SPECTRAL SIMILARITY BETWEEN SPACE-WEATHERED ANORTHOSITE AND D-TYPE SPECTRA ON THE MARTIAN SATELLITES

Satoru Yamamoto[1], Sei-ichiro Watanabe[2], Tsuneo Matsunaga[1], [1]National Institute for Environmental Studies, Japan (yamachan@gfd-dennou.org), [2]Department of Earth and Planetary Sciences, Nagoya University, Japan

INTRODUCTION

Spectral D-type asteroids are characterized by dark, red-sloped, and featureless (FL) spectra in the visible and near-infrared wavelengths, and are thought to be composed of rocks rich in organic compounds. The Martian two satellites, Phobos and Deimos, resemble spectrally D-type asteroids, suggesting that their origins are by capture of asteroids formed in the heliocentric distance beyond the Mars' orbit, while we need to explain how they were captured and evolved into near-circular and equatorial orbits around the Mars [e.g. 1]. An alternative explanation is that the two satellites originated from accumulation in a disc of debris orbiting around the Mars that were ejected by a giant impact of a protoplanet [e.g. 2-4]. Although recent numerical simulations have reproduced the current orbits of Phobos and Deimos [3,4], it remains unclear how to explain the D-type spectra in the giant impact scenario. In addition, while Phobos possesses the red and blue units that are spectrally different in the visible and near infrared wavelengths, there is no information about the difference in composition between the two units [5,6]. This issue can be solved by determining what kind of materials the Martian satellites are composed of.

To examine this issue, we focus on the Earth's Moon, rather than the Martian moons, because many of the FL spectra identified on the lunar surface resemble D-type spectra [7]. In this study, we demonstrate how the lunar FL spectra resemble D-type spectra, and then discuss a possibility that the spectral features of D-type bodies including Phobos and Deimos can be due to anorthosites affected by space weathering.

COMPARISON BETWEEN LUNAR FL SPECTRA AND D-TYPE SPECTRA

The global distribution of the lunar FL spectra has been revealed by data mining analysis based on the hyperspectral data obtained by the Spectral Profiler (SP) onboard the lunar mission SELENE/Kaguya [7]. Some of the lunar FL spectra are similar to those of D-type asteroids, Phobos, and Deimos. Fig. 1(a) shows an example of the lunar FL spectra, which is similar to a spectrum of the inner main-belt D-type asteroid [8], both in its featurelessness and spectral slope. For the lunar FL, the maximum absorption depths $d_{\max}$ within the range $\lambda = 0.75$–

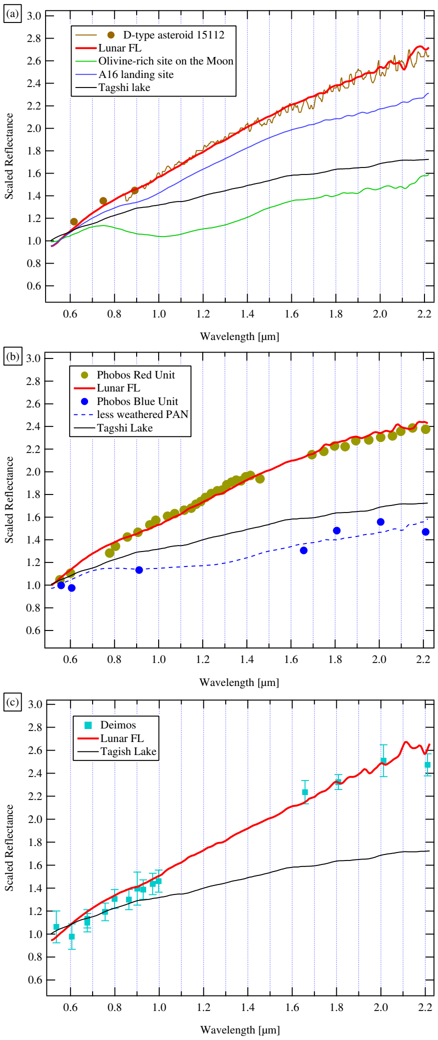

Figure 1: (a) Comparisons of reflectance scaled at $\lambda = 0.55\ \mu$m (scaled reflectance) of lunar FL spectral regions with the D-type asteroids 15112 [8]. For comparison, the scaled reflectances for the Apollo 16 landing site [10], olivine-rich site [11], and a laboratory spectrum for the Tagish Lake meteorite (RELAB data; bkramt011) [12] are plotted. (b) Comparisons of scaled reflectance of lunar FL spectral regions with a red unit of Phobos and of a less weathered PAN spectrum with a blue unit of Phobos [16]. (c) The same as (b), but for Deimos [16].

$1.6\,\mu$m are $d_{\max} < 0.02$. In addition, the spectral slope of the lunar FL spectrum is similar to that of the D-type asteroid. Albedo at $\lambda = 0.75\,\mu$m for the lunar FL spectra shown in this figure is 0.075, which belongs to darker regions on the lunar surface. The darkness for the lunar FL spectral region is consistent with those of D-type asteroids (0.09 ± 0.02) [8]. Fig. 1(b) and (c) shows lunar FL spectra (featurelessness, i.e., $d_{\max} < 0.02$) which are similar to those of the red unit of Phobos and Deimos. There is no clear difference in the featurelessness and spectral slope between the lunar FL spectra and those of the Martian satellites. In addition, albedos at $\lambda = 0.75\,\mu$m for the lunar FL spectra are 0.080 and 0.073, respectively, which are consistent with the average albedo for Phobos and Deimos ($\sim$0.07 around $\lambda = 0.75\,\mu$m)[9].

On the other hand, the lunar spectra at the Apollo 16 landing site [10] and an olivine-rich area [11] clearly show absorption bands centered at $1\,\mu$m, which are different from the D-type spectra (Fig. 1(a)). The spectra for the Apollo 16 landing site and the olivine-rich area exhibit shallower slopes (bluer spectra) than the D-type spectra. Furthermore, the Tagish Lake meteorite, which has been suggested to be a candidate D-type asteroid analog [12], shows a bluer spectrum than the D-type asteroid, Phobos and Deimos. Therefore, the lunar FL spectra are the only category of spectra that almost coincide with the D-type spectra, including those of Phobos and Deimos.

SPACE-WEATHERED ANORTHOSITE AS CANDIDATE FOR D-TYPE SPECTRA

It has been proposed that the lunar FL could be due to PAN (purest anorthosite) soils affected by space weathering [6], where PAN soils are dominated by extremely pure anorthosite with plagioclase contents of $>\sim$98% [13,14]. In this case, it is expected that the PAN soils affected by space weathering exhibit not only featurelessness, but also darker and redder spectra than those of non-weathered PAN, because space weathering lowers the albedo and increases the spectral slope as well as weakening the absorption band. In other words, there is a possibility that the spectral features of D-type for Phobos and Deimos can be due to anorthosites affected by space weathering (space-weathered PAN).

An important signature that can identify the surface materials is a distinct spectral features on Phobos: the red and blue units, which are spectrally different at visible and NIR wavelengths. While the red units, which also resemble the surface of Deimos, show a redder spectral slope and lower albedo and cover most of the surface, the blue units show a less red spectral slope and are exposed in the area associated with $\sim$9-km-sized Stickney crater (ejecta and interior of this crater)[5,6,8]. Such a difference may be explained by different degrees of space weathering; recently exposed blue units are less affected by space weathering, while red units composed of mature regolith are more affected. This explanation is compatible with the space-weathered PAN hypothesis.

DISCUSSION

If the D-type spectra for Phobos and Deimos are accounted for by the space-weathered PAN, we need to explain the origin of anorthosite on the Martian satellites. One possible explanation may be the giant impact scenario, where the two Martian satellites were thought to have been formed in an accretion disk generated by a giant impact into primordial Mars [e.g. 2-4]. If the Martian primordial crust was rich in refractory elements such as Ca and Al, i.e., anorthositic crust, the composition of the accretion disk generated by the giant impact would be rich in Ca and Al. When the formation of embryos of satellites in the disk owing to a gravitational instability occurred at $T <\sim 1400$–$1600\,$K [15] during the cooling processes, plagioclase (anorthite) may be a major condensed mineral in the accretion disk, facilitating the formation of anorthositic satellites.

In any case, our results show that the D-type spectral features of Phobos and Deimos are no longer strong evidence for the capture origin. However, since we cannot conclude a definitive answer for the composition for Phobos and Deimos from only the spectral data, future in-situ analysis and sample return missions targeted to Phobos and Deimos (e.g., MMX; Martian Moons eXploration, which is being developed by JAXA) are needed.

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