (Kamei and Nakamura, 2002) that has two arms; these can rotate in the upper-half plane normal to the sample surface and are equipped with a He-Ne laser source (wavelength 633 nm) and a photo-multiplier, respectively. We measured the intensity of the laser light scattered by the sample surface, for different emergent angles (e) with the incident angle (i) fixed at 0°. The phase angle coverage was from 2 to 80°. The absolute reflectance $r(i, e, g)$ was determined using the standard reflectance of a Ba_2SO_4 surface, the reflectance value of which is given at $i = 0, e = 45, g = 45°$, where g is the phase angle.

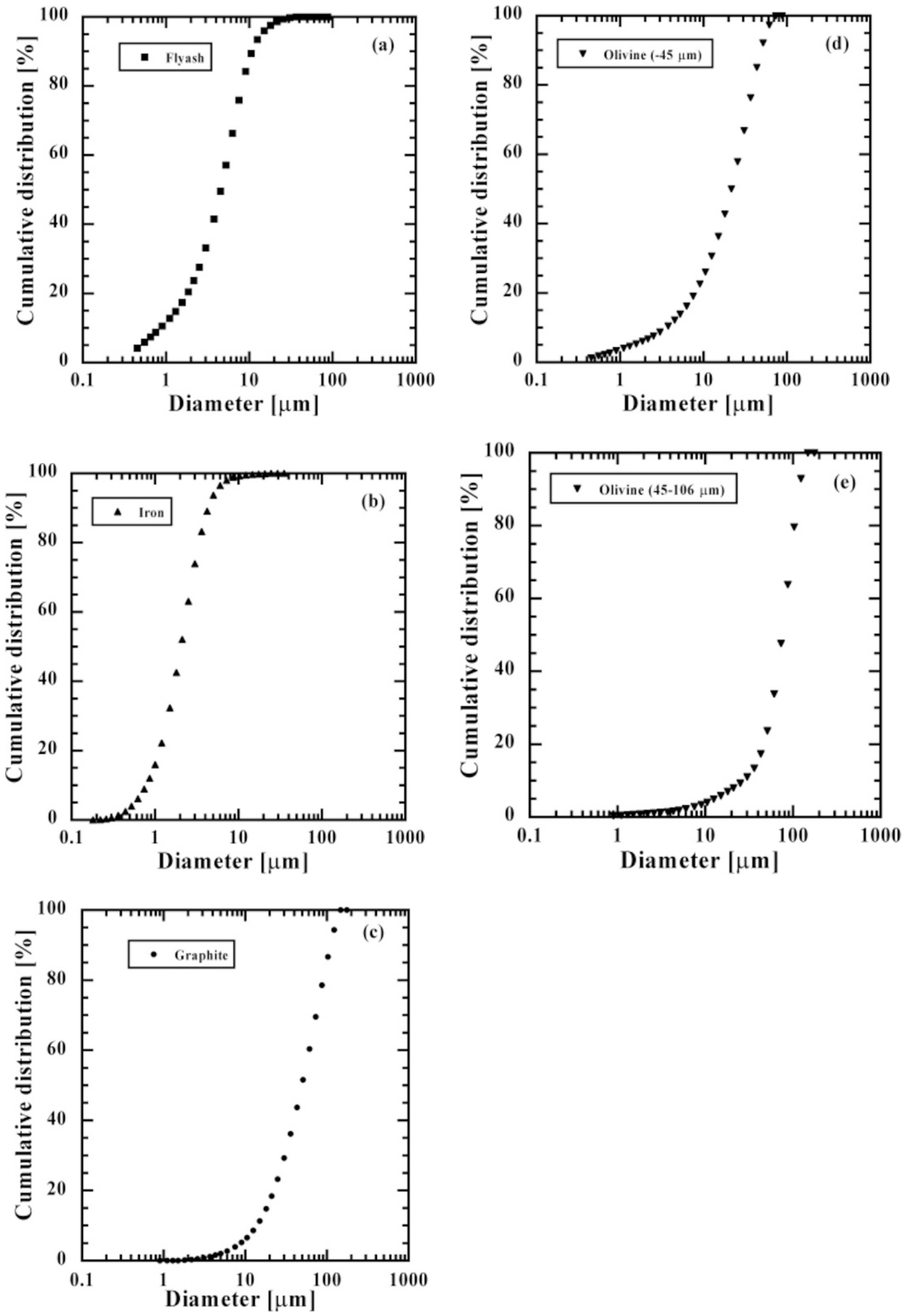

Fig. 1. The diameter distributions of the sample powders.

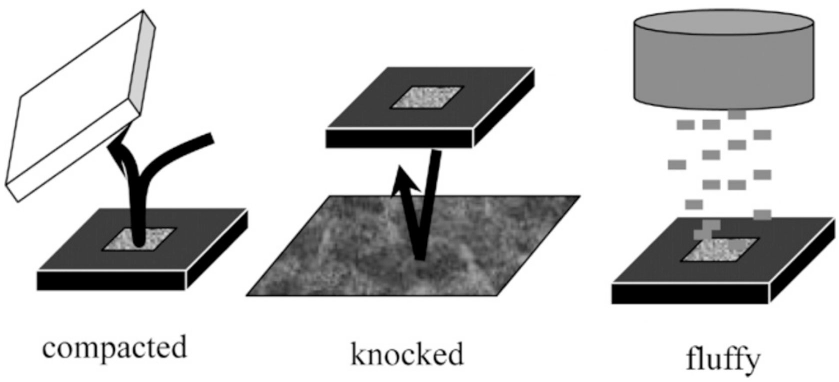

Fig. 2. The method of surface preparation.

2.2 Surface preparation

We used fly ash, iron, carbon, and olivine powders in this experiment. The diameter distributions of the powders were determined using a laser diffractometer (HELOS with RODOS and GRADIS) and are shown in Fig. 1.

We prepared three types of powdery surface (Fig. 2). The powders were sieved over the sample tray to produce fluffy surfaces ("fluffy"), which were not touched directly. We measured the falling velocity of the powders using a high-speed video camera operating at a rate of 125 frames per second. The falling velocity was 20∼40 cm/s, which is equivalent to the escape velocity of small bodies (for a diameter of ∼500 m and a density of ∼2 g/cm^3, the escape velocity is 26.4 cm/s). Such a surface was compacted tightly using a flat plate to produce a smooth surface ("compacted"). A surface with intermediate porosity and roughness was made from a fluffy surface by knocking the tray vertically against a horizontal plane ("knocked"). Figure 3 shows examples of surface topography of "compacted", "knocked", and "fluffy" surfaces.

The surface roughness was determined from elevation data measured using a laser confocal displacement meter, as we described previously (Tomita *et al*., 2002). The surface was mounted on a stage and moved in the x- and y-directions and the elevation (i.e., the z-coordinate) of the surface was determined for grid points spaced at fixed intervals of 1 and 10 μm. The plane equation was determined from the least squares fit to four grid points and the inclination of the normal vector of the facet from the vertical direction (z-direction) defined slope θ of the facet. The mean slope angle $\langle\theta\rangle$ of the 1- and 10-μm lattices, for 10,000 lattices, was defined as the surface roughness.

The porosity of the powdery layers was calculated as

$$P = 1 - \frac{m}{\rho V}$$

where m is the total mass of the powders in the sample tray, ρ is the grain density of the powdery material, and V is the volume of the sample tray. In the porosity calculation, we used 1.95, 7.87, 2.25, and 3.39 g/cm^3 as the grain density for fly ash, iron, graphite, and olivine particles, respectively. The surface roughness and porosity are summarized in Table 1. In this table, ΔP and $\Delta\theta$ denote the standard deviation of P and θ, respectively. Table 2 lists the porosities of various structures packed with identical spheres. The values of the porosity of the most "compacted" surfaces shown in Table 1, except for graphite, are within the range for these structures.

3. Results

3.1 Relationship between porosity and roughness

Figure 4 shows the relationship between the porosity, P, and the roughness, $\langle\theta\rangle$, of the powdery surface. In this figure, there is a systematic relationship between the two parameters for all of the materials. The roughness calculated using the 1-μm pitch data is greater than that calculated from the 10-μm pitch data. In addition, the dispersion value of the roughness calculated at 1 μm ($\Delta\theta$) is greater than that calculated at 10 μm. These results probably arise from the fact that the roughness measured using a shorter pitch is

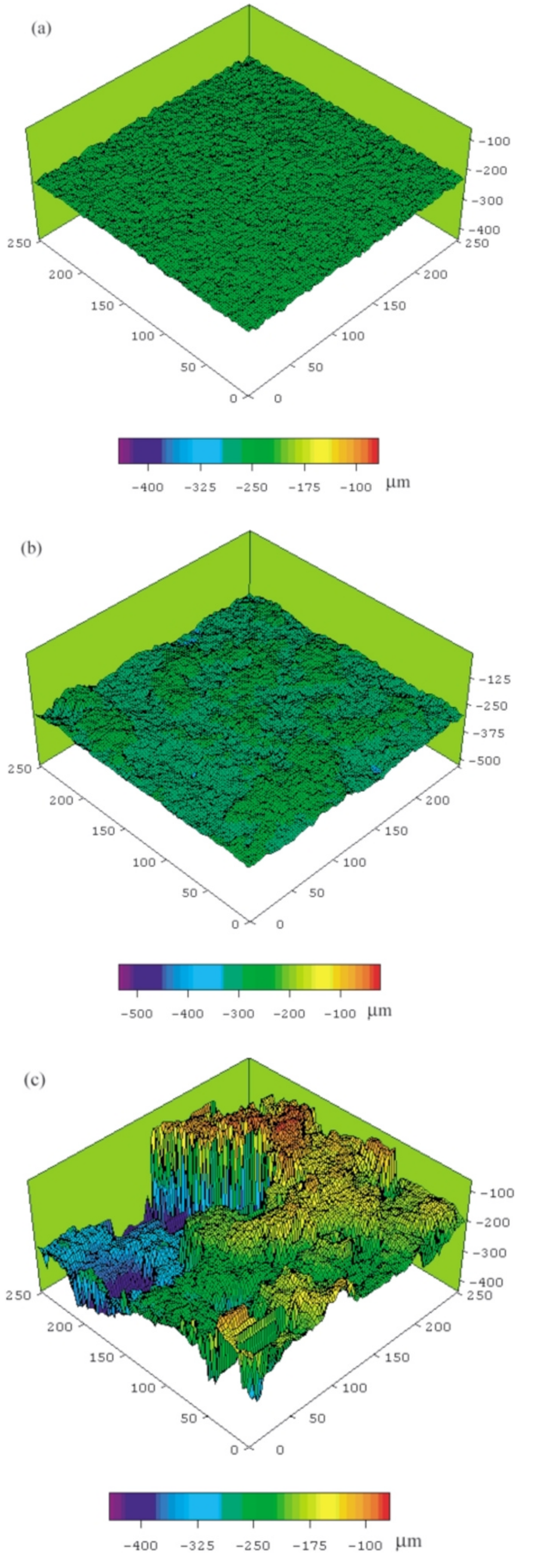

Fig. 3. Surface topography of the (a) "compacted1", (b) "knocked1", and (c) "fluffy1" fly ash surfaces determined by a measurement at 1 μm spacing in horizontal directions. Color indicates relative elevation in μm.

Table 1. Bulk porosity and surface roughness of the powdery surfaces. The standard deviation of the slope angle is shown in the $\Delta\mu$ columns.

Sample		Porosity		Roughness [degree]			
		P	ΔP	1-μm pitch		10-μm pitch	
				θ	Δ	θ	Δ
Fly ash	compacted1	0.40	0.04	41	21	8.8	7.8
	knocked1	0.48	0.04	48	20	23	15
	compacted2	0.49	0.04	39	21	12	11
	compacted3	0.54	0.04	42	19	12.1	9.2
	knocked2	0.56	0.17	61	17	31	15
	knocked3	0.62	0.04	66	18	42	18
	knocked4	0.66	0.17	58	18	37	19
	knocked5	0.72	0.04	64	16	45	18
	knocked6	0.79	0.17	60	21	42	18
	knocked7	0.81	0.17	64	16	52	20
	fluffy1	0.87	0.04	71	15	57	17
	fluffy2	0.89	0.04	69	19	56	18
Iron	compacted1	0.48	0.01	15	13	3.6	2.9
	compacted2	0.53	0.01	18	14	4.2	4.1
	fluffy1	0.88	0.01	61	18	48	17
Graphite	compacted1	0.69	0.04	39	21	13	11
	knocked1	0.69	0.04	52	21	22	15
	knocked2	0.79	0.15	62	20	35	18
	fluffy1	0.89	0.04	71	16	49	20
Olivine	compacted1	0.41	0.02	37	21	11	9
(~45 μm)	compacted2	0.68	0.03	57	18	32	15
	knocked1	0.78	0.03	58	17	34	16
Olivine	compacted1	0.32	0.03	42	22	19	13
(45 ~ 106 μm)	knocked1	0.46	0.02	54	19	28	15
	fluffy1	0.55	0.10	60	19	30	17

Table 2. Porosities of various structures packed formally.

Structure	Coordination number	Porosity
Simple cubic packing	6	0.476
Orthorhombic packing	8	0.395
Wedge-shaped tetrahedron	10	0.302
Rhombohedral packing	12	0.259

influenced more by the shape of the individual powder particles in addition to the roughness owing to the structure of the ensemble of particles. The fitting lines are
$\langle\theta\rangle = (60.0 \pm 11.6)P + (17.8 \pm 7.8)^\circ$ for the 1 μm pitch, and
$\langle\theta\rangle = (100.6 \pm 11.7)P - (30.8 \pm 7.9)^\circ$ for the 10 μm pitch. The correlation coefficients are 0.85 and 0.94 for the 1- and 10-μm pitch results, respectively. Since the correlation was better for the 10-μm pitch, we adopted the roughness calculated using a 10-μm pitch in our subsequent discussions.

3.2 Bidirectional reflectance

Figures 5(a)–(c) show the bidirectional reflectance of the different surface structures. As the surface roughness and bulk porosity increase, the reflectance at a moderate phase angle (around $g = 30^\circ$), where the effect of the opposition surge is weak or negligible, decreases, as Capaccioni *et al.* (1990) showed qualitatively. The degree of darkening differed among the materials and phase angles. The fly ash surfaces showed a nearly equivalent decrease in reflectance at any phase angle (Fig. 5(a)), whereas the iron surfaces showed conspicuous differences at phase angles exceeding $g \sim 30^\circ$ (Fig. 5(b)). Unlike the other materials, the graphite compacted surface showed a larger difference from the knocked and fluffy surfaces at low phase angles below $g \sim 40^\circ$ (Fig. 5(c)). In Fig. 5(c), the reflectance of the knocked sample surface (knocked1) is almost twice that of the fluffy surface. This may explain the discrepancy between the reflectance of carbonaceous meteorite powders

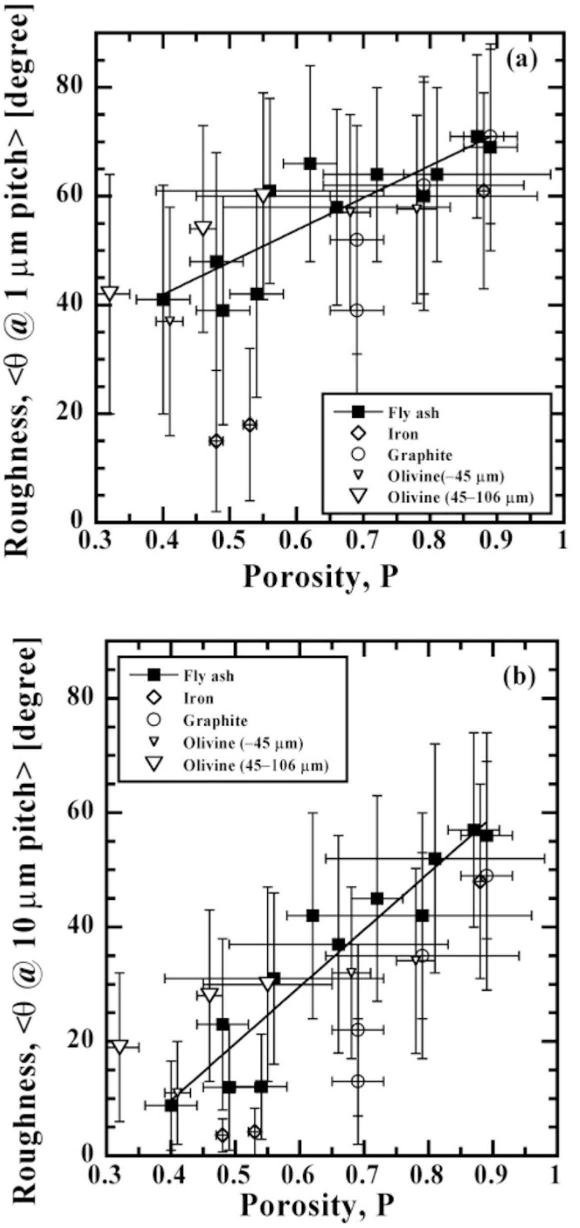

Fig. 4. The relationship between the porosity and roughness of a powdery surface. The roughness was calculated at (a) 1- and (b) 10-μm pitches. The solid lines are the linear fits to the fly ash data.

and that of 253 Mathilde (Kamei and Nakamura, 2002; Nakamura *et al*., 2002).

In Fig. 6, there is a negative correlation between the surface roughness, in terms of the mean slope angle, and the reflectance at $g = 30°$. The data on meteorite surfaces are from Tomita *et al*. (2003). Again, the degree of darkening owing to the surface roughness or porosity exceeded 25% for fly ash, iron, and fine meteorite particles (5–20 μm) and 50% for graphite. The meteorite surfaces consisting of medium (45–75 μm) and large (180–500 μm) particles showed less difference in both reflectance and surface roughness (Tomita *et al*., 2003). This is probably because particles of such sizes cannot form a porous structure at the terrestrial gravity condition and the pores between particles have a greater effect on the bidirectional reflectance of relatively small particles.

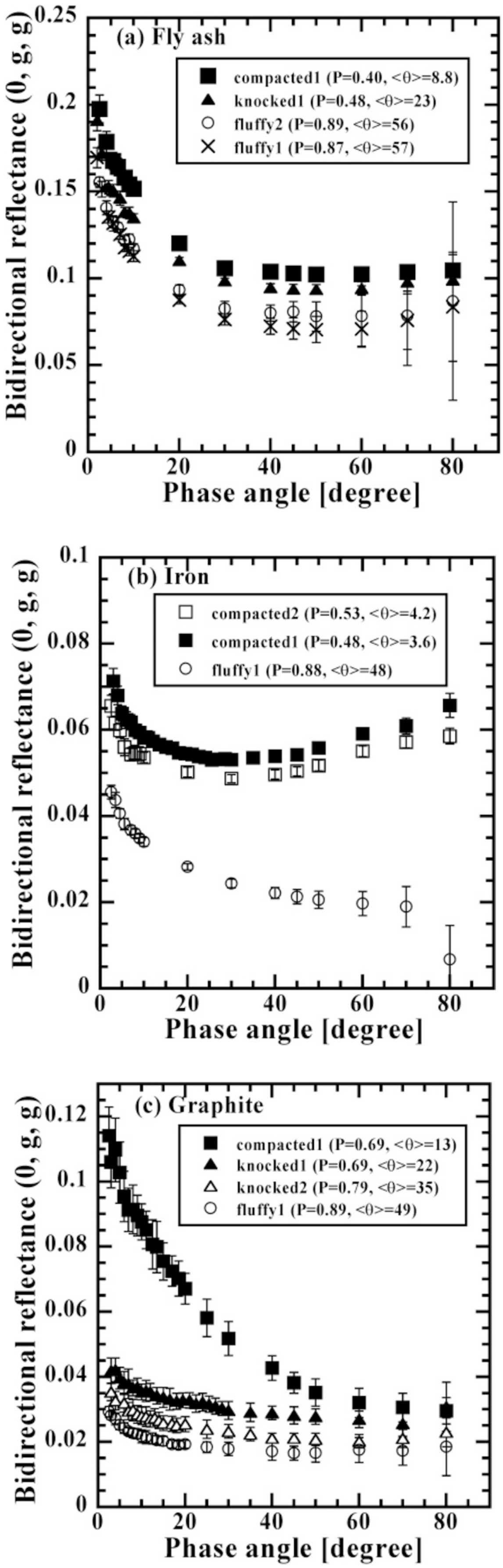

Fig. 5. Bidirectional reflectance of powdery surfaces of (a) fly ash, (b) iron, and (c) graphite. The roughness values shown in the parentheses are those of 10-μm pitches and are in unit of degree.

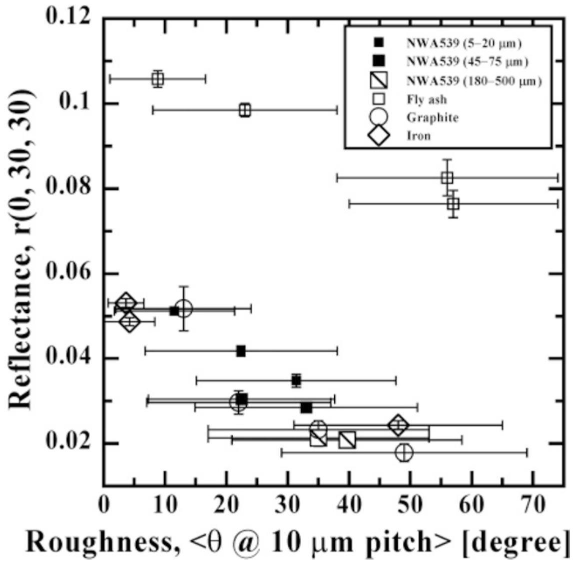

Fig. 6. Bidirectional reflectance values at $g = 30°$ versus surface roughness.

4. Summary

To quantify the effects of the surface structure of a powdery layer on its light scattering properties, bidirectional reflectance was measured in the laboratory using powdery surfaces with various degrees of roughness and porosity.

We found a systematic relationship between the bulk porosity and the surface roughness, and the reflectance of the powdery surfaces was greatly influenced by the surface structure. Consequently, the surface of a sample must be treated carefully when light-scattering measurements of powdery samples are performed to compare with asteroid surfaces.

Further investigation of the effects of surface structure on bidirectional reflectance with different incident angles is required in order to study the shallower phase curve of meteorite surfaces obtained in the laboratory and to provide new information on the absolute reflectance of the surface of meteorite powders. Such work will be useful in analyzing the reflectance condition of the regolith on small bodies in terms of the bidirectional reflectance determined using optical instruments onboard asteroid missions, in the same manner as Domingue *et al*. (2002) investigated the porosity of the regolith surface of 433 Eros. This work is one of the first steps in the experimental verification of such studies.

Acknowledgments. This work was supported by grants-in-aid of science research (137402690) from the Japanese Society for the Promotion of Science (JSPS), and was carried out as part of the "Ground-based Research Announcement for Space Utilization" program promoted by the Japan Space Forum. T. S. was supported by "The 21st Century COE Program of Origin and Evolution of Planetary Systems" in Ministry of Education, Culture, Sports, Science and Technology (MEXT).

References

Adams, J. B. and A. L. Filice, Spectral reflectance 0.4 to 2.0 micron of silicate rock powders, *J. Geophys. Res.*, **72**(22), 5705–5715, 1967.

Buratti, B. J. and J. Veverka, Photometry of rough planetary surfaces: The role of multiple scattering, *Icarus*, **64**, 320–328, 1985.

Capaccioni, F., P. Cerroni, M. A. Barucci, and M. Fulchignoni, Phase curve of meteorites and terrestrial rocks: laboratory measurements and applications to asteroids, *Icarus*, **83**, 325–348, 1990.

Domingue, D. L., M. Robinson, B. Carcich, J. Joseph, P. Thomas, and B. E. Clark, Disk-integrated photometry of 433 Eros, *Icarus*, **155**, 205–219, 2002.

French, L. M. and J. Veverka, Limb darkening of meteorites and asteroids, *Icarus*, **54**, 38–47, 1983.

Hapke, B., *Theory of Reflectance and Emittance Spectroscopy,* Cambridge Univ. Press, 1993.

Housen, K. R., Laboratory simulations of large-scale fragmentation events, *Icarus*, **94**, 180–190, 1991.

Kamei, A. and A. M. Nakamura, Laboratory study of the bidirectional reflectance of powdered surfaces: On the asymmetry parameter of asteroid photometric data, *Icarus*, **156**, 551–561, 2002.

Michikami, T., Evolution of asteroid regolith layers by cratering, Ph. D. thesis, Univ. of Tokyo, Japan, 2001.

Nakamura, A. M., A. Kamei, and T. Mukai, Modeling asteroid phase curves: Laboratory study on bidirectional reflectance of asteroid—surface analogues, *Mem. Italian Astron. Soc.*, **73**, 722–725, 2002.

Shkuratov, Yu., A. Ovcharenko, E. Zubko, O. Miloslavskaya, K. Muinonen, J. Piironen, R. Nelson, W. Smythe, V. Rosenbush, and P. Helfenstein, The opposition effect and negative polarization of structural analogs for planetary regoliths, *Icarus*, **159**, 396–416, 2002.

Tomita, N., H. Nakayama, A. M. Nakamura, and A. Kamei, Laboratory study on surface structure of regolith, *Mem. Italian Astron. Soc.*, **73**, 739–742, 2002.

Tomita, N., A. M. Nakamura, A. Kamei, and T. Mukai, Measurements of bidirectional reflectance of ordinary chondrite for MUSES-C in-situ detection, *Advances in Space Research*, **31**(12), 2495–2499, 2003.

T. Sakai and A. M. Nakamura (e-mail: amnakamu@kobe-u.ac.jp)