SECULAR VARIABILITY OF THE SOLAR WIND COMPOSITION? - THE CASE OF Xe/Kr IN THE LUNAR REGOLITH. R. Wieler[1] and P. Bochsler[2], [1]Institute of Petrology and Geochemistry, ETHZ, Sonneggstrasse 5, CH-8092 Zürich/Switzerland, wieler@erdw.ethz.ch. [2]Physics Department, University of Bern, Sidlerstrasse 5, CH-3012 Bern/Switzerland, peter.bochsler@unibe.ch

Introduction: Since the first lunar regolith samples became available, possible records of solar wind composition variability have been investigated. The best-documented evidence is the apparent secular decrease of the Xe/Kr ratio in lunar samples [e.g., 1-4]. Here we discuss possible causes for this variability.

The data base: Xe/Kr as function of time of solar wind irradiation (antiquity) was most comprehensively studied by stepwise combustion and in-vacuo etching of lunar mineral separates (mostly ilmenites) as well as single mineral grain analyses [1,2,4, see Fig. 1]. Xe/Kr in samples with "young" solar wind ($^{40}Ar/^{36}Ar$ <0.8) is close to the Genesis-derived solar wind value, whereas samples with "old" solar wind ($^{40}Ar/^{36}Ar$ >2 show twice as high Xe/Kr. This was suggested to indicate a secular variability of solar wind composition [1-4]. Lunar bulk samples in Fig. 1 (various authors) indicate a similar trend, although with considerable scatter and with highest Xe/Kr values being almost four times above the Genesis value. Firm lower limits for the antiquity of regolith breccias is given by their known compaction ages [5,6]. It is unclear to what extent the scatter among "old" samples reflects secularly variable trapped Xe/Kr ratios: i) error bars indicate scatter for samples with multiple analyses. ii) Apollo 17 samples 742.. suffered complex exposure histories [7], hence contain also low-antiquity solar wind. iii) Samples may contain Xe from recent air, however expected amounts are probably too low to sizeably affect Xe/Kr [8], as is also indicated by essentially identical Xe isotopic compositions in lunar soils and Genesis [9], iv) Xe/Kr ratios vs. Kr/Ar, show no trend, hence post-depositional elemental fractionation is unlikely.

Secular variability of the solar wind composition due to variable FIP/FIT-effect? Details of the FIP/FIT-effect working in the solar chromosphere and shaping solar wind abundances are still poorly understood. Astronomical observations of young solar-analogues indicate that the young Sun was more active, emitting orders of magnitude higher EUV-fluxes than at present [10]. Also, EUV-spectra of young sun-like stars are steeper, with flux ratios of X-Ray/EUV being much higher than today. The first ionization potentials (FIP) for Kr and Xe are 14.0 eV and Xe 12.1 eV, resp. Hence, if EUV dominates ionization of Kr and Xe, Kr/Xe should be higher in the early solar wind. Alternatively, high-FIP species Kr and Xe could be ionized by shock-heating and electronic collisions. This could favor Xe due to its somewhat larger atomic size. However, Genesis samples with solar wind from coronal mass ejections (CME) show no significant modification of the Xe/Kr ratio [11]. A special mechanism, unexplored in FIP/FIT-models, favoring the ionization of Xe, could be resonant charge exchange with protons [12] (see below).

Variability due to changing implantation efficiency and varying lunar magnetic fields? The early bombardment of the lunar surface produced a largely unsaturated regolith containing less volatiles per unit mass; consequently, re-implantation of sputtered Kr and Xe seems less relevant in the past than it is today. Since Xe/Kr in present-day regolith reflects largely modern solar wind composition, we conclude that (changing) selective re-implantation plays at most a minor role.

The primordial lunar magnetic field might have modified implantation of minor solar wind species. However, from detailed modeling it seems implausible that the implanted Xe/Kr ratio could have been modified by a factor of two or more, without similarly affecting other elemental ratios [13]. Furthermore, since Xe isotope masses differ by up to 10%, one would expect significant changes in the isotopic composition between recent and ancient samples.

Lunar sources of Xe in regolith? Outgassing of lunar Xe and retrapping has been reported specifically for radiogenic and fissiogenic isotopes from radioactive species [14]. However, outgassing of non-radiogenic and non-fissiogenic, primordial Xe isotopes seems far less important.

An early terrestrial atmosphere: An alternative source of Xe in the early lunar regolith may be the Earth's atmosphere [15], as was already proposed for N [16,17]. The deficit of Xe in the terrestrial atmosphere compared to other planetary atmospheres and meteorites is a long-standing problem. Here we argue that Xe lost to space before the early oxygenation of the atmosphere around 2 Ga ago could explain the apparent Xe-excess in old lunar samples. Ancient terrestrial samples containing atmospheric Xe are isotopically fractionated, with heavy isotopes being depleted compared to modern Xe [18]. A mechanism to deplete Xe without affecting Kr and invoking resonant charge exchange of Xe with protons in the ionosphere was proposed to operate during periods of high hydrogen loss [12]. To estimate a possible contribution of such

atmospheric Xe to the lunar regolith, we conservatively assume that Xe was depleted by approximately a factor of 5. Xe-ions lost to space by the process mentioned above will most likely end up in the magnetotail. To roughly deduce how much such Xe-ions might contribute to the lunar regolith inventory, we need to estimate their probability to hit the near-side of the Moon and compare this flow with the input from the solar wind. The most important ingredient for such an estimate is the size of the terrestrial magnetotail at the orbit of the Moon and the fluence (ions per m^2) onto the lunar surface.

In the distant magnetotail weakly ionized species (e.g. O^+) and molecules such as N_2^+, NO^+, O_2^+ have been frequently observed [19]. The typical extension of the magnetotail at the lunar orbit out of ecliptic is $\pm 10R_E$, and within the ecliptic $\pm 30R_E$. We assume that the Moon spends typically 10% of its time in the magnetotail with its near side exposed to ions from the terrestrial ionosphere. Assuming a homogeneous distribution of ions within the tail, one expects a fluence of terrestrial ^{130}Xe ions of ~4 x 10^{18} per m^2 on the near side of the Moon over ~3 Ga. Comparing to a solar wind fluence of 10^{18} ^{130}Xe-ions over the same timespan, this illustrates that an early terrestrial Xe-flux into the regolith on the lunar near-side might be similar to or even larger than the solar wind Xe-flux.

A more realistic comparison requires modelling the probably strongly decreasing atmospheric Xe-loss [18] and the fact that available lunar samples were exposed over relatively short time spans, probably often towards the end of the loss process proposed by [12].

Predictions: The isotopic composition of presumed Earth-Wind-Xe needs further investigation. It may be expected to be enriched in light isotopes, tending towards solar wind Xe composition. The available data base of Xe isotopes in lunar samples with high solar wind antiquity is scarce, but trapped Xe in samples such as regolith breccia 79035 might tend slightly towards terrestrial atmospheric composition compared to nominal solar wind composition given by low-antiquity samples and Genesis.

Since the present-day near side of the Moon has been facing Earth probably during most of lunar history, regolith on the far side should show at best minor traces of Earth-wind-Xe. We also expect a longitudinal variation of the Earth-Wind/solar-wind proportion on the near side, but no significant latitudinal variability. The longitudinal variation is, however, probably too weak to be distinguishable by available samples. Regoliths on planetary bodies other than the Moon should essentially reflect the undisturbed solar wind Kr/Xe-ratio.

Conclusions: At this time, we doubt that the lunar regolith provides evidence for a secular change of the solar wind composition. In particular, we see no reason to believe that the solar wind feeding- and acceleration-mechanisms have produced a significant decrease in the Kr/Xe-ratio over the lifetime of the lunar regolith. On the other hand the contribution of an early Xe-rich Earth-Wind seems to us a plausible explanation for the secular change in the Kr/Xe-content of the regolith.

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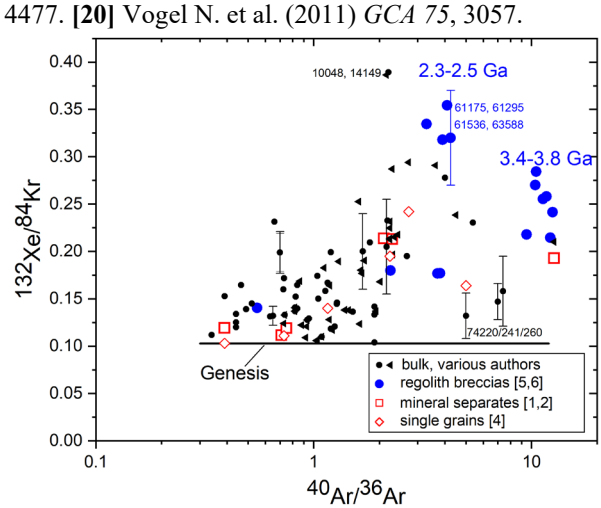

Fig. 1: $^{132}Xe/^{84}Kr$ vs. the solar-wind antiquity parameter $^{40}Ar/^{36}Ar$. Shown are bulk soil values from various authors, regolith breccia data from [5,6] with antiquities in [Ga] for two sample groups as given by [6], data for mineral separates obtained by stepwise gas extraction (combustion or in-vacuo etching [1,2]) and single grain data [4]. Dots indicate $^{40}Ar/^{36}Ar$ of trapped component, triangles measured $^{40}Ar/^{36}Ar$, representing upper limits for the antiquity parameter. Horizonal line represents Xe/Kr in the solar wind measured with Genesis targets [9,20] .