MODELING SOLAR-EVOLUTION AND LUNAR-PALEOMAGNETIC IMPACTS ON THE LUNAR ^{40}AR/^{36}AR ANTIQUITY INDICATOR. A. R. Poppe[1], I. Garrick-Bethell[2], and S. Fatemi[3], [1]Space Sciences Lab., Univ. of California, Berkeley (poppe@berkeley.edu), [2]Univ. of California, Santa Cruz, [3]Univ. of Umeå, Sweden.

Introduction: Age-dating of lunar samples provides critical information on the timing of key events in lunar history with significant implications for our understanding of the evolution of the Moon and other inner solar system bodies. Among various age-dating methods, the ^{40}Ar/^{36}Ar 'antiquity indicator' is a useful method of constraining the formation (or closure) age of lunar regolith samples in a semi-quantitative manner [1,2]. Specifically, the ratio of trapped ^{40}Ar to trapped ^{36}Ar within lunar samples correlates well with the exposure age of the sample (calibrated using separate methods such as ^{235}U–^{136}Xe dating), with higher ^{40}Ar/^{36}Ar values corresponding to older samples. The current operating theory of the antiquity indicator maintains that the trapped ^{40}Ar originates from the radioactive decay of endogenic ^{40}K within the lunar interior and, after outgassing into the lunar exosphere, is ionized and implanted into the lunar soil [3]. In parallel, ^{36}Ar originates from the solar wind and is also implanted into the lunar soil. This theory rests on (at least) three key assumptions: (i) the rate of ^{40}Ar formation and subsequent outgassing into the lunar exosphere tracks the radioactive decay rate of lunar ^{40}K ($t_{1/2}$ = 1.28 Ga); (ii) the implantation efficiency of exospheric ^{40}Ar via ionization and pickup remains constant over geologic time; and (iii) the flux of solar wind ^{36}Ar remains constant (or near constant) over geologic time.

In this work, we revisit assumptions (ii) and (iii) in light of recent developments in our understanding of both the presence of a lunar paleo-magnetosphere [4] (which affects both ^{36}Ar and ^{40}Ar implantation) and the variation of the solar wind flux over the age of the solar system [5,6] (which affects the ^{36}Ar flux).

Methodology: We first address the long-term variation in the solar wind flux inferred from remote observations of nearby stellar systems [5]. These measurements are consistent with higher solar activity and solar wind flux at earlier epochs. For example, solar wind fluxes are projected to be between 10 and 100 times higher than current at a solar system age of 1.0 Ga, depending on the specific scaling models used. If such increases truly described the solar wind flux from the Sun in particular, one would expect similarly increased flux of ^{36}Ar into lunar samples, thereby violating assumption (iii). We do note that recent analyses of gas-rich meteorites has failed to find evidence for such large secular changes in solar wind input [7], so this concept remains controversial.

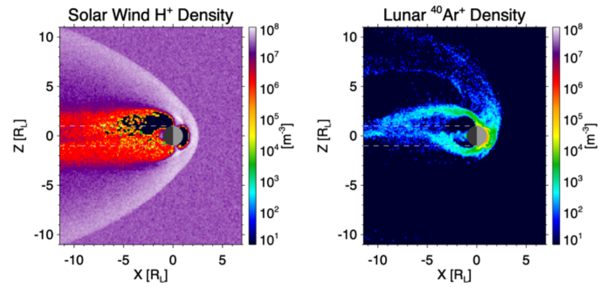

Figure 1: Amitis hybrid model results for (left) solar wind density and (right) lunar ^{40}Ar^{+} density with a paleomagnetic field strength of 1000 nT.

We next model the effects of lunar paleo-magnetic fields on the flux of ^{36}Ar and ^{40}Ar to the lunar surface by using the Amitis hybrid plasma model [8], e.g., Figure 1. We have previously used Amitis to model the effects of lunar paleomagnetic fields on the accretion of lunar volatiles [9] and the fractionation of precipitating solar wind minor ions [10]. Here, we model the precipitation of both ^{36}Ar^{+} and ^{40}Ar^{+} ions over a range of paleomagnetic strengths, up to 4 μT. ^{36}Ar^{+} is modeled as a minor solar wind species injected in the upstream flow while ^{40}Ar^{+} is injected into the model from a neutral exospheric distribution (similar to that observed and modeled in the present epoch [11]). Our results show that both the ^{36}Ar^{+} and ^{40}Ar^{+} fluxes to the lunar surface can be highly disturbed by the presence of paleomagnetic fields. For example, in the 4 μT case, ^{36}Ar^{+} fluxes are suppressed by an order-of-magnitude relative to non-paleomagnetic conditions. The ^{40}Ar^{+} fluxes at 4 μT are similar to that for 0 nT; however, simulations suggest that lower paleomagnetic field strengths (~100 – 1000 nT) result in much lower ^{40}Ar^{+} flux due to more efficient loss through the lunar paleo-magnetotail.

Conclusions: Our preliminary work suggests that the presence of both long-term variations in the solar flux and the complex effects of a lunar paleomagnetosphere on solar wind and exospheric ion dynamics significantly complicates the interpretation of the Ar-Ar antiquity indicator. We discuss possible resolutions to this and areas for future research.

References: [1] Eugster et al., *Met. Plan. Sci.*, 2001; [2] Joy et al., *Geo. Cosmo. Acta*, 2011; [3] Manka and Michel, *Science,* 1970; [4] Tikoo et al., *Sci. Adv.*, 2017; [5] Wood et al., *Ap. J.*, 2005; [6] Vidotto, *Liv. Rev. Sol. Phys.*, 2021; [7] Obase and Nakashima, *Icarus*, 2023; [8] Fatemi et al., *J. Phys.: Conf. Ser.,* 2017; [9] Garrick-Bethell et al., *Geophys. Res. Lett*., 2019; [10] Poppe et al., *Plan Sci. J.*, 2021; [11] Grava et al., *Icarus*, 2015.