A POSSIBLE CONTRIBUTION FROM THE ANCIENT TERRESTRIAL ATMOSPHERE TO THE TRAPPED XENON INVENTORY OF LUNAR SOILS. R. Wieler[1] and P. Bochsler[2], [1]ETH Zürich, Earth Sciences, Clausiusstrasse 25, CH-8092 Zürich, Switzerland, wieler@erdw.ethz.ch, [2]Physikalisches Institut, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland, peter.bochsler@space.unibe.ch.

Introduction: The solar wind (SW) is the source of the overwhelming part of the noble gases trapped in lunar soils [e. g. 1], and the lunar regolith provides a long-term archive of the composition of noble gases and other volatile elements in the SW. Kerridge [2] proposed that the regolith conserves a record of secular changes of several elemental and isotopic compositions of the SW, but Wieler [3] later argued that only for one of the proposed variations good evidence exists: a decrease of the Xe/Kr ratio by almost a factor of two over the past few billion years. However, no mechanism has been proposed to explain such a secular variation in the SW. Here we therefore consider another possible cause for the variable Xe/Kr ratios in the lunar regolith: a contribution of xenon from the terrestrial atmosphere in samples exposed several billion years ago.

Motivation: This hypothesis is motivated by two recent findings. First, the Xe isotopic composition in the terrestrial atmosphere has become isotopically heavier by ~21 ‰ per amu between about 3.5 and 1.7 Ga BP, before it reached the present-day composition [4, 5], indicating a substantial loss of Xe (but not of Kr) from the atmosphere until 1.7 Ga ago. Second, Xe might have been lost from an early hydrogen-rich atmosphere without a concomitant loss of Kr [6]: Xe could be efficiently ionized by resonant charge exchange with protons, a process which would not work for the other noble gases with their higher first ionisation potentials. If part of the escaping Xe ions had reached the Moon, early irradiated samples would have a higher Xe/Kr ratio than the SW value in targets from the Genesis mission [7, 8].

One crucial lunar sample providing evidence for a secularly variable Xe abundance is regolith breccia 14301 [9,10]. It contains parentless radiogenic ^{129}Xe and fissiogenic Xe from the decay of now extinct ^{129}I and Pu and has an unusually high ratio of trapped ^{40}Ar/^{36}Ar of about 20 [11], indicating that it has a very high "antiquity", i. e. it trapped its noble gases likely around 3.7 Ga ago [12]. Other samples with a high, although less well defined antiquity on the order of 1 - 3 Ga such as regolith breccia 79035 also have high ^{132}Xe/^{84}Kr of ~0.2-0.25 versus ~0.12 for more recently irradiated samples [9, 10].

Earth Wind: Trapping of an "Earth Wind" has been considered previously as a possible explanation of the large overabundance of nitrogen in lunar soils relative to inferred solar wind values [13-15]. Terada et al. [16] actually observed O^+ ions from the terrestrial atmosphere in the distant magnetotail with the lunar orbiter Kaguya. Oxygen ions from the Earth's magnetotail had also been observed by the Geotail mission within a circle of roughly 20 Earth radii at a location near the lunar orbit [17].

The model: We constructed a simple model involving first order differential equations to describe the secular loss of Xe from the early atmosphere. Following [6] we assume that no Kr is concomitantly lost. Similarly to [13-15] we assume that the lost Xe ions completely end up in the magnetotail flowing outwards with energies comparable to those of solar wind ions. For simplicity we assume that at the lunar orbit the flow is spread homogeneously over an area of approximately 40 Earth radii, which implies that the Moon spends ~10% of its time in the Earth wind, exposing exclusively its near side.

Model runs start after an assumed complete early loss of the terrestrial atmosphere at ~80 Ma as indicated by the low remaining fraction of 0.8% of radiogenic ^{129}Xe in the atmosphere [18]. We assume a gradual and simultaneous replenishing of Xe and Kr by outgassing from the Earth's interior and, superposed, a loss of Xe from the newly formed atmosphere by the process described of [6]. Both processes rapidly decrease with time following an exponential law. The Xe loss is assumed to be mass-dependent, favouring the light isotopes to satisfy the observations by [5]. We assume that at present about 1% [cf. 19] of the original Kr and Xe are retained in the Earth's interior. In our model the isotopic composition of Kr in the Earth's interior corresponds to the composition of atmospheric Kr, while the initial isotopic composition of light isotopes of Xe in the interior reflects meteoritic (type Q) Xe. The resulting system of differential equations is solved by using the thus prescribed initial isotopic composition of Xe in the Earth's interior and the composition of the present-day atmosphere as boundaries.

Alternatively, following [5, 20] we consider the atmospheric Xe concentration to have been ~20, 10, and 4 times its present-day value right from the beginning when the loss according to [6] started, without any replenishing from the Earth's interior.

Results: To explain the difference of a factor of two in Xe/Kr between samples with high antiquities and those irradiated much more recently, requires some high-antiquity samples to have trapped similar amounts of Xe from Earth Wind and SW. Fig. 1 shows that - provided the SW flux remained constant - this will happen at t ~1.6 - 2.6 Ga after Earth/Moon formation for all assumed loss fractions and also for the case where the heavy noble gases first outgassed from the mantle. This is consistent with the estimated exposure times of some of the high-antiquity samples.

Fig. 2 shows a fit of the expected isotopic composition of the remaining atmosphere to the data of [5] for the cases without outgassing. A very similar fit (not shown) is obtained for the outgassing case. Note that the exact isotopic composition of trapped Xe in high antiquity lunar samples is not very well constrained, and no clear evidence exists that it is different from that of the more recently exposed samples and the SW-Xe composition from Genesis [8]. This does not contradict the Earth Wind hypothesis, however, as the early atmospheric Xe would have been closer to the SW composition than the present day atmosphere [5], and the escaped Earth Wind Xe would additionally have been fractionated towards a lighter, i. e. SW like composition.

Conclusions: The preliminary model presented here is able to qualitatively explain the secularly variable Xe/Kr ratio in lunar regolith samples by Xe contributed by an early Earth Wind to the high-antiquity samples according to [6], superposed to Xe implanted by the solar wind. Both cases studied, with and without mantle outgassing, supply sufficient Xe to the Earth Wind until some 2 -3 Ga before present. A more sophisticated model will have to include effects of ingassing of atmospheric Xe into the mantle [21]. Crucial tests for our hypothesis could be provided by samples from the lunar back side and additional samples from the nearside with well-constrained antiquities.

References: **[1]** Eberhardt P. et al. (1970) *Proc. Apollo 11 LSC*, 1037. **[2]** Kerridge J. F. (1980) *Proc. Conf. Ancient Sun*, 475. **[3]** Wieler R. (2016) *Chem. Erde, 76*, 463. **[4]** Avice G. et al. (2017) *Nature Comm. 8*:15455. **[5]** Avice G. et al. (2018) *GCA, 232*, 82. **[6]** Zahnle K. J. et al. (2019) *GCA, 244*, 56. **[7]** Vogel N. et al. (2011) *GCA, 75*, 3057. **[8]** Meshik A. et al. *GCA, 127*, 326. **[9]** Wieler R. & Baur H. (1995), *ApJ, 453*, 987. **[10]** Wieler R. et al. (1996), *Nature 384*, 46. **[11]** Bernatowicz T. J. et al. (1979) Proc. LPSC 10th, 1587. **[12]** Eugster O. et al. (2001) *MAPS* 36, 1097. **[13]** Geiss J. & Bochsler P. (1991) *In: The Sun in Time*, 98. **[14]** Bochsler P. (1994) *Adv. Space Res. 14*, 161. **[15]** Ozima M. et al. (2005) *Nature, 436*, 655. **[16]** Terada K. et al. (2017) *Nature Astron. 1*:26. **[17]** Seki K. et al. (1998) *GRL 103*, 4477. **[18]** Pepin R. O. & Porcelli D. (2002) *Rev. Mineral. Geochem. 47*, 191. **[19]** Ozima M. & Podosek FA (2002) *Noble Gas Geochemistry 2nd ed., Cambridge Univ. Press.* **[20]** Pepin R. O. (1991) Icarus, 92, 2. **[21]** Mukhopadhyay S. & Parai R. (2019) *Annu. Rev. Earth Planet. Sci.* 389.

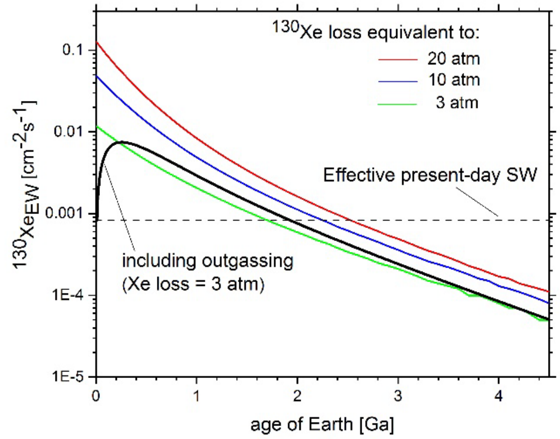

Fig. 1: Modelled time-dependent Earth Wind Xe fluxes at the lunar surface for various Xe losses from the terrestrial atmosphere (three coloured curves, losses in multiples of ^{130}Xe amounts in today's atmosphere). The black solid line shows the Earth wind flux for the case where Xe in the atmosphere was entirely supplied by mantle outgassing totalling 3 times present-day atmospheric Xe. The dashed line shows the effective present-day SW flux of ^{130}Xe reaching the lunar nearside center surface. Modelled Earth Wind fluxes at Earth ages around 1.6 - 2.6 Ga equal the present-day SW flux; hence regolith samples exposed some 2 - 3 Ga ago on the lunar nearside may have obtained about half their trapped Xe from an Earth Wind.

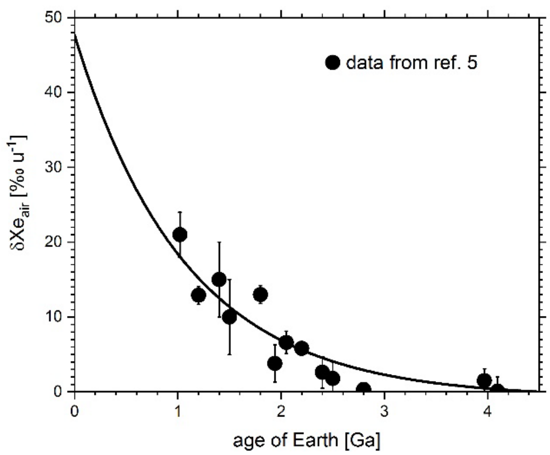

Fig. 2: : Error weighted least square fit to isotopic enrichments in atmospheric Xe inclusions summarized by [5] using our model with time dependent fractionation of Xe. A fit to the data with a model which includes outgassing (not shown here) is of similar quality.