MUOGRAPHY FOR FUTURE PHOBOS LANDING MISSION. H. Miyamoto[1], H. Tanaka[1], T. Yoshimitsu[2], M. Otsuki[2], M. Taguchi[3], S. Saito[3], Y. Uchiyama[3], S. Kameda[3], H. Kikuchi[1], and J. M. Dohm[1], [1]University of Tokyo (7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; hm@um.u-tokyo.ac.jp), [2]ISAS/JAXA (3-1-1 Yoshinodai, Sagamihara, Kanagawa 252-5210, Japan), [3] Rikkyo university (3-34-1 Nishiikebukuro, Toshimaku, Tokyo 171-8501, Japan)

Introduction: Subsurface structures of planets, satellites, and small bodies are considered to provide key information about the origins and evolutional histories of these bodies. However, different from surface features, which can be observed using remote-sensing devices, subsurface structures are generally difficult to study even on Earth. Because there is no definitive method for revealing subsurface structures on Earth, multiple approaches are usually taken, and their results compared and comprehensively interpreted to determine the structural type, extent, and origin.

Traditional and standard methods used for this purpose on Earth, including seismic methods, such as reflection seismology and seismic tomography, seismoelectrical, magnetic, electromagnetic, and electrical methods, and graviometry and gravity gradiometry, have been thoroughly tested in various locations on Earth. However, their applications to extraterrestrial bodies are sometimes challenging because most of them require direct contact with the surface of the target body. Also, even if some of these methods could be applied to an extraterrestrial body, they would require inverse analyses before converting observational data of subsurface structures into useful information, which often causes additional problems in their interpretations even on Earth.

Muography: Muography is a new method to obtain three-dimensional density structures of geological features at high resolution. It uses muons, which are penetrating particles generated by cosmic rays. Comparing with X-rays having a < 1 m penetration depth of solid rock, muons can travel several kilometers through rocks. Thus, the technique provides the means to measure the density of a structure of kilometer-size. For example, this technique has been used to acquire three-dimensional images of volcanoes including their internal structures and their composing rocks of varying density, temperature, water content, and porosity [e.g., 1-3]. Particularly important for planetary explorations is that Muography does not require direct contact between the target body and detector. Also, because a muon detector is a passive instrument without emitting signals such as seismic and electromagnetic waves, required power and an instrumental structure are respectively lower and simpler, compared to other ordinary approaches. Furthermore, the acquired data does not require inverse analysis, which significantly reduces the amount of data transmitted to the Earth. Therefore, once a Muography instrument is developed for an extraterrestrial mission, it will become a standard method for detailing the internal structures of a wide variety of features, information of which will significantly increase our understanding of the origin and evolutional histories of extraterrestrial bodies.

Phobos, a unique target of a small body: Asteroids and comets can be a target of a Muography instrument. Here we propose that Phobos is an especially interesting target for Muography.

Muons are ultimately generated from cosmic rays accelerated by supernova; on Earth, cosmic rays collide with atmospheric nuclei such as nitrogen and oxygen and the resultant mesons such as pions and kaons decay to eventually form muons. Similar situations would be expected on other planetary bodies where sufficient atmospheres exist. Muons occur on Mars, for example, due to its CO2 atmosphere; estimates of muon production on Mars indicate that the flux of horizontal muons is sufficiently strong [4]. Similarly, we can expect muon productions in the atmospheres of Venus and Titan to be at levels sufficient for possible Muography-based imaging.

Muon productions through collisions of cosmic rays with silicates are also discussed as a possible source of muons for Muography-based investigation on asteroids. However, in this case, the efficiency might be significantly lower than those produced from the atmosphere because the interaction lengths of secondary mesons are shorter than their decay lengths. Therefore, applicability of Muography to airless bodies remains uncertain. Nevertheless, Phobos, a Martian satellite, is one interesting exception; it is a 20-km-diameter airless body located close enough to Mars for muons generated in the Martian atmosphere to travel before decaying and to penetrate through it at a sufficiently high rate.

Phobos is one of two satellites of Mars. The size of Phobos is about 27x21x18 km, with dimensions similar to that of asteroid Eros. The reflectance spectra of Phobos show patterns similar to D-type asteroids believed to be one of the most primitive bodies in the solar system, and thus this satellite might be a captured asteroid from the main belt. However, the orbit of Phobos does not support this possibility because the eccentricity of Phobos and the inclination to Mars are only 0.0015 and 1 degrees, respectively.

The surface of Phobos is likely covered by fine-grained materials, including dust, because more than 90 % of ejecta materials from Phobos are trapped by the gravity of Mars, ultimately falling back to the satellite's surface. This makes the original, unmodified materials, which are intrinsically important to understand the origin of Phobos, obscured from the usual spectroscopic inspection. Therefore, subsurface features should be explored in a future mission. Especially important objectives include: (1) determining whether subsurface ice is still remaining; the low density of Phobos (1870 kg/m3) may be explained by the existence of internal ice, (2) understanding the structure and rock composition of the original body, and (3) identifying large boulders buried by dust deposits which will aid in (2).

Muography on Phobos: JAXA/ISAS is now actively discussing a future Phobos mission to be launched in 2022, which includes a Muography instrument as one of the possible onboard instruments. A sample-return misson from Phobos is in the forefront of the discussion, involving a landing on the Martian satellite. Though the number of landings (or touch downs) has yet to be determined, we expect at least one to likely occur on (or near) the so-called "blue unit", located in and in the nearby surroundings of the Stickney crater. The "blue unit", considered to be a prime target as it is unique from the otherwise ubiquitous reddish and homogenized materials that cover the surface of Phobos, could hold key information about the satellite's origin and evolution. Stickney is ideal for the Muography instrument because: (1) it occurs on the near-side of Mars, where the largest Muon count from Mars' atmosphere is expected; (2) the slope of its rim is steep enough allowing higher depth (D)/penetrating length (L), meaning that the deepest part of Phobos can be observed at the condition of a limited muon count; and (3) the density of its surface and subsurface structures holds high scientific value especially in understanding the nature of the blue unit.

We perform topographic analysis of Phobos by using the numerical shape model developed by Bob Gaskell (Gaskell Phobos model; Fig. 1). We find that utilizations of muons from Mars' atmosphere become geometically possible along the floor of the basin of Stickney crater. On the floor, we can observe density structures of Phobos about 200-600 m in depth at better than 30 % accuracy (assuming 30 muon counts of the muon energy of 0.5-1TeV for a linear density of 1000-2000hg/cm^2, we estimate the muon intensity to be 10^{-6}-10^{-7} cm^{-1} s^{-1} sr^{-1}, which ultimately provides about 2-20 muons/year/pixel at 50-100 horizontal resolution). The Muography instrument (MOI) is composed of two 10 x 10 cm muon detectors placed 10 cm apart. Each detector is composed of 18 mm scintillator and 30 mm of photomultiplier. This allows us ±20° of FOV (field of view) with 60 mrad resolution. Such an instrument would be adequately placed on the surface of Phobos with sufficient time for observation using a small rover similar to MINERVA onboard Hayabusa [5] or MINERVA 2 onboard Hayabusa 2.

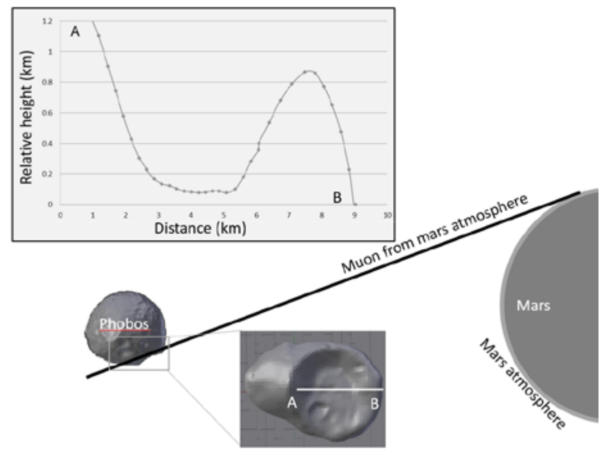

Figure 1. Schematic configuration portraying muography on Phobos, including muons being genereated from Mars' atmosphere and arriving at Phobos before becoming completely decayed and the most optimal muographic vantage point being the rim of Stickney crater. The upper inset is the topographic crossection of the Stickney crater along the line indicated at the bottom of this figure.

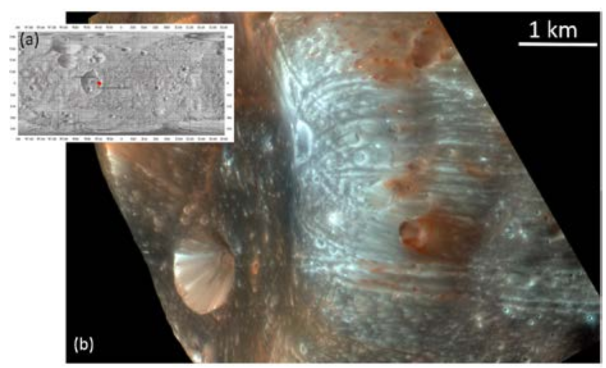

Figure 2. (a) The location of a possible landing site indicated on a shaded relief map of phobos prepared by the U.S. Geological Survey ; (2) HiRISE close-up image of the rim of Stickney crater highlighting the blue unit (NASA/JPL-Caltech/University of Arizona).

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