WEATHERING OF LUNAR POLAR CRATER INTERIORS BY NORTHWARD/SOUTHWARD IONS: ION OBSERVATIONS BY THE ARTEMIS PROBES

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Introduction: Permanently shadowed regions (PSRs) inside lunar polar craters can be sheltered from micrometeoroids and solar wind ions. The cold and relatively unweathered environments of PSRs may therefore accumulate water ice and other volatiles that not only hold clues on the origin of water in the inner solar system, but are also of high interest for in-situ resource utilization.

To zeroth order, solar wind ions form a beam of 1 keV/nucleon ions flowing parallel to the ecliptic plane and therefore do not impact the interior of lunar polar craters. However, the development of plasma wakes at the edge of the craters lead to electrostatic potentials that deflect the horizontal ions inside the craters. Recently, Rhodes and Farrell (2020) [1] computed the lunation-averaged flux of ions deflected this way in four lunar polar craters, including Shackleton. The previous authors have in particular revealed that the depth-to-width ratio of the Shackleton crater does not allow any of the horizontal solar wind ion flux to access and alter the central region of the floor of Shackleton.

Here, we determine the long-term averaged flux of ions that travel northward or southward and that can therefore directly access the inside of lunar craters located near respectively the South Pole and North Pole. These out-of-ecliptic ions have 4 known origins: (1) suprathermal ions, (2) terrestrial foreshock ions, that are solar wind ions reflected and accelerated away from the Earth bow shock, (3) shocked and deflected ions in the terrestrial magnetosheath and (4) ions encountered in the terrestrial magnetotail.

Methods: This study relies on in-situ ion measurements gathered by the ElectroStatic Analyzer (ESA) experiment onboard the two ARTEMIS probes orbiting the Moon.

Previously, Poppe et al. (2018) [2] put together *omnidirectional* (averaged over all look directions in the sky) ion observations collected by ARTEMIS ESA from 2012 to 2018 to determine the characteristics of ion fluxes as a function of the position of the Moon along its orbit (i.e., upstream solar wind, in the terrestrial magnetosheath or magnetotail) and as a function of ion kinetic energy.

Here, in order to determine the long-term averaged northward and southward ion fluxes, we aggregate *directionally-resolved* measurements gathered by ARTEMIS ESA from January 2012 to January 2019.

We exclude from our analysis lunar exospheric ions and ions backscattered, reflected or sputtered from the Moon, as it is unknown how many of these ions then re-impact Earth's satellite. The so-called "lunar" ions are mostly convected downstream of the Moon [3], so that, in order to avoid them, we aggregate data obtained only far upstream of the natural satellite (XSSE>3 Rl, purple region on Figure 1).

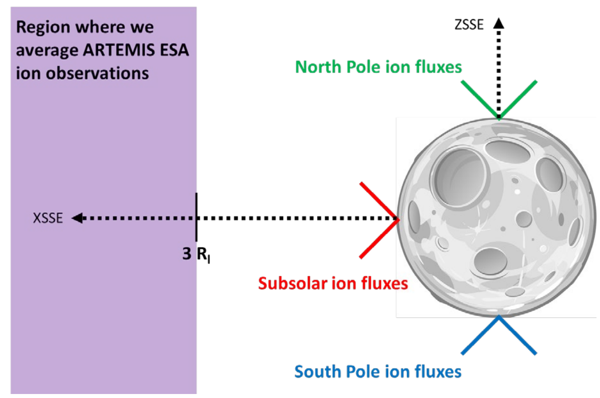

Figure 1 We average measurements gathered at XSSE>3 Rl only (purple region). Directionally-resolved ion observations are averaged over directions within a cone with half opening angle of 45°. It enables to compute ion fluxes impacting the subsolar point (red), North Pole (green) and South Pole (blue).

Finally, we average directionally-resolved measurements over look directions to compute the flux of ions that impact the subsolar, North Pole and South Pole locations. At each of the three locations, we only consider ions that come from directions within a cone with half opening angle of 45° around the zenith direction (see Figure 1). By doing so, we capture all of the ion flux impacting the subsolar point when the Moon is in the upstream solar wind region and magnetosheath region. In addition, the width and depth of Shackleton crater near the South Pole enable the crater's central region to be exposed to ions coming with an angle of 59° from the zenith direction. Fluxes averaged within a 45° cone at the South Pole therefore represent a lower limit on the intensity of ion fluxes weathering Shackleton's floor.

Results: Figure 2 shows in which plasma regions crossed by the Moon (upstream solar wind, magnetosheath, magnetotail) ions that can directly enter inside lunar South Pole craters are encountered.

Northward ions (impacting the South Pole) in the upstream solar wind region (red curve on Figure 2) are a negligible contributor to the GSE-longitude-averaged spectrum (black curve). We note that the bump at ~8 keV/q in the solar wind region (red curve) comes from terrestrial foreshock ions. Shocked and deflected ions in the magnetosheath (green curve) significantly contribute to 0.1-2 keV/q ions inside South Pole craters. However, we find that most of northward ion fluxes at all energies are encountered when the Moon crosses the terrestrial magnetotail, where ion fluxes are quasi-isotropic [4], even if this region is encountered less than 5 days per lunar orbit.

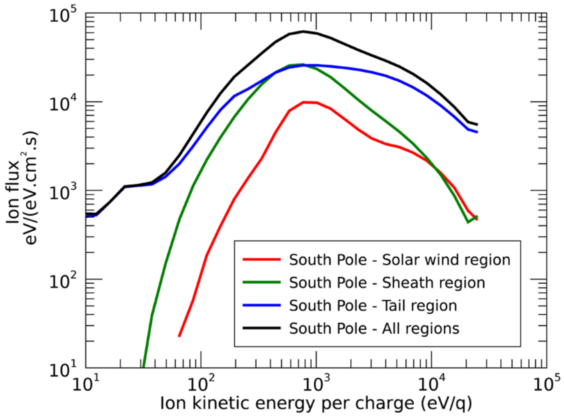

Figure 2 Long-term averaged flux of ions with a direct access to the interiors of polar craters near the South Pole. The spectrum in each plasma region gives the contribution to the total GSE-longitude-averaged spectrum (in black).

Finally, we compare in Figure 3 the intensity of ion fluxes impacting the equatorial and polar locations. The tidally locked rotation of the Moon was taken into account to convert subsolar ion fluxes to the flux seen by a point at the equator. We conclude that:

- For ~1 keV ions, the central floor of Shackleton's crater is weathered by a flux of ions that is not 0 but that is that is ~10^{-3} the equatorial flux, because of shocked-deflected ions in the magnetosheath and isotropic ion distributions in the terrestrial magnetotail.
- For ~1 keV ions, electrostatically-deflected horizontal ions have a flux higher than 10^{-2} times the solar wind flux on the walls and in most locations inside polar craters (except Shackleton's floor) [1]. The flux of these ions is much higher than the northward/southward ion fluxes computed here. Electrostatic deflection is therefore a dominant source of ions inside lunar craters.
- For the lowest and highest kinetic energies studied here, ion fluxes inside lunar polar craters are similar to equatorial ion fluxes.

Future work: Sputtering, implantation, atomic defects and the creation of optically opaque particles in Shackleton's central floor induced by the low ion flux computed here should be the object of future studies. These alterations would also have to be compared with possible weathering effects linked to dielectric breakdown [5].

Finally, the contribution of solar wind protons reflected and backscattered from the lunar surface to the flux of ions entering lunar polar craters is unknown. We may have therefore not yet identified the dominant source of ions weathering the interior of lunar polar craters.

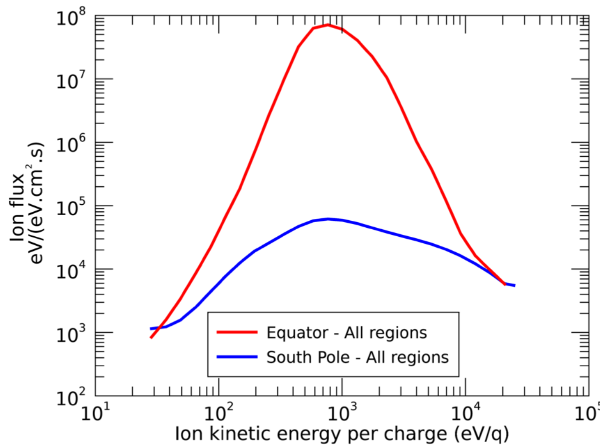

Figure 3 Long-term averaged flux of ions impacting an equatorial location on the Moon (in red) and having a direct access to the interiors of South Pole craters (in blue). The spectrum for North Pole craters (not shown here) is exactly the same as for the South Pole craters.

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References: [1] Rhodes D. J. and Farrell W. M. (2020) *The Planetary Science Journal, 1,* 13. [2] Poppe A. R. et al. (2018) *JGR: Planets, 123,* 37-46. [3] Harada Y. et al. (2015) *JGR: Space Physics, 120,* 4907-4921. [4] Wang C. (2013) *JGR: Space Physics, 118,* 244-255. [5] Jordan A. P. (2015) *JGR: Planets, 120,* 210-225.