EXPERIMENTAL INVESTIGATION OF THE SPACE WEATHERING OF PHOBOS BY PLANETARY OXYGEN IONS.

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Introduction: Recent investigations on the space weathering of the Martian moon Phobos have revealed an important sputtering mechanism besides solar wind sputtering: Phobos is also significantly eroded by planetary oxygen ions that originate in the Martian atmosphere [1, 2]. MAVEN measurements show that Mars shadows the solar wind from reaching Phobos in the Martian magnetotail region. Here space weathering models predict planetary ions at energies between several 100s to several 1000s eV to be the dominant sputtering contribution [2]. However, these calculations might have inaccuracies due to their sputtering inputs from SRIM simulations [3]. Besides previously reported inaccuracies of SRIM sputtering yields [4, 5], effects such as ion implantation or chemical sputtering are not included in these calculations. Sputtering measurements with planetary analog samples are still rare and mostly focus on the H^+ and He^{2+} component of the solar wind. We have now investigated the sputtering of Phobos analog samples by atomic and molecular O ions to improve the understanding of their effect on the space weathering of Phobos. We find that those sputtering yields are lower than previously calculated, but the experimental results support the conclusion that planetary O ions are the most important sputtering contribution in the magnetotail [6].

Methods for Investigations of Phobos Analog Samples: We used thin films of augite $(Ca,Mg,Fe)_2Si_2O_6$ deposited on a Quartz Crystal Microbalance (QCM) as analog samples for the surface of Phobos. These films were deposited by Pulsed Laser Deposition and their chemical composition was found to be similar to estimations for the surface composition of Phobos [2, 7]. Using the QCM technique for sputtering measurements allows real time in-situ measurements of the mass change, from which sputtering and ion implantation can be deduced. Experimental results are compared to simulations with the code SDTrimSP, where consistent input values for accurate sputtering simulations of augite and the similar mineral wollastonite $CaSiO_3$ exist [5, 8].

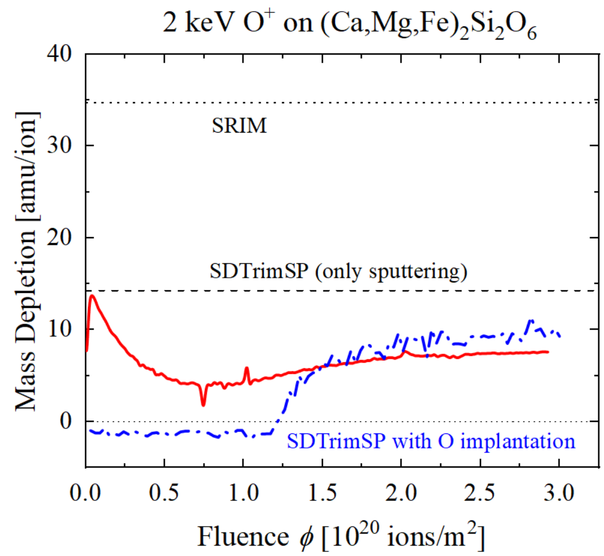

Figure 1: Fluence dependent mass depletion of augite under 2 keV O^+ irradiation. Experimental results (red) are compared to a calculation with SRIM (black dotted line) and SDTrimSP. Simulations are shown that only account for sputtering (black dashed line) and that also include O implantation (blue). Figure adapted from [6].

Sputtering by O^+ ions and O implantation: O^+ irradiations of augite samples were performed at energies between 1 and 5 keV at different angles of incidence. SRIM was found to significantly overestimate the sputtering yield by O ions. The mass change of the sample shows a significant fluence dependence before reaching a steady state after about 3×10^{20} ions/m^2 (Figure 1). Even for steady state yields an offset compared to SDTrimSP predictions was observed (Figure 2). Both the fluence dependence and the steady state values can be much better reproduced by dynamic SDTrimSP simulations that include O implantation up to local concentrations of 67% (see Figure 1 and 2). It can thus be concluded that we observe a combination of sputtering and O ion implantation at the same time [6], as only mass changes are measured with a QCM. No evidence for O implantation is found in wollastonite (Figure 2), indicating the O implantation is connected to the Fe content in augite.

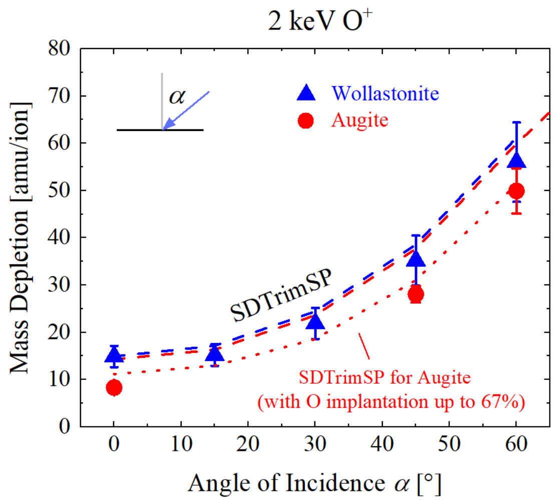

Figure 2: Angular dependence of the sputtering by 2 keV O^+ ions for augite (red) and wollastonite (blue). Results from measurements (dots) are compared to SDTrimSP sputtering simulations (dashed lines). For augite, a simulation with both sputtering and O implantation is included (dotted line). Figure adapted from [6].

Sputtering by Molecular Ions: As MAVEN measurements showed that both atomic and molecular O ions contribute to the sputtering of Phobos, experiments were performed to compare their effects. For the investigated energies of 1 and 2 keV/O atom, no signs of any molecular effects were found. One O_2^+ ion behaves the same as two independent O^+ ions at the same velocity [6]. This indicates an immediate dissociation upon impact and no significant overlap of collision cascades in the solid.

Consequences for the Space Weathering of Phobos: Even when O implantation is accounted for, the measured sputtering yields are about 50% lower than previously assumed. This leads to a smaller contribution of O sputtering compared to solar wind sputtering, which is even further reduced, when an estimation for potential sputtering by solar wind ions is included (see Figure 3) [5, 6]. Nevertheless, this does not affect O sputtering being dominant in the Martian magnetotail region. Our experimental results therefore underline the importance of sputtering by planetary ions. The observed O implantation in Fe-bearing augite is also relevant for Phobos. Implantation of planetary ions in the Mars-facing side of Phobos would be of interest for investigations by the upcoming MMX mission of JAXA, which provides a good opportunity for further investigations in the future.

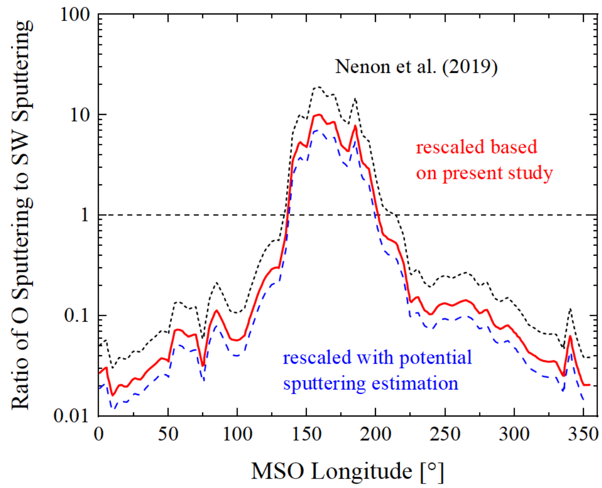

Figure 3: Ratio of O sputtering to solar wind sputtering over the orbit of Phobos around Mars. Calculations by Nenon et al. ([2], black) are rescaled based on experimental findings (red) and an estimation of potential sputtering by He^{2+} ions ([5], blue). Figure taken from [6].

References: [1] Poppe A. R. and Curry S. (2014) *Geophys. Res. Lett.*, *41*, 6335-6341. [2] Nenon Q. et al. (2019), *J. Geophys. Res.: Plan.*, *124*, 3385-3401. [3] Ziegler J. et al. (2010), *Nucl. Instrum. Methods Phys. Res. B*, *268 (11)*, 1818-1823. [4] Szabo P. S. et al. (2018), *Icarus*, *314*, 98-105. [5] Szabo P. S. et al. (2020), *Astrophys. J.*, *891(1)*, 100. [6] Szabo P. S. et al. (2020), *J. Geophys. Res.: Plan.*, *125*, e2020JE006583. [7] Cipriani F. et al. (2011), *Icarus*, *212(2)*, 643-648. [8] Biber H. et al. (2020), *Nucl. Instrum. Methods Phys. Res. B*, *480*, 10-15.