Visible and near-infrared reflectance spectral analysis model and the applied approach for Asteroid.

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It is believed that because most asteroids were destroyed in the process of evolution and remained small, they did not experience as strong erosion, thermal metamorphism, or remelting as the Earth, Mars, or Moon did. By examining asteroidal mineralogy and the degrees of secondary processes such as aqueous alteration, thermal metamorphism, and space weathering, the initial distribution of materials in the Solar System and the environment (temperature, pressure, etc.) they experienced can be understood, and constraints can be given to the Solar System formation model calculations.

Visible and near-infrared reflectance spectroscopy has been a useful method for remotely detecting mineralogy of planetary surface materials. However, there have been two problems in the analysis.

(1) On airless bodies such as asteroids, there exists a phenomenon called space weathering which is a process of alteration due to exposure to the harsh space environment including solar wind and micrometeorite bombardments (Fig.1.). Their surface reflectance spectra show reddened continua, lowered albedos, and attenuated absorption features [Pieters et al., 1993], which makes it more difficult to analyze their spectra(Fig.2.).

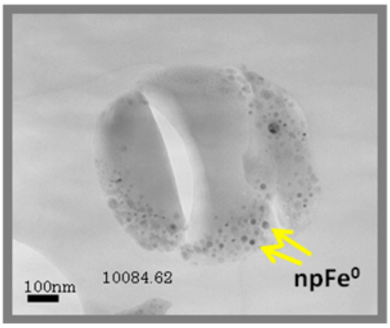

Fig.1. Transmission electron microscope bright-field image of a lunar grain with a npFe^0-rich coating.

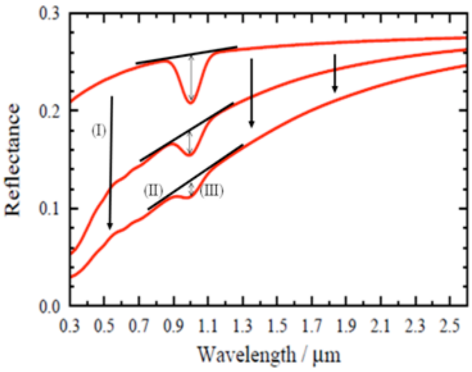

Fig. 2. Space weathering effect on visible and near-infrared reflectance spectra. Space weathering alters the surfaces of airless bodies in such a manner that their reflectance spectra show lowered albedos (I), reddened continua (II), and attenuated absorption features (III) [Pieters *et al.,* 1993]. Thus, it becomes more difficult to use important diagnostic features for detecting their

(2) In the reflectance spectra of solid planetary surfaces, we often find that each component mineral shows multiple broad bands which overlap with one another and with those of other minerals, making it very difficult to deconvolve them and assign the deconvolved bands into individual mineral components(Fig. 3).

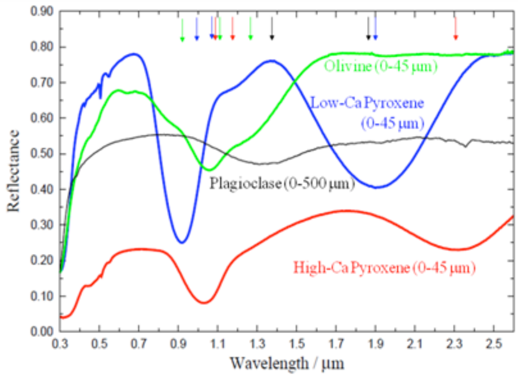

Fig. 3. Visible and near-infrared spectra of olivine (Fa#=11, Fo#=89) [Sunshine and Pieters, 1998], low-Ca pyroxene (Fs#=30, En#=70) [Kilma *et al.*, 2007] and high-Ca pyroxenes (Wo#=40, Fs#=30, En#=30), and plagioclase [Pieters, 1996], plotted in green, blue, red, and black lines, respectively. Each mineral species has multiple absorption bands indicated with arrows.

The purpose of this study is to solve these two problems.

First, this study made a progress toward solving the problem (1) by modeling the light-scattering property of a regolith particle having a vapor coating containing nanophase reduced iron ($npFe^0$) particles, including not only the effect on absorption coefficient as in Hapke [2001] but also the change in boundary reflectivities. This model can provide reasonable estimates of the volume concentration of $npFe^0$ particles and thickness of the coating layer from the visible and near-infrared reflectance spectra even in cases such as lunar regoliths wherein their reflectance spectra change drastically just by the difference in the degree of space weathering even if their compositions are similar to one another (Fig. 4.).

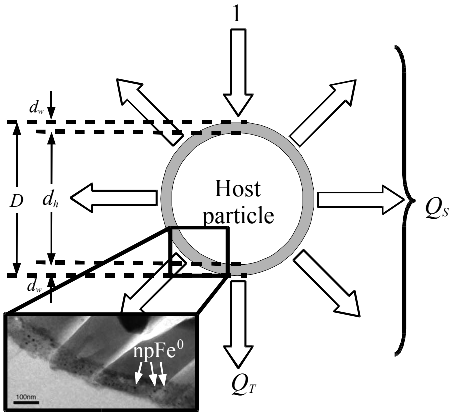

Fig. 4. A schematic view of a space-weathered particle. Denoted as D, d_h, and d_w are the diameters of the whole particle, the host particle, and the weathering layer, respectively. Inset: Transmission electron microscope bright-field image of a lunar plagioclase grain with a $npFe^0$-rich coating [Noble, 2002]. Denoted as Q_S and Q_T are scattering and transmitting efficiencies, respectively.

Next, the absorption spectra of silicates were studied. As a method of deconvolving the complex absorption spectra of silicates into individual absorption bands, the modified Gaussian model (MGM) is commonly used [Sunshine *et al.,* 1990] (For example Fig. 5.). In this study, we investigated the relationships between the chemical composition (Fe, Mg, and Ca content) and the absorption band parameters (band center, width, and relative strength) of major rock-froming minerals: olivine, low-Ca pyroxene, and high-Ca pyroxene, and also determined the band center, width, and relative strength of plagioclase (For example Fig. 6.). These relationships were utilized in MGM calculations. In this way, we solved the problem (2).

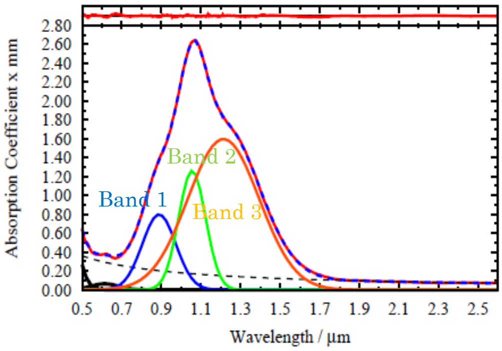

Fig. 5. MGM fits of olivine absorption coefficient spectra. In each plot, measured spectrum is plotted in a red line, calculated fit pectrum in a dashed blue line, continuum background in a dashed black line, and modified Gaussians in blue (M1 site), green (M2 site), orange (M1), and black lines. A red line in the top portion represents the error spectrum in the fitting process.

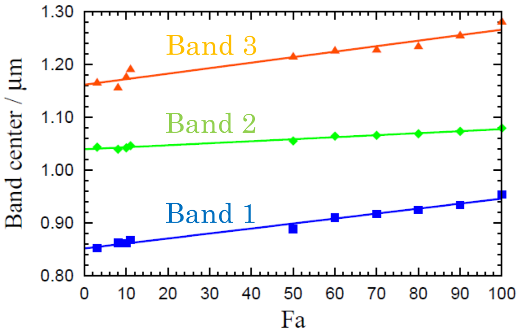

Fig. 6. Band centers of three olivine absorption bands. Bands 1 and 3 are assigned to the M1 site, and the band 2 the M2 site.

Utilizing the above two models and a mineral mixing model, we have constructed a unified model for estimating the mineral assemblage, chemical compositions of the component minerals, mineral grain size, and the degree of space weathering from the visible and near-infrared reflectance spectrum of a given airless celestial body.

This new model has been applied to the visible and near-infrared reflectance spectra of asteroids 6 Hebe, 433 Eros, and 25143 Itokawa (For example Fig. 7.). The results indicate that their surface compositions correspond to those of H chondrites (6 Hebe) and LL chondrites (433 Eros and 25143 Itokawa) which are abundant in our meteorite collections. Although such results had been also given by past studies, this study has also determined their Mg numbers, mineral mixing ratios of four major minerals of olivine, low-Ca pyroxene, high-Ca pyroxene, and plagioclase, mineral grain sizes, and the degree of space weathering from their visible and near-infrared reflectance spectra only (Table 1). These model calculations have demonstrated that there are differences in the thickness of vapor coating layer and the concentration of $npFe^0$ in the coating layer among the asteroids. The former indicates that airless celestial bodies having boulders and coarse regoliths may be more space-weathered than those having fine regoliths. The reason behind this may be that the surface of larger asteroids having stronger gravity are gardened and renewed more frequently. The latter is a new finding that the Fe concentration in the impact vapor varies among the three asteroids, which can be explained by the difference in the metallic iron abundance on these ordinary chondrite like asteroid surfaces. This is consistent with the fact that H chondrites contain significantly more metallic iron than LL chondrites, and the recognition that 433 Eros which is much larger than 25143 Itokawa should have a regolith which is fine enough to separate metallic iron particles from the remaining silicates in the LL chondrite mineral assemblage and the separated metallic iron may be concentrated on the top of the regolith, which may constitute the ponds on 433 Eros observed by NEAR spacecraft.

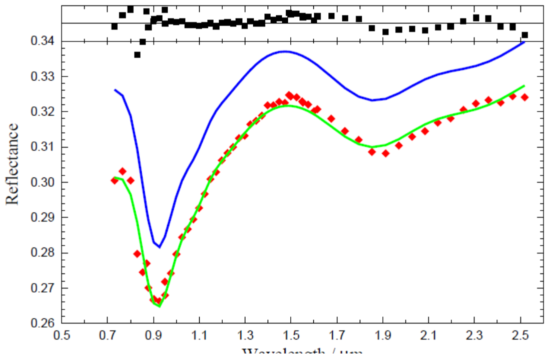

Fig. 7. Model fit of the reflectance spectra of asteroids 6 Hebe [Chapman and Gaffey, 1979; McFadden 1984], In each plot, observed and model spectra are shown in red diamonds and a green line. The blue line shows the model spectrum with space weathering effect removed. The top black squares represent the residual error spectrum.

Table 1. Results of analyzing reflectance spectra of asteroids. Parameters d_h, d_w, ϕ_w, and Φ_w denote the diameter of host material, thickness of space weathering layer, and volume fraction of npFe^0 in this layer, , respectively. The Mg# is defined as Mg×100/(Mg+Fe). OL : LCP : HCP : PL denotes the volume ratio of olivine, low-Ca pyroxene, high-Ca pyroxene, and plagioclase.

	6 Hebe (Telescopic)	433 Eros (Telescopic)	25143 Itokawa (Telescopic)	25143 Itokawa (Hayabusa NIRS)
d_h (μm)	40	40	50	60
d_w (nm)	6	7	9	8
Mg#	83	75	75	75
OL : LCP : HCP : PL	43:39:6:12	58:19:5:18	62:21:5:11	58:21:6:15
Meteorite type	H	LL	LL	LL

This study is a new, ambitious attempt to determine the composition of an unknown mixture of minerals from its reflectance spectrum by significantly reducing the number of unknown variables through restricting the visible and near-infrared absorption coefficient spectra of the end member minerals utilizing Gaussians with the characteristics of mineral absorption bands built in and by simultaneously applying a mineral mixing model and a space weathering model. This is the first attempt in the world and is a method having a potential of continuing to develop in the future.