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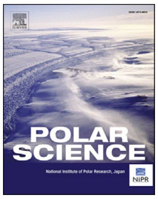

Visible and near-infrared spectral survey of lunar meteorites recovered by the National Institute of Polar Research

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ABSTRACT

Lunar meteorite chip samples recovered by the National Institute of Polar Research (NIPR) have been studied by a UV–visible–near-infrared spectrometer, targeting small areas of about 3 × 2 mm in size. Rock types and approximate mineral compositions of studied meteorites have been identified or obtained through this spectral survey with no sample preparation required. A linear deconvolution method was used to derive end-member mineral spectra from spectra of multiple clasts whenever possible. In addition, the modified Gaussian model was used in an attempt of deriving their major pyroxene compositions. This study demonstrates that a visible-near-infrared spectrometer on a lunar rover would be useful for identifying these kinds of unaltered (non-space-weathered) lunar rocks. In order to prepare for such a future mission, further studies which utilize a smaller spot size are desired for improving the accuracy of identifying the clasts and mineral phases of the rocks.

1. Introduction

Lunar meteorites, along with returned U. S. Apollo and Soviet Luna samples, have been serving as hands-on samples of the Moon for petrologists and other planetary scientists to study the composition and evolution of the Moon. Unlike the returned samples, lunar meteorites likely came from all over the lunar surface including the far side, which makes them complementary to the abundant Apollo sample collection. Recent spacecraft observations such as those by Multiband Imager (MI) and Spectral Profiler (SP) onboard Japanese SELENE (Kaguya) spacecraft and Moon Mineralogy Mapper (M^3) onboard Indian Chandrayaan-1 spacecraft enhanced our knowledge of the lunar surface composition by providing images and reflectance spectra with increasingly higher spatial and spectral resolutions, wider wavelength coverages, and better signal-to-noise (S/N) ratios (e.g., Matsunaga et al., 2008; Ohtake et al., 2009; Pieters et al., 2010).

On the other hand, laboratory studies on reflectance spectra of returned lunar samples and lunar meteorites focused mostly on bulk samples in powder form to simulate lunar surface regolith, which is usually dominant in the spatial scale observable from Earth by ground-based telescopes. However, interpreting data from the above recent missions and future spacecraft and rover missions with increased spatial resolutions to the Moon would require a new set of database covering individual rocks and their clasts. Because returned lunar samples do not represent the entire range of lunar rock lithological diversity, studying individual clasts in lunar meteorites which are mostly breccias could yield new information on their parent rocks and expand our knowledge of the compositional range of the lunar surface by studying samples that may not be represented in the returned lunar sample collections.

In order to help interpreting recent new remote-sensing data of the Moon, prepare for future rover missions, and enhance the value of Antarctic lunar meteorite collection at the National Institute of Polar Research (NIPR) in Tokyo, we have conducted a visible and

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near-infrared (VNIR) spectral survey of lunar meteorites collected by the NIPR.

2. Experimental

Antarctic lunar meteorite samples collected by the NIPR were considered for this study. Out of the nine Antarctic lunar meteorites, nine subsamples were selected for our measurements by considering freshness and texture (having a natural, broken surface). Those considered meteorite samples are listed in Table 1, and the photographs of those samples are shown in Fig. 1 with the total of twenty measured spots (about 3 × 2 mm in size) indicated. Each of those spots were selected as representative of either the average or an end member of each sample.

The details of spectral measurement are the same as those in our previous survey on Martian meteorites stored at NIPR (Hiroi et al., 2011). Bidirectional UV-VNIR diffuse reflectance spectra of those spots were obtained in the ambient condition (in normal atmosphere at room temperature) using a diffuse reflectance spectrometer manufactured by Bunko-Keiki installed in Mizusawa campus of the National Astronomical Observatory of Japan (NAOJ). The measurement geometry was set to 30° incidence and 0° emergence angles in order to avoid specular reflection and facilitate easy comparison with other spectral datasets such as the Reflectance Experiment Laboratory (RELAB) database (http://www.planetary.brown.edu/relab/). The wavelength range was 250–2500 nm, data were recorded at every 5 nm, and the spectral resolution was about 5 nm.

All spectra were measured relative to Spectralon purchased from Labsphere, a near perfect diffuse reflector over this wavelength region, and the relative reflectances were corrected for the absolute reflectance of Spectralon, especially for the prominent absorption bands starting at around 2150 nm in wavelength, using the calibration table used at RELAB (Pieters, 1983; Pieters and Hiroi, 2004). There is a study comparing the performance of the Bunko-Keiki spectrometer with the RELAB spectrometer (Hiroi et al., 2016), which shows they produce highly consistent reflectance spectra except for their difference in spectral resolution.

3. Models for spectral analysis

Reflectance spectra of chip samples tend to be difficult to analyze with high precision because of their surface texture and significant surface boundary reflection compared with spectra of powder samples with mostly volume scattering (absorption). However, there is also a merit of measuring the spectra of chip surfaces in that their component minerals may be mixed linearly as areal mixtures instead of nonlinearly as intimate mixtures. Here, the term “areal mixture” is defined as denoting a state where surface minerals are separated from one another in a much larger scale than the average grain size and wavelength so that reflected light from different minerals do not interact significantly. On the other hand, the term “intimate mixture” is defined as denoting a state where different minerals are mixed closely (intimately) in a similar scale to the grain size or wavelength so that incident light is scattered multiply by grains of different minerals before reflected from the sample surface. Models appropriate for analyzing reflectance spectra in those cases are linear interpolation/extrapolation models for areal mixtures, and mixing models for intimate mixtures.

A linear extrapolation model employed in our previous study on Martian meteorite chips (Hiroi et al., 2011) was also applied to the lunar meteorite chips in this study. In addition, the modified Gaussian model (MGM) (Sunshine et al., 1990) was employed in this study, as was done in our previous studies (Hiroi et al., 2012; Isaacson et al., 2012). MGM has been mostly used for reflectance spectra of intimate mixtures such as laboratory powder samples and regolith on planetary bodies (e.g., Hiroi et al., 2007). Although using MGM for chip samples is somewhat unusual, it is attempted in this study to assess its validity for such chip spectra.

A typical MGM deconvolution is performed by first converting a reflectance spectrum into a natural logarithm reflectance spectrum (an approximated absorbance spectrum) and deconvolving it into a continuum that is linear to wavenumber and a set of Gaussians in the wavelength space (modified Gaussians):

$$\ln R(\lambda) \cong c_0 + c_1/\lambda + \sum_i s_i \cdot \exp\left\{ -(\lambda - \mu_i)^2 \Big/ 2\sigma_i^2 \right\} \tag{1}$$

where denoted as $R(\lambda)$ is reflectance at wavelength λ, c_0 and c_1 are the coefficients for the continuum background, s_i, μ_i, and σ_i are the strength, center, and width of the i-th modified Gaussian band. The strength s is a negative value, and the width σ is usually expressed in terms of the full width at half maximum (FWHM) derived from the width by

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\cdot\sigma \cong 2.35482\ \sigma \tag{2}$$

(e.g., Hiroi et al., 1995). These formula were adopted for MGM deconvolutions in this study. The initial conditions such as the starting parameters and the optimization procedures in the MGM deconvolutions in this study were the same as in Hiroi et al. (2005).

4. Results and preliminary analysis

All the reflectance spectra measured on the meteorite sample spots are plotted in Fig. 2. Although the spectral data quality seems high enough for the purpose of this study, data quality decreases as the sample becomes darker although this plot does not show it clearly. Triangular absorption band near 1.95 and 2.2 μm in wavelength are likely due to either structural water or hydroxyl in plagioclase crystals or terrestrial hydrous products in veins thereof (e.g., Adams and Goullaud, 1978). Although other mineral components may also contain water, high transparency of plagioclase

Table 1
List of Antarctic lunar meteorites recovered by the National Institute of Polar Research considered for this study.

Meteorite Name	Original Weight (g)	Classification	Pairing	Subsample No.	Studied Spots
Y-791197	52.4	Anorthositic regolith breccia		64	A, B
Y-793169	6.07	Unbrecciated basalt		22, 40	
Y-793274	8.66	Basaltic regolith breccia		10	A
Y-82192	36.67	Anorthositic fragmental breccia	Y-86032	83	A
Y-82193	27.04	Anorthositic fragmental breccia	Y-86032	62	B, C
Y-86032	648.43	Anorthositic fragmental breccia		14	A, B, C, D, E
A-881757	442.12	Gabbro		60	A, B, C
Y 981031	185.83	Basaltic regolith breccia	Y-793274	20, 60	A, B, C, D, E
Y 983885	289.71	Anorthositic polymict breccia		79	A