DO LUNAR REGOLITH SAMPLES TESTIFY OF A CONTRIBUTION OF COMETARY XENON ONTO THE MOON? R. Wieler[1], P. Bochsler[2], B. Marty[3], [1]ETH Zürich, Earth Sciences, NW D77.2, CH-8092 Zürich, Switzerland, wieler@erdw.ethz.ch, [2]Physikalisches Institut, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland, [3]Université de Lorraine, CNRS, CRPG, F-54000 Nancy, France

Cometary Xe in lunar rocks and soils? Xenon in comet 67P/Churyumov-Gerasimenko (hereafter 67P/C-G) is strongly depleted relative to solar wind Xe (SW-Xe) in the heaviest isotopes ^{134,136}Xe [1]. Cometary xenon with a low abundance in ^{134,136}Xe appears also to be present in lunar rocks [2, 3], and Meshik et al. [4] concluded that also lunar regolith samples contain - in addition to implanted SW-Xe - a minor fraction of primordial Xe depleted in ^{134,136}Xe, which they presume to be of cometary origin. Here we discuss this hypothesis.

Xenon in Genesis targets and "young" lunar soils: Meshik et al. [4] compare SW-Xe in Genesis targets with the SW-Xe isotopic composition largely derived from "young" lunar regolith samples, irradiated by the SW in the past ~100 Ma [5, 6]. This comparison has to be taken with a grain of salt, as it is not straightforward to determine the true composition of SW-Xe from lunar samples [e.g. 5, 7]. Further work seems necessary to test whether the observed difference between Genesis Xe and trapped lunar Xe does not reflect, e.g., minor isotopic fractionation during implanation or recycling of the latter (see below). However, if the hypothesis of [4] is correct, it would allow us to discuss the flux of 67P/C-G-type cometary Xe onto the Moon and Earth, under the assumption that the cometary Xe in the soils was added rather late, i.e., once cometary fluxes approached or reached present-day values.

Trapping time for cometary Xe: Refs. [2&3] argue for an early delivery of the Xe in the lunar rocks ([3] also consider later influx of cometary micrometeorites), and also [4] argue for early delivery of the cometary Xe in the SW-bearing soils. However, we believe that soil grains would probably have incorporated their cometary Xe much later, in conjunction with their trapping of SW noble gases: data used to derive the SW-Xe isotopic composition are largely from mineral grains that had been released from their host rocks not earlier than the soils' cosmic ray exposure ages [5, 6], e.g., ~100 Ma for soil 71501 [7]. The Xe isotopic spectra of individual etch fractions do not show variable ^{134,136}Xe abundances apart from those expected from mass fractionation upon implantation [7].

Trapping process for cometary Xe: We assume that cometary Xe has been delivered to the Moon predominantly by the icy fraction of large cometary impacts [8], with a Xe/H_2O ratio as measured in 67P/C-G [9]. We do not consider cometary micrometeorites [3], which presumably have lost their water at 1AU and hence have Xe concentrations similar to those of CI chondrites, (about five orders of magnitude lower than the ice of 67P/C-G). No evidence for 67P/C-G-like Xe is found in micrometeorites [10]. Also an addition of CI-Xe (essentially Q-Xe) to the lunar regolith would lead to an excess in heavy isotopes, contrary to the observation by [4]. We consider two processes to firmly incorporate cometary ice into lunar mineral grains: i) trapping of Xe ions from the exosphere accelerated by the SW electromagnetic field, as proposed by Manka & Michel [M&M, ref. 11] to explain "parentless" ^{40}Ar in lunar soil, and ii) trapping by "irreversible Xe adsorption" on the lunar surface [12, 13]. We will also consider recycling of cometary Xe between exosphere, regolith and lunar polar ice traps, which implies that – though finally incorporated not earlier than, say, ~100 Ma ago – much of the cometary Xe may have been delivered earlier, perhaps 1-2 Ga ago (see below).

Recent trapping of cometary xenon onto the Moon? With the assumption of simultaneous trapping of cometary Xe and SW noble gases, the flux of 67P/C-G-like Xe trapped in lunar soil samples can be constrained by normalizing it to the known recent flux of SW Xe. The cometary ^{132}Xe fraction is ~1.5±0.8% (using ^{132}Xe as normalizing isotope; ^{130}Xe would yield about 3% [4]). Taking a present day $^{132}Xe_{SW}$ flux of 0.017±0.001 atoms/(cm^2*s^1) [14] and an effective SW flux close to the near side center of the Moon (location of studied samples) of ~30% of the full flux (shielding by the terrestrial magnetosphere and the Moon) results in ~9.1*10^{20} ^{132}Xe atoms per year trapped on the lunar surface. Adopting the ^{132}Xe/H_2O [atoms/molecule] ratio of ~6.2*10^{-8} in 67P/C-G [9] to be typical for comets, this corresponds to a cometary ice flux onto the Moon of about 440 kg/a (4.4*10^{11} kg/Ga), in the improbable case – discussed next – that every Xe atom carried by the ice would end up trapped in the regolith.

Ong et al. [8] considered impacts of (0.5 – 34) km size comets, with, on average, ~6.5% of the impactor mass being retained by the Moon's gravity field. They note that any estimate of cometary water delivered is highly uncertain, due to the ill-constrained impactor flux but also due to the scarcity of very large impactors which mainly determine the effective flux. They consider a 34 km body as likely the largest impact on the Moon over the last 1 Ga. This would result in ~1.2*10^{13} – 3.9*10^{14} kg of cometary water being deposited on the Moon in the past 1 Ga. Comparing this ice mass flux with the 4.4*10^{11}kg/Ga of cometary ice required in the case of quantitative trapping would result in an overall probability of between ~4% - 0.1% for a cometary Xe atom to become firmly trapped in a lunar grain surface. We next discuss this required trapping efficiency, being aware of its inherent large uncertainty.

The overall trapping efficiency of the M&M process [11] depends mainly on the trapping efficiency (proper) of these low-energy ions and on the fraction of ions with trajectories leading to impact on the lunar surface. Accordingly, ~8.5% of the exospheric ^{40}Ar ions will get trapped [11]. Due to the lower scale height of exospheric Xe, somewhat more Xe ions than Ar ions reach the surface, but Xe will have a considerably lower energy than Ar. We estimate average implantation energies of Xe ions to be ~120 eV, which leads to a very surficial implantation on the order of at most a few nm, likely insufficient for long-time trapping. Losses by diffusion or sputtering will lead to a cycling of Xe between regolith, exosphere and ice traps on lunar poles. However, an ultimately firmer fixation of loosely trapped atoms by deposition of materials onto grain surfaces, including condensed vapor from (micro-) meteorite impacts [13, 15] seems possible. The M&M process would lead to isotopic fractionation, depleting heavy isotopes. Apart from cometary Xe, this also involves the more abundant SW Xe, hence a depletion of heavy Xe isotopes in implanted gases cannot unambiguously be ascribed to a cometary component.

Irreversible adsorption of Xe (requiring release temperatures ≥750 ºC) is observed upon crushing lunar rocks in air or a Xe atmosphere [12]. To evaluate from these experiments the trapping efficiency of cometary Xe from the lunar exosphere is difficult. Xe fixation takes place during crushing while mechanical and thermal energy is supplied [12]. This, together with fixation by added material (see above) appears also feasible on the Moon. Hence, irreversible adsorption might also be relevant for lunar Xe.

Influx of cometary Xe onto Earth? A recent flux of cometary Xe would also influence the present-day xenon concentration of the terrestrial atmosphere. Unlike the lunar case, estimates would not have to rely on ill-known trapping efficiencies. Assuming essentially quantitative retention of cometary ice in Earth's gravity fields (rather than the 6.5% for the Moon) and scaling the ~$1.2 * 10^{13} – 3.9*10^{14}$ kg of cometary water per Ga estimated to hit the Moon [8] with the respective cross-sectional areas (gravitational focusing is negligible), Earth would have trapped ~$5.2*10^{33} – 1.7*10^{35}$ ^{132}Xe atoms from cometary ice per Ga (again assuming the Xe/H_2O ratio in 67P/C-G [9]). This would correspond to an addition to the terrestrial atmosphere of 0.21% - 6.4 % over 1 Ga. The upper bound of this interval might become potentially observable for 67P/C-G-like Xe depleted in ^{134,136}Xe.

Conclusions: Meshik et al. [4] propose that "young" lunar regolith samples [5, 6] likely contain a minor fraction of cometary Xe strongly depleted in the two heaviest isotopes [1]. We evaluate this hypothesis under the assumption that the putative cometary Xe has been trapped essentially contemporaneously with the SW Xe. Adopting the Xe concentration in ice of comet Churyumov-Gerasimenko [9] and a range of cometary ice mass estimated to reach the Moon [8], this would require that a fraction in the permil to percent region of the Xe from this ice would get firmly trapped in the lunar regolith. Although this estimate is highly uncertain due to the ill-constrained cometary water flux onto the Moon, it also holds in the case of Xe being recycled through polar ice traps, as long as this involves only ice delivered once the comet impact frequency appoached the present day values, which is likely given an ice gardening depth of ~1.6 m in the last 1 Ga [16]. More work is required to evaluate the efficiency of the Xe trapping processes and whether the presumed difference between the Xe isotopic composition in lunar soils and that of Genesis targets is indeed caused by 67P/C-G-like Xe. Xenon from cometary ice might contribute a detectable addition to the terrestrial atmosphere during the past few Ga.

Acknowledgement: We appreciate discussions with Erik Asphaug.

References: **[1]** Marty B. et al. (2017) *Science, 356*, 1069. **[2]** Bekaert D. V. et al. (2018) *GCA*, *218*, 114. **[3]** Pernet-Fisher J. F. et al. (2020) *Icarus*, *352*, 113977. **[4]** Meshik A. et al. (2020) *GCA*, *276*, 289. **[5]** Pepin R. O. et al. (1995) *GCA 59*, 4997. **[6]** Wieler R. (2002) *Rev. Mineral. Geochem. 47*, 21. **[7]** Wieler R. and Baur H. *Meteoritics* 29, 570. **[8]** Ong L. et al. (2010), *Icarus 207*, 578. **[9]** Rubin M. et al. (2018) *Sci. Adv. 4*, eaar6297. **[10]** Baecker B. et al. (2018) *GCA* 242, 266. **[11]** Manka R. H. & Michel F. C. (1970) *Science* 169, 278; & (1971) *Proc. LSC 2nd*, 1717. **[12]** Niedermann S. & Eugster O. (1992) *GCA* 56, 493. **[13]** Hohenberg C. M. et al. (2002) *MAPS* 37, 257. **[14]** Vogel N. et al. (2011) *GCA 75*, 3057. **[15]** Kerridge J. F. & Kaplan I. R. (1978) *LPSC 9th*, 1687. **[16]** Crider D. H. & Vondrak R. R. (2003) *JGR* 108, 5079.