SCIENTIFIC VALUES OF MARTIAN IMPACT EJECTA ON ITS MOONS. R. Hyodo[1,2], K. Kurosawa[3], H. Genda[2], T. Usui[1], and K. Fujita[1], [1]ISAS, JAXA (hyodo.ryuki@jaxa.jp), [2]Earth-Life Science Institute, Tokyo Institute of Technology, [3]Planetary Exploration Research Center, Chiba Institute of Technology.

Introduction: Mars has two small moons, Phobos and Deimos. Their origin is debated. Historically, the moons are thought to be gravitationally captured asteroids [1,2]. However, explaining their orbital properties – almost circular and almost coplanar orbits – is challenging due to the isotropic nature of capture process. Recently, more and more studies investigated the giant impact scenario where the moons accrete within the debris produced by a large impact on Mars [3,4,5,6,7]. The endogenous bulk material properties of the moons strongly depend on its origin. If the moons are the captured objects, the bulk materials would be analogous to a type of chondrite [8]. If a giant impact has produced the moons, the bulk materials of the moons would be a mixture of Martian and impactor materials that experienced a high temperature phase [6]. In addition, – regardless of its formation scenarios – materials delivered by natural influx of background asteroids and impact-ejecta of Mars produced by numerous small impacts are expected to be mixed in the surface regolith of the moons [9,10].

Here, we re-visited the amount and condition of a recent delivery of impact ejecta from Mars to its moons by using state-of-the-art numerical approaches [11], whereas previous studies used a simple analytical models [9,10]. We report about 10-100 times increase of the mass transferred from Mars to its moons than the previous estimations due to mainly better numerical approach to this problem [11].

Martian moons are the target bodies of the Japan Aerospace eXploration Agency (JAXA) sample return mission Martian Moons eXploration (MMX). MMX plans to collect surface material from Phobos and return samples to Earth (launch in 2024 scheduled) [12]. Therefore, a detailed study of the surface materials on Phobos (potential sample material) is required to maximize the scientific results of the MMX mission.

Numerical Methods: In order to study the amount and condition of mass transfer from Mars to its moons, we proceeded with the following two steps. Firstly, impact simulations under a variety of impact conditions expected for asteroidal impacts on Mars were performed to obtain datasets of positions and velocities of the impact debris immediately after impact. The obtained datasets were then used in 30,000 Monte Carlo runs of impact bombardment on Mars, which include the long-term orbital evolution of the impact debris, to assess the quantitative likelihood of delivery to the Martian moon(s).

The impact location on the surface of Mars, orbital phase of the moons were fully randomized. Other impact parameters, such as impact velocity and impactor mass, were chosen from the expected impactor distribution within the last 500 Myr [13].

In addition, the delivery from the five largest recent (<10 Myr) craters, Mojave, Tooting, McMurdo, Corinto, and Zunil were also investigated selectively by 10,000 Monte Carlo runs for each crater. In these specific cases, the impact location on the Martian surface and the impact energy were fixed as that of the current crater position and that capable of producing the observed crater diameter, respectively.

In the calculations, Phobos is fixed at the current orbital distance to Mars. During the last 500 Myr, Phobos orbit has shrunken and its cross section increased about ×5. Thus, we multiplied the conservative value of 1/5 to the results obtained from the Monte Carlo simulations to derive values within the last 500 Myr.

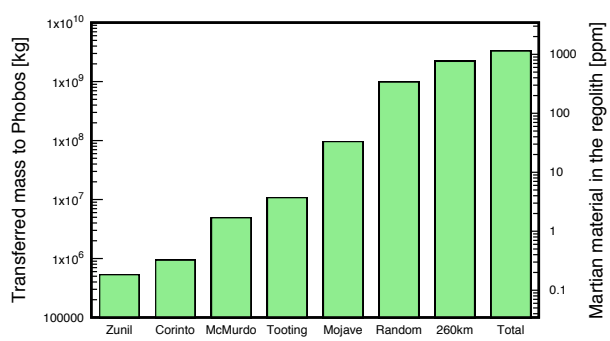

Fig. 1: The mass transferred from Mars to Phobos at different impact events on Mars [11]. "Random" and "260km" are those at the sum of numerous impacts that formed *D*=2-100 km craters and a single impact that formed *D*=260 km crater during the last 500 Myr, respectively. "Zunil", "Corinto", "McMurdo", "Tooting" and "Mojave" are those at the five largest recent crater-forming events (*D*>10 km and <10 Myr). "Total" is the sum of all the cases considered here. *Y*-axis on the right side of the panel shows the corresponding fraction of Martian materials assuming they are mixed homogeneously within a 1 m-depth of Phobos regolith. Further details are found in Hyodo et al. (2019) [11].

Mass Transfer from Mars to Phobos: Together with the Martian crater isochron [13], our Monte Carlo simulations provide the median values of net mass transfer from Mars to Phobos (Figure 1; see also Hyodo et al. (2019) [11]).

During the last 500 Myr, the total number of craters in Hartmann isochrons is more than 10 for their diameters of $2<D<100$ km (hereafter, the "Random" case) [13]. On the other hand, D=260 km-sized impact is expected to occur at least one time within the last 500 Myr (hereafter, the "D=260km" case) [13]. The median values of the transferred masses for these cases are as follows [11]:

1. ~9.8×10^8 kg (~340 ppm) is transferred from Mars to Phobos by numerous small impacts that formed D=2-100 km-sized craters (the "Random" value)
2. ~2.2×10^9 kg (~760 ppm) is transferred from Mars to Phobos by an impact that formed a D ~ 260 km-sized crater (the "D=260km" value)

On the recent delivery from the five largest craters (D>10 km) to Phobos within the last 10 Myr, the mass transferrers are as follows [11]:

1. ~9.6×10^7 kg from Mojave-crater forming event (D=58 km)
2. ~1.1×10^7 kg from Tooting-crater forming event (D=29 km)
3. ~4.9×10^6 kg from McMurdo-crater forming event (D=23 km)
4. ~9.3×10^5 kg from Corinto-crater forming event (D=13.5 km)
5. ~5.3×10^5 kg from Zunil-crater forming event (D=10.1 km)

Note that, the mass transferred to Deimos is about ~1/20 from that to Phobos due to the difference of their cross sections to Mars.

Properties of Martian Materials on Phobos: Ejection velocity of >3.8 km/s is required to reach Phobos from Martian surface. On the other hand, ejection velocity of >5 km/s is required to escape from Mars system. Martian meteorites found on Earth, as a comparison, are all igneous rocks (their experienced peak pressure are >5 GPa) with a limited range of ages [e.g. 14]. It is not easy for a fragile Martian material to reach Earth's ground due to required high ejection velocity that accompanies high shocked process and due to the ablation in Earth's atmosphere. We found that Martian materials on Phobos delivered as impact ejecta are less shocked (<5 GPa) and potentially cover all Martian geological eras and consist of all types of rocks, from sedimentary to igneous [11].

Scientific Values of Martian Materials on its Moons: MMX plans to collect samples of >10 g of Phobos regolith. Assuming a typical cubic grain diameter for the Mars fraction of 300 μm and a density of 3 g/cm, our results indicate that at least ~34 Martian grains (~340 ppm from the "Random" case) would exist in the returned sample. In addition, another ~76 Martian grains from stochastic large impacts are also potentially available (~760 ppm from "D=260 km" case). Martian grain in the regolith on Phobos with a typical grain diameter of 300 μm is expected to contain more than one "chronometer" mineral (e.g., zircon, baddeleyite, or Ca-phosphate for U–Pb dating) in the case that the typical size (<30 μm) and abundance (~0.1–1%) of chronometer minerals are comparable to those of Martian meteorites. Thus, the >34 Martian grains returned by MMX would provide a wealth of "time-resolved" information on the evolution of Martian surface environments because these grains would have been transported randomly from any of the seven geologic units: pre-Noachian, Noachian (early, middle, & late), Hesperian (early & late), Amazonian. We conclude that MMX sample could be the first MSR from its moon and extend the scientific concept of Martian moons from simply "Martian moon science" to "Mars system science" [11].

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