A Photometric Study of Regolith Intimate Mixing with Ice-Like Impurity

Dwaipayan Deb (✉ dwaipayandeb@yahoo.co.in)

Ramanuj Gupta College, Silchar <https://orcid.org/0000-0002-6359-7903>

Pavan Chakraborty

Indian Institute of Information Technology Allahabad

Research Article

Keywords: asteroids, surfaces, photometry, regoliths

Posted Date: October 14th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-832144/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Surfaces of solid solar system objects are covered by layers of particulate materials called regolith originated from their surface bedrock. They preserve important information about surface geological processes. Often regolith is composed of more than one type of particle in terms of composition, maturity, size, etc. Experiments and theoretical works are being carried out to constrain the result of mixing and extract the abundance of compositional end-members from regolith spectra. In this work we have studied, photometric light scattering from simulated surfaces made of two different materials – one is highly bright quartz particles $\approx 80\mu\text{m}$ and the other moderately bright sandstone particles $\approx 250\mu\text{m}$. The samples were mixed with varying proportions and investigated at normal illumination conditions to avoid the shadowing effect. Said combinations may resemble ice mixed regolith on various solar system objects and therefore important for in situ observations. We find that the combinations show a linear trend in the corresponding reflectance data in terms of their mixing proportion and some interesting facts come out when compared to previous studies.

1. Introduction

Light scattering from particulate surfaces is presently of great interest in various fields of science and engineering that include – remote sensing applications, various geological studies, interpretation of astronomical observations on cometary, asteroidal, or planetary surfaces, and also in the study of organic cells in biology. In planetary sciences and solar system studies, the scattered sunlight from floating dust grains in a cometary coma plays an important role in determining their composition, structure, and size distribution which retain various information about the history and evolution of the object. However, objects like asteroids and terrestrial and icy planets do not exhibit a coma, rather dust or ice grains are present on the surface in the form of regolith. Light scattering from regolith is a bit more complicated process than that of coma due to multiple scattering of light. Moreover, regolith grains are irregular-shaped and coarser than cometary dust grains, and regolith surfaces bear surface roughness and porosity which makes computational work a bit more difficult. In addition to all the above, a regolith may be a combination of two or more different kinds of regolith in terms of composition, particle size, maturity, etc (e.g. Gault et al. 1974). For example- the impact of meteorites on bodies like asteroids may result in the mixing of materials at depth with that on the surface and thereby albedo and spectral properties get modified (e.g. Hoffmann et al. 2013). In particular, mixing of high albedo fresh regolith with low albedo weathered regolith on small objects like Vesta is evident from Dawn mission (Pieters 2012). 1 Ceres and 4 Vesta are both known to have an icy mantle and a bright crust which is probably a mixture of rocky dust (originated from meteorite impact) and water ice and thereby decreasing its albedo (e.g. Russel et al. 2007, Pieters et al. 2011). In the case of high albedo outer solar system icy objects, water ice regolith crystal on these bodies often gets mixed with various unknown impurities which absorb light strongly in the visible and UV region and thereby altering the albedo and spectral features to a considerable extent (Clark et al. 2014). In our neighborhood, based on Lunar Orbiter Laser Altimeter data at 1064nm Lucey et al. 2014 predicted the possibility of water ice mixed regolith on some polar regions of

the Moon, and also the same is evident on Mars (Hudson 2009). Variation of reflectivity detected by Mercury Laser Altimeter (MLA) on the permanently shadowed region of Mercury predicts the presence of ice mixed regolith in these regions (Neumann et al. 2013). So, to detect the presence of ice and other impurities in the regolith, laboratory-based observations, as well as theoretical modeling works, are both important.

In this work we performed an experimental study to outline the constraints and suitable conditions in light scattering observations to detect ice-like impurity in planetary regolith. We used 'sand stone' powder as primary regolith analog and a highly bright sample of white quartz as ice analog. Some important observations come out when the results are compared with previous studies.

2. Background

Based on the homogeneity of mixing, regolith mixing can be mainly of two types – (i) macroscopic and (ii) microscopic or intimate (Mustard and Pieters 1989). In both of the above two types, grains of the two (or more) separate compositions remain isolated from each other. However, due to various weathering or geological processes, grains may get fused forming a different type of mixture called complex mixture (e.g. pyroclastics used by Souchon et al. 2011). Another type of mixing may be a Linear mixture (or areal mixture) where the physical distance between the constituent particles is enough large so that they scatter light independently and therefore multiple scattering can be ignored in this case. Other mixing types may be 'coating' – where particles of regolith are coated by another material, and 'molecular mixing' – where mixing takes place at the molecular level (Clark 1999).

From spectroscopic studies, it is known that, other than macroscopic mixture and linear mixture, no other mixing is expected to give linearity in reflectance spectra in general (e.g. Clark 1999, Poulet and Erard 2004). As far as photometric observations are concerned, in this case, light intensity (or reflectance) at a particular wavelength at different illumination and viewing angles are measured. Although an adequate amount of photometric experiments have been performed for single regolith analogs, this area remains vastly unexplored for mixing. Spectroscopic observations are performed at a given angle of illumination and viewing, and therefore the extension of the results at other angular geometry is not necessarily correct. Photometric observations are required to understand the angular regime where a general conclusion can be made.

The resultant intensity is the sum of single scattering and multiple scattering. Single scattering may result in a linear combination of resultant intensity whereas multiple scattering may contribute to some non-linearity in the result. However, there are other factors like porosity, surface roughness, etc. which may also take part in the result of mixing. Many experimental and theoretical modeling works have been conducted in the field of reflectance spectroscopy of intimate mixtures. **Among them**, Yoldi et al. (2015,2020), Cord et al. (2003,2005), Hapke (1981, 1986, 1993, 2002, 2008), Johnson et al. 1985, Mustard and Pieters (1987,1989), Sunshine et al. 1990, Poulet and Erard 2004, Hiroi and Pieters (1992,1994), Hiroi and Takeda 1990 **are important**.

In general intimate mixtures are not expected to give linear reflectance combinations in all cases. However, in some cases, linearity is possible and therefore important to be determined from experiments. In this work, we performed a photometric experiment on two regolith analog samples and their intimate mixtures to constrain the geometry conditions and other factors suitable for their linear combinations. We find that, at a wavelength of light 650 nm and normal incidence condition, quartz particles ($\sim 80\mu\text{m}$) when mixed with sandstone particles ($\sim 250\mu\text{m}$), the effect of mixing can be easily detected even if the abundance of quartz is as low as 10 wt %, which is in contrast with Yoldi et al. (2015,2020) (Sec. 5.2). The results also indicate that subject to some conditions, photometry can be linear in terms of abundance of the constituent samples when the phase angle is less than 45° . The surface roughness appears to have a minor role to affect the linear mixing at small phase angles but important at large angles.

3. Instrumentation And Data Sampling

The experiment was carried out with a goniometric device which is schematically shown in Fig. 1. A diode laser at 650 nm was used as the source of light and the detector unit comprises of two Silicon-based photosensors (NORPS12) viz. Comparator and Detector as shown in Fig. 1(b). Comparator measures the irradiance of the laser beam after reflection from a transparent glass plate placed at an angle 45° to the laser ray (Beam Splitter in Fig. 1(b)) and remains fixed in its position with respect to the laser beam. The Detector measures the intensity of light scattered by the sample at different angles from vertical. The photosensors are interfaced to the computer via a microcontroller unit and capable of recording data with 10 bit ADC resolution and a Windows software was written to acquire the digitized data from the microcontroller and to perform numerous data sampling and processing tasks including geometric correction ($\cos i / \cos e$) needed to calculate the intensity of the scattered light from the measured flux values.

The type of reflectance under study, in this case, is called bidirectional reflectance (Hapke 1993) which is defined as the ratio between the intensity of scattered light along a particular direction to the irradiance of the collimated incident beam. In this case, the Detector measures intensity, whereas the Comparator measures beam irradiance. Both sensors read almost simultaneously (with 10 milli-sec. time lag). As the counts are proportional to the flux density at the sensors, (Detector Count)/(Comparator Count) gives a normalized intensity which may also be termed as uncalibrated bidirectional reflectance. Due to this direct measurement of laser irradiance by Comparator, inconsistency in the intensity measurement was reduced to within $\pm 5\%$, which goes up to $\pm 15\%$ or even higher due to laser beam fluctuations without the use of this arrangement.

Often intensity-count response of photosensors deviate considerably from the manufacturer specifications and therefore before starting the experiment both sensors were re-calibrated at the wavelength under consideration by using inverse square law of flux (i.e. from a point light source the sensor count (flux) should vary proportionally to the inverse of (distance)²).

In the present experiment angle of incidence i (Fig. 1(a)) was kept fixed at 0° , however, it is possible to go up to 90° in both directions from zenith. The angle of emergence e (Fig. 1(a)) can be varied from about 0° to 90° on the free side and from 0° to a little less than the incidence angle on the laser beam side. The field of view of the detector is 2.2° and maximum angular inaccuracies in i and e measurements are less than a degree. Throughout the experiment, normal to the sample plane lie on the plane of scattering, i.e. tilt angle was always zero and thus the phase angle g is equal to $i + e$ (Fig. 1(a)). The minimum phase angle that could be achieved with this instrument was 2° .

All experimental observations at a particular geometry were averaged from more than 120 numbers of data acquired at an interval of 1 sec. Error bars in the data (Fig. 3) indicate $\pm 1.5\sigma$ value (where σ is the standard deviation) in the data set. A large number of identical observations on a test surface at $i = 0^\circ$ and $e = 45^\circ$ taken on different days show that any single observation is within $\pm 5\%$ of their average value which may be considered a good level of accuracy in a light scattering experiment. However, at grazing viewing angles ($e \geq 70^\circ$) higher inaccuracy is possible due to signal to noise (flux goes lower noise remains same). All the reported data are relative to the intensity value for Barium Sulphate pressed surface at $i = 0^\circ$ and $e = 45^\circ$ which is known to be very close to a Lambertian surface[†] (Lambert reflectance $r_{\text{Lambert}} = (\cos i) / \pi$). With the above setup very low albedo measurement (as for dark materials like graphite, gao meteorite, etc.) was not possible and therefore the work was limited to moderate and high albedo samples only. **A comprehensive discussion of the theory and description of a subsequent and recently developed more sophisticated version of the instrument is described in** Deb 2020.

[†] It is evident from Jaglarz et al.2006 that BaSO_4 , MgO and Spectralon surfaces (which are widely used as perfect diffusers) are not perfectly diffusing in nature, Spectralon is only the closest substitute to a perfectly diffusing surface called a Lambert surface.

Table-1

Code	Sample*	Mean Particle Size (Volume weighted)	Origin	Porosity	Symbols (Fig.3)
SS1	Sand Stone (crushed)	253.757 μm	Crushed	0.45	Open square
Q1	Quartz (powder)	78.336 μm	Natural	0.51	Filled square
QS1	10%Q1+90%SS1	-	-	0.47	Open circle
QS2	25%Q1+75%SS1	-	-	0.45	Open triangle
QS3	50%Q1+50%SS1	-	-	0.48	Filled triangle
QS4	75%Q1+25%SS1	-	-	0.47	Filled circle

*Percentages indicate (weight/total weight) $\times 100$

4. Samples

Samples used in this experiment are- (i) highly bright and pure white quartz (SiO_2 crystal) powder of fine particles and (ii) relatively coarser gray sandstone powder (Sandstone is a sedimentary rock typically composed mostly of silica with a small percentage of other compounds like oxides of aluminum and iron). Other samples were prepared from the intimate mixtures of the above samples in different proportions. **While sandstone may mimic silicate abundant regolith found on many objects of our solar system and regolith originated from sedimentary rocks of Mars, the reason for choosing quartz as a substitute to ice is as follows – Nelson et al 2000 used alumina (Al_2O_3) as ice analog for planetary regolith in their work because it's a high reflecting crystalline material with hexagonal crystal structure which may mimic ice that naturally occurs in hexagonal structure on earth. Depending upon the condition of formation, the crystal structure of ice can also be different. Cubic and trigonal structures of ice are also possible (Grabouska 2019, Murray et al. 2015). Quartz is a trigonal crystal (e.g. see <https://www.mindat.org/min-3337.html>) and also the sample we used was low absorbing like alumina (see reflectance data in Fig. 3). Therefore we can use it as a substitute for ice – like alumina.**

All the samples were pressed gently in their respective sample tray to make a smooth surface (Fig. 2(a)). Shapes of the particles are irregular (Fig. 2 (b) & (c)). Figures 2 (d) & (e) show their particle size distributions performed at **Central Salt & Marine Chemicals Research Institute, Bhavnagar, Gujrat, India**. Table-1 shows all other known details of the samples. The porosity of the original samples (SS1 & Q1) has been calculated by using the relation given by Eq. (1) (Sakai and Nakamura 2005)

$$p = 1 - (m/v)/\rho \dots\dots\dots(1)$$

where p is the sample porosity, m is the mass of the powdered sample within the container, v is the volume of the sample within the container in powdered form and ρ is the density of the original material in the solid form.

The porosity of the mixed samples can be calculated by the same equation but density ρ , in this case, will be a weighted mean of the two end-members which can be calculated as follows:

Let us consider two materials-1 & 2 with solid density ρ_1 & ρ_2 respectively. Also, let m_1 & m_2 are the masses of the respective materials in the mixed sample so that the total mass of the mixed sample is $M = m_1 + m_2$. Thus $P_1 = m_1/M$ & $P_2 = m_2/M$ give the weight fraction of two materials in the mixed sample, and in percentage, these give the abundance of the contributors. Now, if v_1 is the volume occupied by material-1 of mass m_1 in its *solid* form, we can write

$$m_1 = \rho_1 v_1$$

$$\text{Or, } P_1 M = \rho_1 v_1$$

$$\text{Or, } \rho_2 P_1 M = \rho_2 \rho_1 v_1 \dots\dots\dots(2)$$

similarly,

$$m_2 = \rho_2 v_2$$

$$\text{Or, } P_2 M = \rho_2 v_2$$

$$\text{Or, } \rho_1 P_2 M = \rho_1 \rho_2 v_2 \dots\dots\dots(3)$$

adding (2) and (3) we get

$$(\rho_2 P_1 + \rho_1 P_2) M = \rho_1 \rho_2 (v_1 + v_2)$$

$$\text{Or, } M / (v_1 + v_2) = \rho_1 \rho_2 / (\rho_2 P_1 + \rho_1 P_2)$$

$$\text{Or, } \rho_m = 1 / (P_1 / \rho_1 + P_2 / \rho_2) \dots\dots\dots(4a)$$

$$\text{Or, } 1 / \rho_m = P_1 / \rho_1 + P_2 / \rho_2 \dots\dots\dots(4b)$$

Where ρ_m is the weighted mean solid density of the mixed sample under consideration to be used in Eq. (1) to calculate porosity. The meaning of m and v in Eq. (1) remains unchanged. Porosity values in Table-1 were calculated by considering $\rho_{\text{quartz}} = 2.62 \text{ g/cc}$ (www.webminerals.com) and $\rho_{\text{sand stone}} = 2.8 \text{ g/cc}$ (measured).

Credit: Figures (d) and (e) above are given from Result Analysis Report from CSIR - Central Salt & Marine Chemicals Research Institute, Bhavnagar, Gujarat, India.

5. Results And Discussion

5.1 Results: The observations were carried out at normal illumination to avoid the shadowing effect. Apart from that, the angle of incidence is frequently zero during laser altimeter observations onboard spacecraft visiting various solar system objects, and therefore this is an important observation condition. Reflectance data obtained from each of the samples in Table-1 are shown in Fig. 3. The curves show a similar trend at low phase angles but quite different at large angles. From these results three observations can be pointed out – (i) At small phase angles (up to 10°) all the curves have a decreasing trend which appears to be the end trail of opposition effect. (ii) At large phase angles $\geq 70^\circ$, the reflectance phase curve of SS1 shows an increasing nature while that of Q1 shows a decreasing trend which can be compared with Mie calculations for spherical particles with the Hapke formula (Hapke 1993) for a monodisperse medium as shown in Fig. 4. Since surface roughness is known to be related to particle size, it is expected to affect differently in the above two cases, and hence the nature of phase curves at large angles. The curves of mixed samples are flattened in this region, which may be due to the combined effect of albedo and roughness variation.

(iii) In a region between 5° and 45° phase angle most of the curves are nearly parallel and horizontal. Careful observation reveals that the reflectance in this region is linear with the proportion of sample mixing (Fig. 5). **The reflectance of the combined sample can be calculated from their end members with the following relationship**

$$r_{\text{calculated}} = r_{\text{SS1}} \times (\text{Mass fraction of SS1}) + r_{\text{Q1}} \times (\text{Mass fraction of Q1}) \dots \dots \dots (5)$$

Here r_{SS1} and r_{Q1} are reflectances of SS1 and Q1 respectively, and $r_{\text{calculated}}$ is the theoretically calculated reflectance assuming linear combination for the intermediate sample with mass fractions of end members as used at the RHS of Eq. 5.

In Fig. 5 experimentally measured values at constant phase angles have been plotted against calculated reflectance for phase angles $\leq 45^\circ$. The points clearly show a linear trend about the line of unit gradient, which means that calculated and measured values are in good agreement with each other.

5.2 Discussion: Comparing the results of this experiment with previous studies following observations can be pointed out –

1) Working with mixed samples, Cord et al. 2005 conclude that – “....(1) the textural roughness, essential for the accurate determination of mineralogical abundances”. However, they used reflectance data at a higher angle of incidence (e.g. Figure 3 of Cord et al. 2005) where the shadowing effect comes into play. In our observation, we find that at normal illumination conditions the reflectance values are linearly dependant on the abundance of their components at phase angles $\leq 45^\circ$ (Fig. 5). At higher phase angles, however, this behavior is destroyed (Fig. 3), which may be due to the hiding effect due to surface roughness (i.e. if we assume that, the rough surface is like hilly terrain, the valleys are visible at small viewing angle but not at large). Hence it turns out that, the effect of textural roughness on abundance determination may be neglected for normal illumination of light and phase angles $\leq 45^\circ$.

2) Yoldi et al. (2015 and 2020) experimented with real water-ice samples of two different particle sizes (i) SPIPA-A ($4.5 \pm 2.5 \mu\text{m}$) and (ii) SPIPA-B ($67 \pm 31 \mu\text{m}$), and their intimate mixtures with primary regolith - JSC Mars-1 ($24 \mu\text{m}$) and Dark Basalt (50wt% of the particles $> 109 \mu\text{m}$ and 50 % $< 109 \mu\text{m}$). Yoldi et al. 2015 concluded that bigger ice particles (i.e. SPIPA-B) are difficult to detect at low phase angles even if their abundance is as large as 75% in the primary regolith, and therefore laser altimeters are not recommended for ice detection on planetary regolith. The size of our Q1 sample is comparable to SPIPA-B, but Fig. 3 indicates an opposite result. However, if we compare Fig. 3 and phase curves of SPIPA-A mixtures at $i = 20^\circ$ (Fig. 2(a), Yoldi et al 2015), they look similar – which means SPIPA-A is easily detectable, unlike SPIPA-B. Interestingly, the size of Q1 ($78 \mu\text{m}$) is comparable to SPIPA-B, not SPIPA-A. Instead of size, if we compare their size ratio with primary regolith, we see that $\text{SS1/Q1} = 3.24$ and $\text{JSC Mars-1/SPIPA-A} = 5.33$, whereas $\text{JSC Mars-1/SPIPA-B} < 1$. This suggests that it is not the size of ice particles – rather their relative size to the primary regolith which matters when it comes to their detection. If ice particles are relatively larger than primary regolith particles, they are difficult to detect. Also, low

phase angle observations may be important if ice particles are relatively smaller than the primary regolith particles.

If we talk about the linearity of mixing, from Fig. 5 we see that intimate mixtures of Q1 and SS1 show a linear trend consistent with their abundance. A similar graph has been plotted in Fig. 6 for three intimate mixtures used in Yoldi et al. 2020 with the help of data derived from Fig. 8 (a)(c) and (d) of Yoldi et al. 2020 at $\lambda = 0.65 \mu\text{m}$. The relative albedo of samples are as follows –

JSC Mars-1/ice* ≈ 0.116

Basalt/ice ≈ 0.0779

SS1/Q1 ≈ 0.38

If we compare the relative albedo of the samples we see that brighter the primary regolith – closer it is to the line of unit gradient (i.e. reflectance is linear in terms of abundance). Therefore, it might be easier to detect the abundance of ice as an impurity by using a linear relationship like Eq.(5) in a brighter terrain like silicate-rich S-type asteroids.

*Both SPIPA-A and SPIPA-B have similar reflectance at $0.96 \mu\text{m}$, hence their average is considered

6. Conclusions

Conclusions from this study can be summarized in the following points –

1. Textural roughness may be neglected while trying to retrieve the abundance of ice-like intimate mixtures from photometric data at normal illumination conditions, provided the phase angle is $\leq 45^\circ$.
2. Comparing the results of our experiment with Yoldi et al. 2015 we find that, low phase angle data at zero incidence angle can easily detect ice as an impurity in a regolith when the size of ice particles is relatively smaller than the primary regolith particles.
3. Comparing Fig. 5 and Fig. 6 as described in Sec.5, we see that, ice as an impurity is more easily detectable in a brighter terrain than a darker one, and the photometry is linear in terms of mineralogical abundance when relative albedo of the primary regolith (sandstone powder in this case) as compared to the ice (quartz) is about 40% or higher. Thus, laser altimeters may be useful in space missions aimed at bright objects (like S-type asteroids) for the detection of ice-like impurities in regolith and their abundance determination.

Declarations

Funding: No funding was received for this work

Conflict of interest/Competing interests: No conflict of interest/ competing interest applicable

Availability of data and material: Data reported in this work are available to be used by anyone without restrictions.

Code availability: N/A

Author's Contribution: Light scattering experiment was done by D. Deb whereas P. Chakraborty did the sample PSD analysis

Acknowledgement: Authors acknowledge Chemi Enterprise, Mumbai, for providing the barium sulfate powder used for reflectance calibration. Maa Banbhor Industries, Bankura, is acknowledged for providing the sample of quartz powder used in this work. Faculty members of the Department of Biology, Ramanuj Gupta Memorial College, Silchar, are acknowledged for allowing us to use their high-resolution microscope. We are thankful to CSIR - Central Salt & Marine Chemicals Research Institute, Bhavnagar, Gujarat, India for performing the particle size analysis of the samples SS1 and Q1 used in this work. At last but not least, we acknowledge a positive response from Olga Munoz of Instituto de Astrofisica de Andalucia – CSIC, Granada, which has helped to improve the design of the instrument used in this work.

References

1. Clark, R. N., Perlman, Z.S., Pearson, N., Hendrix, A.R., Cuzzi, J.N., Cruikshank, D.P., Bradley, E.T., Filacchione, G., Nicholson, P.D., Hedman, M.M., Brown, R.H., Buratti, B.J., Baines, K.H., Sotin, C., Nelson, R.M. 2014, Surface composition and physical mixture state of the regoliths of outer solar system satellites: The role of scattering and absorption by the non-ice components and implications for Rayleigh absorption and Rayleigh scattering. American Geophysical Union, Fall Meeting 2014, abstract #P43B-3988
2. Clark, R. N., *Spectroscopy of Rocks and Minerals, and Principles of Spectroscopy, Volume 3, Remote Sensing for the Earth Sciences*, volume 3, chapter 1: Spectroscopy of Rocks and Minerals, and Principles of Spectroscopy, pages 3– 58. (A.N. Rencz, ed.) John Wiley and Sons, 1999.
3. Cord, A.M., Pinet, P.C., Daydou, Y., Chevrel, S.D. 2003, Planetary regolith surface analogs: optimized determination of Hapke parameters using multi-angular spectro-imaging laboratory data, *Icarus* 165 414–427
4. Cord, A.M., Pinet, P.C., Daydou, Y., Chevrel, S.D. 2005, Experimental determination of the surface photometric contribution in the spectral reflectance deconvolution processes for a simulated martian crater-like regolithic target, *Icarus* 175, 78–91
5. Deb, D., 2020, Making an efficient but cost-effective automated goniometric device for a light-scattering study, *Eur. J. Phys.*, 42, 015303
6. Gault, D. E., Horz, F., Brownlee, D. E., Hartung, J. B., 1974, Mixing of the lunar regolith. *Proceedings of the fifth lunar conference*, Vol.3, pp 2365-2386
7. Grabouska, J., 2019, Why is the cubic structure preferred in newly formed ice?, *Phys. Chem. Chem. Phys.*, 21, 18043-18047

8. Hapke, B., 1981, Bidirectional reflectance spectroscopy, 1, Theory, J. Geophys. Res., 86, 3039-3054.
9. Hapke, B., 1986, Bidirectional reflectance spectroscopy. IV-The extinction coefficient and the opposition effect, Icarus, 67(2), 264–280, doi:10.1016/0019-1035(86)90108-9.
10. Hapke, B. Theory of Reflectance and Emittance Spectroscopy. Cambridge University Press, New York, NY, 1993
11. Hapke, B., 2002, Bidirectional reflectance spectroscopy: 5 The coherent backscatter opposition effect and anisotropic scattering, Icarus, 157, 523–534.
12. Hapke, B., 2008, Bidirectional reflectance spectroscopy: 6. Effects of porosity, Icarus, 195, 918–926.
13. Hapke, B., 2002. Bidirectional reflectance spectroscopy. 5. The coherent backscatter opposition effect and anisotropic scattering. Icarus 157, 523-534.
14. Hiroi, T., Pieters, C. M., 1992, Effects of grain size and shape in modeling reflectance spectra of mineral mixtures, Proc. Lunar Planet. Sci., 22, 313–325.
15. Hiroi, T., Pieters, C. M., 1994, Estimation of grain sizes and mixing ratios of fine powder mixtures of common geologic minerals, J. Geophys. Res., 99(E5), 10,867–10,879, doi:10.1029/94JE00841.
16. Hiroi, T., Takeda, H., 1990, A method to determine silicate abundances from reflectance spectra with applications to asteroid 29 amphitrite associating it with primitive achondrite meteorites, Icarus, 88, 205–227.
17. Hoffmann, M., Nathues, A., Vincent, J.B., Sierks, H., 2013, Vesta and low gravity impact mixing, EGU General Assembly 2013, held 7-12 April, 2013 in Vienna, Austria, id.EGU2013-6789
18. Hudson, T. L., Growth, diffusion, and loss of subsurface ice on Mars: Experiments and models, Ph.D. thesis (2009), Calif. Inst. of Technol., Pasadena, Calif
19. Johnson, P. E., Smith, M. O., Adams, J. B. 1985, Quantitative analysis of planetary reflectance spectra with principal components analysis, J. Geophys. Res., 90, 805– 810.
20. Jaglarz, J., Duraj, R., Szopa, P., Cisowski, J., Czternastek, H., 2006, Investigation of white standards by means of bidirectional reflection distribution function and integrating sphere methods., Optica Applicata, XXXVI, No. 1, 98-103.
21. Lucey, P. G., et al. 2014, The global albedo of the Moon at 1064 nm from LOLA, J. Geophys. Res. Planets, 119, 1665–1679, doi:10.1002/2013JE004592.
22. Mustard, J. F., Pieters, C. M., 1989, Photometric phase functions of common geologic minerals and applications to quantitative analysis of mineral mixture reflectance spectra, J. Geophys. Res., 94, 13,619 –13,634.
23. Murray, B.J., Slazmann, C.G., Heymsfield, A.J., et al., 2015, Trigonal Ice Crystals in Earth's Atmosphere, Bulletin of the American Meteorological Society, 96(9) 1519-1531
24. Mustard, J. F., Pieters, C. M., 1987, Quantitative abundance estimates from bidirectional reflectance measurements, J. Geophys. Res., 92(B4), e617–e626, doi:10.1029/JB092iB04p0E617
25. Nelson, R.M., Hapke, B.W., Smythe, W.D., Spilker, L.J., 2000 The Opposition Effect in Simulated Planetary Regoliths. Reflectance and Circular Polarization Ratio Change at Small Phase Angle, Icarus

26. Neumann, G. A., et al. 2013, Bright and dark polar deposits on Mercury: Evidence for surface volatiles, *Science*, 339, 296–300, doi:10.1126/science.1229764.
27. Pieters, C.M., McFadden, L. A., Prettyman, T., Sanctis M. C. De, McCord, T.B., Hiroi, T., Klima, R., Li, J.Y., Jaumann, R., 2011, Surface composition of Vesta: Issue and Approach. *Space Sci Rev*, 163, 117-139
28. Pieters, C.M., Ammannito, E., Blewett, D.T., Denevi, B.W., Sanctis, M.C. De, Gaffey, M.J., Corre, L. Le, Li, J.Y., Marchi, S., McCord, T.B., McFadden, L.A., Mittlefehldt, D.W., Nathues, A., Palmer, E., Reddy, V., Raymond, C.A., Russell, C.T., 2012, Distinctive space weathering on Vesta from regolith mixing processes, 491, 79-82
29. Poulet, F., Erard, S., 2004. Nonlinear spectral mixing: Quantitative analysis of laboratory mineral mixtures, *J. Geophys. Res.*, 109, E02009. doi:10.1029/2003JE002179
30. Russell, C.T., Capaccioni, F., Coradini, A., Sanctis, De M.C., Feldman, W.C., Jaumann, R., Keller, H.U., McCord, T.B., McFadden, L.A., Mottala, S., Pieters, C.M., Prettyman, T.H., Raymond, C.A., Sykes, M.V., Smith, D.E., Zuber, M.T., 2007. Dawn Mission to Vesta and Ceres, *Earth Moon Planet*, 101, 65–91. doi:10.1007/s11038-007-9151-9
31. Sakai, T., Nakamura, A.M., 2005, Quantification of porosity and surface roughness in laboratory measurements of the bidirectional reflectance of asteroid surface analogues, *Earth Planets Space* 57, 71–76
32. Schroder, S. E., Grynko, Y., Pommerol, A., Keller, H. U., Thomas, N., Roush, T.L., 2014, Laboratory Observations and Simulations of Phase Reddening, *Icarus*, 239, 201-216
33. Souchon, A.L., Pinet, P.C., Chevrel, S.D., Daydou, Y.H., Baratoux, D., Kurita, K., Shepard, M.K., Helfenstein, P., 2011, An experimental study of Hapke's modeling of natural granular surface samples, *Icarus*, 215, 313–331
34. Sunshine, J. M., Pieters, C. M., Pratt, S. F., 1990, Deconvolution of mineral absorption bands: An improved approach, *J. Geophys. Res.*, 95, 6955– 6966
35. Yoldi, Z., A. Pommerol, B. Jost, O. Poch, J. Gouman, and N. Thomas, 2015, VIS-NIR reflectance of water ice/regolith analogue mixtures and implications for the detectability of ice mixed within planetary regoliths, *Geophys. Res. Lett.*, 42, 6205–6212, doi:10.1002/2015GL064780.
36. Yoldi, Z., A. Pommerol, O. Poch, N. Thomas, 2021, Reflectance study of ice and Mars soil simulant associations – I. H₂O ice, *Icarus*, Volume 358, 114169, <https://doi.org/10.1016/j.icarus.2020.114169>

Figures

Figure 1

(a) Bidirectional reflection – SO is the incident ray, OD is the scattered ray towards detector and ON is the normal to the sample surface. If angle between normal to the sample surface and scattering plane is zero then $g=i+e$ (b) Schematic of goniometer device (for convenience of drawing angle of incidence is shown to be zero).

a

b

c

d

e

Figure 2

(a) Two prepared samples of Sand Stone (SS1) and Quartz (Q1) powders for observation. (b) Microscope image of sand stone particles (c) Microscope image of quartz particles. (d) Size distribution analysis of SS1 (e) Size distribution analysis of Q1.

Figure 3

Phase curves of the samples used in this experiment. Symbols are explained in Table-1. For clarity of depiction, all the curves are plotted separately in Appendix-A.

Figure 4

Mie scattering with Hapke formula for monodisperse medium with typical (n,k) values for non-absorbing and moderately absorbing silicate materials. The shape of the curves varies slowly with n and particle radius in this region. Reflectance values are normalized to unity at zero phase angle.

Figure 5

Calculated and measured reflectance values are plotted for mixed samples (last four items in Table-1) at different phase angles.

Figure 6

Calculated reflectance using Eq.(5) has been plotted against measured reflectance values for the three intimate mixtures in Yoldi et al. 2020. Data were derived from Fig.8(a)(c) and (d) of Yoldi et al. 2020 at the wavelength of 0.65 μm .

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Appendix.docx](#)