AN APPLICATION OF A UNIFIED MODEL OF INTIMATE MIXING, SPACE WEATHERING, AND MODIFIED GAUSSIAN DECONVOLUTION TO A GROUND-BASED SPECTRA OF ASTEROIDS.

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Introduction: Visible and near-infrared reflectance spectroscopy by ground-based observation has been carried out on some asteroids (e.g., [1-11]). These reflectance spectra contain some information on asteroidal surface materials, such as mineralogy, chemistry and degree of space weathering. This information has been a source of considerable in asteroid science. The purpose of this study is to make a model for estimating the composition and degree of space weathering and apply it to some reflectance spectra by ground based telescopes.

Reflectance Model of Space Weathered Regolith: A reflectance spectra of asteroidal surfaces show reddened continua, lowered albedos, and attenuated absorption features caused by space weathering. One form of space weathering products is a vapor coating containing nanophase reduced iron (npFeO) particles around each regolith particle. The reflectance spectrum of a regolith particle has been modeled [12,13] as:

\[
R_M = cR_c, \tag{1}
\]

\[
R_c = \frac{R(i, e, g, w)}{R(i, e, g, w = 1)}, \tag{2}
\]

\[
r_0 = \frac{2}{1 + \sqrt{1 - w}} \tag{14}
\]

\[
\mu_s = \cos \theta_s, \quad \mu_t = \cos \theta_t, \tag{14}
\]

\[
w = Q_s / Q_e, \tag{14}
\]

\[
Q_s = 1 - Q_r \tag{15}
\]

\[
Q_r = t_w s_w p_h, \tag{11}
\]

\[
p_h = \exp(-\alpha_w d_h), \tag{12}
\]

\[
s_w = \frac{r_w}{1 - r_w} \left( \frac{1 - r_w}{1 - r_w} \right) \frac{p_h}{1 - r_w p_h} \tag{13}
\]

\[
t_w = \frac{\left( \frac{1 - r_w}{1 - r_w} \right) p_h}{1 - r_w p_h} \tag{14}
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\]

\[
t_w = \frac{\left( \frac{1 - r_w}{1 - r_w} \right) p_h}{1 - r_w p_h} \tag{16}
\]

\[
p_w = \exp(-\alpha_w d_w), \tag{17}
\]

\[
\alpha_w = 4\pi k_w/\lambda, \tag{18}
\]

\[Q_r = 1 - Q_r \tag{15} \]

\[Q_r = t_w s_w p_h \tag{11} \]

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R_M: model reflectance of a space-weathered regolith particle
c : normalization factor
R_c : reflectance relative to a perfect reflector
e.g: incidence, emergence, and phase angle, respectively
R : bidirectional reflectance
w : single scattering albedo
Q_s : scattering efficiency
Q_e : extinction efficiency
\[Q_s = s_w + t_w s_w t_w p_h \tag{9} \]
\[
\alpha(\lambda) = c_0 + \frac{c_1}{\lambda} + \sum_{i=1}^{N} s_i \exp \left[ -\frac{(\lambda - \mu_i)^2}{2\sigma_i^2} \right]
\]

where \(c_0 + c_1/\lambda\) is a continuum, \(s_i, \mu_i, \) and \(\sigma_i\) are band strength, center, and width of the \(i\)-th absorption band, respectively. The relationship of the band strength, center, and width of each band with the mineral type and chemical composition are assumed to be linear:

Olivine:
\[
\begin{align*}
\mu_i &= L_{\text{Fa}i} \cdot Fa + L_{\text{oli}} \\
\sigma_i &= M_{\text{Fa}i} \cdot Fa + M_{\text{oli}} \\
s_i &= N_{\text{Fa}i} \cdot Fa + N_{\text{oli}} 
\end{align*}
\]

Low and high-Ca pyroxene:
\[
\begin{align*}
\mu_i &= L_{\text{Wo}i} \cdot Wo + L_{\text{Fa}i} \cdot Fs + L_{\text{ps}i} \\
\sigma_i &= M_{\text{Wo}i} \cdot Wo + M_{\text{Fa}i} \cdot Fs + M_{\text{ps}i} \\
s_i &= N_{\text{Wo}i} \cdot Wo + N_{\text{Fa}i} \cdot Fs + N_{\text{ps}i}
\end{align*}
\]

Plagioclase:
\[
\begin{align*}
\mu_i &= L_{\text{pl}i} \\
\sigma_i &= M_{\text{pl}i} \\
s_i &= N_{\text{ps}i}
\end{align*}
\]

where \(L, M, \) and \(N\) with the suffix \(Fa, ol, Wo, px,\) and \(pl\) are constants. The \(Fa\) show the ratio of \(Fe/(Fe+Mg)\) in olivine, and the \(Wo\) and \(Fs\) show the ratio of \(Ca/(Ca+Fe+Mg)\) and \(Fe/(Ca+Fe+Mg)\) respectively. The pyroxene has two sets of parameters for Equations (23)-(25), each for low and high Ca pyroxene. Equations (19)-(28) give \(a_0\) value for equation (12) of each mineral. Equations (20)-(28) give chemical composition of asteroidal surface. In case of this study, Mg# is assumed to be the same among olivine, low-Ca pyroxene, and high-Ca pyroxene. The constants were derived from reflectance spectra of RELAB [e.g., 10, 11, 12, 13].

Mineral Mixing Model: In case of mineral mixture, scattering and extinction efficiency in equation (8) are shown as:
\[
\begin{align*}
Q_S &= \sum_j Q_{Sj} \sigma_j \\
Q_E &= \sum_j Q_{Ej} \sigma_j \\
\sigma_j &\propto m_j / \rho_j \cdot d
\end{align*}
\]

[6, 7] where \(Q_s\) and \(Q_E\) are scattering and extinction efficiencies of the component \(i\) respectively, and the linear combination coefficient \(\sigma_i\) is proportional to the total geometric cross section of the component \(i\) derived from its mass fraction \(M_i\) density \(\rho_i\), and grain size \(d_i\). The obtained relative scattering cross sections \(\sigma_i\) of component minerals on equation (29) are converted into the mass fraction \(M_i\) by Equation (30) for various values of the grain size \(d\). The mixing ratios (wt%) are calculated by Equations (29) and (30).

Analysis of Reflectance Spectroscopy on Asteroidal Surface: As an example the 24-filter [1, 2] and 52-color spectra [3] of the asteroid 6 Hebe have been analyzed. The diameter of host mineral and coating layer, and volume fraction of \(npFe^0(\phi_e)\) are given as 10 \(\mu\)m, 32 \(\mu\)m, and 0.9 vol\% respectively from the model. The mineral and chemical compositions are derived by this model as olivine : low-Ca pyroxene : high-Ca pyroxene : plagioclase = 36 : 41 : 13 : 10 with Mg# of 81 for olivine and pyroxene. Wo of Equations (23)-(25) are 0 for low Ca pyroxene and 46 for high Ca pyroxene. In this study, the model is applied to some ground-based observation data of asteroids.

Fig. 1. A model fit of the normalized reflectance spectrum of asteroid 6 Hebe [1,2,3]. Observed and model spectra are shown in red diamond 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.