ON THE LONG-TERM WEATHERING OF AIRLESS BODY SURFACES BY THE HEAVY MINOR IONS OF THE SOLAR WIND: INPUTS FROM ION OBSERVATIONS AND SRIM SIMULATIONS.

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Introduction: Airless body surfaces exposed to the solar wind are weathered by solar wind ions, which sputter atoms and molecules, participate to the creation of optically opaque particles, alter the regolith composition and create amorphous rims atop regolith grains. As protons and alpha particles dominate the density of solar wind ions, these two species may be the main contributors to ion weathering. However, the importance of solar wind ions heavier than alpha particles, sometimes referred as 'minor' ions, for the ion-induced alteration of airless body surfaces is an open debate. The fundamental question at stake is whether the variety of different minor ion species, their high masses, and their high charge states may overcome their low densities in the solar wind to enable them to significantly contribute to ion weathering processes. In this presentation, we investigate long-term effects which develop on geological time scales of hundreds to millions of years.

The long-term averaged kinetic energy spectra of protons, alpha particles and heavy minor ions: We first estimate as best as possible the long-term averaged kinetic energy spectrum (thermal and suprathermal) of solar wind ions that impact airless body surfaces by compiling and contrasting ion measurements gathered over extended periods of time by the ACE, Wind, STEREO, ARTEMIS, and MAVEN missions. ACE and Wind are located at the Sun-Earth L1 Lagrange point, the STEREO A and B satellites are in orbit around the Sun at a distance of a 1AU, the two ARTEMIS probes are in orbit around the Moon and MAVEN orbits the red planet Mars. Among all these satellites, only ACE, Wind, STEREO A and STEREO B were equipped to observe solar wind minor ions, but ARTEMIS and MAVEN data help to estimate the flux of protons and alpha particles.

Figure 1 shows the compilation of all available long-term spectra of solar wind iron ions. The green curve was published by Mewaldt et al. [2001] [1] and aggregates data obtained during 11 months in 1999 at "low" kinetic energies (E_k < 30 keV per nucleon) and measurements gathered from 1997 to 2000 at higher kinetic energies.

For kinetic energies below 30 keV per nucleon, we find that the spectra published by Mewaldt et al. [2001] provide the most comprehensive picture to investigate the role of minor ions compared to protons and alpha particles. At higher kinetic energies, one can see on Figure 1 that all spectra computed over different periods of time with different ion measurement systems onboard different satellites are in excellent agreement. These ion spectra are the best available estimate of the number of ions impacting airless body surfaces over hundreds to millions of years.

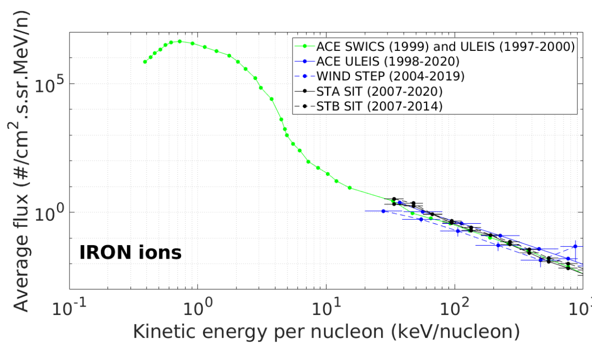

Figure 1 Compilation of long-term averaged omnidirectional kinetic energy spectra of solar wind iron ion fluxes. Acronyms give the names of space missions and particle instruments (see [4] for details).

Figure 2 shows the ratio of helium fluxes (alpha particles) to iron ion fluxes computed at each kinetic energy per nucleon. It can be noted that this ratio is lower at high kinetic energies compared with thermal energies of ~1 keV per nucleon. This is an intrinsic property of the solar wind which may be linked to the fact that relative minor ion densities are enhanced during solar wind events. The enhanced proportion of minor ions relative to alpha particles at high kinetic energies may increase the importance of minor ions in weathering material at depth, where only high kinetic energy ions can access.

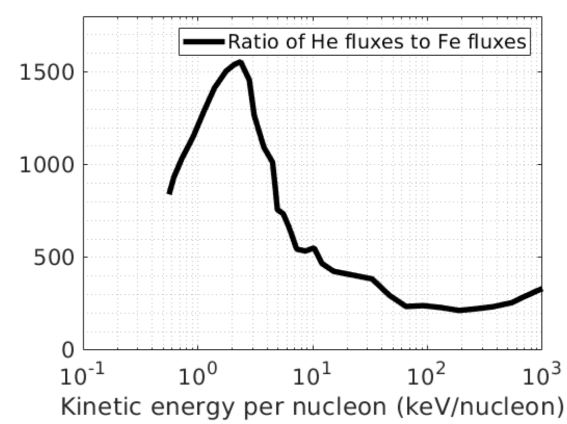

Figure 2 Ratio, at each kinetic energy per nucleon, of the average flux of helium ions to iron ions.

Importance of solar wind minor ions for the ion weathering of airless body surfaces: In order to investigate the contribution of minor ions to surface weathering, we have computed two quantities: (1) the flux of material sputtered from the surface, as preferential sputtering modifies relative material atomic concentrations, and (2) the generation of atomic displacements inside the material, which creates amorphous rims observed atop grains brought back from the Moon and asteroid Itokawa [2,3]. To estimate these two effects, we convolve the long-term averaged kinetic energy spectra of ions with simulations of ion-induced effects conducted with the SRIM software (Stopping and Range of Ions in Matter).

Importance of the minor ions for surface sputtering: SRIM allows to estimate kinetic sputtering yields only. Another source of sputtering for the multiply charged minor ions of the solar wind is 'potential sputtering', by which the energy stored in the multiple charge state of ions is released into the material and contributes to atomic displacements and therefore sputtering. Depending on the level of potential sputtering for alphas and minor ions, we find that solar wind minor ions contribute to 8%-14% of the total flux of atoms sputtered by impacting ions. We also find that most of sputtering is caused by energies around 0.7-2 keV per nucleon, i.e. higher and lower kinetic energies do not contribute to this process.

Contribution to the generation of atomic displacements: Figure 3 shows the contribution of solar wind minor ions to the total number of atomic displacements generated by ions, as a function of depth inside the material (taken here to be Fe50 olivine with a density of 3.8 g/cc). We find that the enhanced proportion of minor ions at high kinetic energies (Figure 2) corresponds to a contribution of minor ions to atomic displacements that increases with increasing depth. In particular, minor ions generate more than ~20% of atomic displacements deeper than 100 nanometers. They therefore accelerate the creation of thick amorphous rims, that can be as thick as 250 nanometers [2].

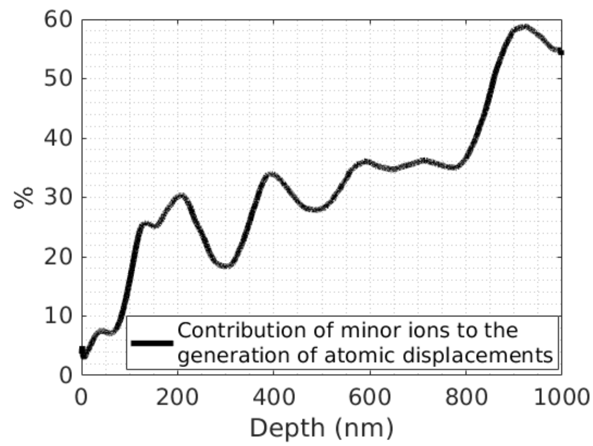

Figure 3 Contribution of solar wind minor ions to the generation of atomic displacements, as a function of depth inside Fe50 olivine (3.8 g/cc). This was computed from the long-term averaged fluxes of ions convolved with SRIM simulations.

Conclusions: To advance the debate on the importance of solar wind minor ions on airless body ion weathering, we have compiled ion observations, at thermal and suprathermal kinetic energies, with SRIM simulations. This new approach confirms that solar wind minor ions play an important role in the weathering of airless body surfaces in the solar system.

The results of this study are published in an article of the Planetary Science Journal [4].

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References: [1] Mewaldt R. A. et al. (2001) *AIP Conf. Proc.* [2] Keller L. P. and Zhang S. (2015) *in Space Weathering: an integration of remote sensing data, laboratory experiments and sample analysis workshop* [3] Christoffersen R. and Keller L. P. (2015) *LPSC XLVI, contribution number 1832* [4] Nénon Q. and Poppe A. R. (2020) *The Planetary Science Journal 1 (3)*, 69