POTASSIUM ISOTOPE ANOMALIES FROM EVAPORATIVE MASS LOSS IN PLANETESIMALS. M. Calogero[1], F. Nimmo[2] and R.C. Hin[1], [1]Bayerisches Geoinstitut, Universität Bayreuth, 95440 Bayreuth, Germany (Meredith.Calogero@uni-bayreuth.de), [2]Dept. Earth and Planetary Sciences, UCSC, Santa Cruz CA 95064 (fnimmo@ucsc.edu).

Introduction: The terrestrial planets are depleted in moderately volatile elements (MVEs) relative to chondritic material [1]. This depletion could be due to either incomplete condensation [2] or partial mass loss, either in precursor material or in accreting bodies. The Earth has an excess of the heavier Mg and Si isotopes [3], which may be due to evaporative loss caused by impact-driven melting during accretion [3] or by heating due to ^{26}Al decay [4].

MVEs like potassium and zinc also show isotopic anomalies [5,6]. Potassium isotopes show a correlation with body mass [6], with the smaller bodies being isotopically lighter. This observation could imply evaporative loss from the fully-formed bodies. However, the correlation of isotopic fractionation with elemental concentration is weak, and evaporative loss from a body as large as the Earth is challenging [4].

In this work we apply a quantitative model of evaporative loss to potassium isotopes, coupling it with an N-body accretion model [7] to investigate how fractionation and loss proceed as planetesimals grow. Here we focus on the potential for loss driven by ^{26}Al heating [4] rather than by impacts [3,8].

Evaporative Loss: We first explore mass loss for an array of initial accreting body conditions, with initial masses in the range 0.01-1.38x10^{23} kg corresponding to a range of radii from ~408 to ~2112 km. Evaporative mass loss from initially molten bodies occurs via hydrodynamic escape [3,4] with the surface pressure determined by the temperature of the molten interior. We consider both isothermal and adiabatic conditions for mass flux and elemental escape. The adiabatic mass loss rate is solved following [9]. The effective surface temperature of the molten body is determined by balancing the isoviscous convective and radiative heat fluxes [3] and the interior temperature decreases as the model run proceeds.

To calculate the loss of potassium we assume a temperature-dependent partition coefficient. The isotopic evolution is then tracked assuming equilibrium fractionation at the melt-vapour interface [4] and a constant fractionation factor α. Each simulation ends under one of two potential conditions. Either the magma ocean cools to its solidus, set at 1400 K, or the interior temperature drops to the point at which adiabatic escape is no longer energetically possible [10]. Either scenario results in mass loss ceasing. Realizations at each initial temperature were run for increasing body masses until negligible mass loss was achieved after the first time step.

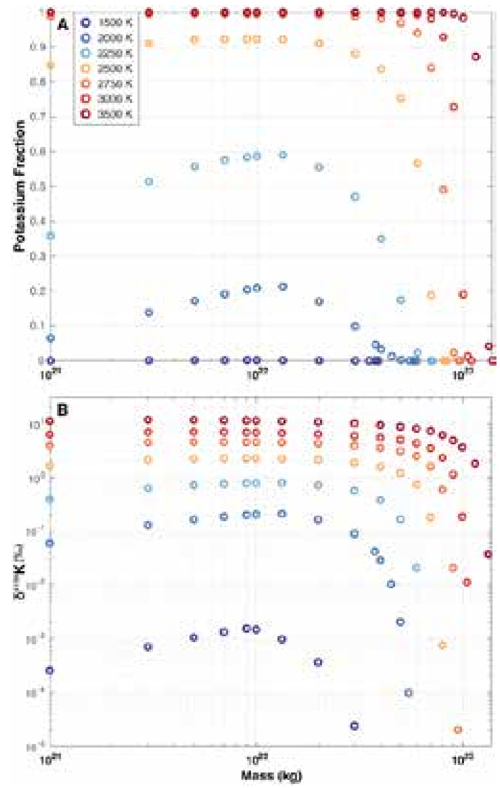


Figure 1. A. Fraction of potassium lost via hydrodynamic escape as a function of initial interior temperature and body mass. Here an adiabatic atmosphere with n=0.2 is assumed. B. Potassium isotope anomaly, assuming α=0.99913.

Single-body Results: Figure 1A shows the fraction of potassium lost for various initial body masses and internal temperatures. For high initial temperatures (above ~2750 K), all the potassium is lost. Mass loss does not occur for bodies exceeding roughly 10^{23} kg. We observe a maximum fraction lost at intermediate masses. This is because large bodies have a high gravity, impeding escape, while small bodies cool rapidly, limiting the time for escape to occur. Figure 1B shows that the $\delta^{41/39}$K is generally higher for higher initial temperatures and smaller masses, with again a maximum at intermediate masses where mass loss is most efficient.

N-body Model: Planetary bodies grow by collisions, so that the final elemental and isotopic composition of an object is a mixture of the starting bodies' compositions. We use the approach outlined above and track the evolution of potassium as bodies collide, assuming simple mixing. That is, we assume all potassium loss and fractionation happens early, as the bodies form, and that impact vaporization or mechanical erosion during subsequent collisions is negligible. For our accretion model we use output from [7] in which planetesimal growth through the runaway and oligarchic stages of accretion is tracked, and the influence of migrating giant planets is included.

We assume that each starting body has an initial temperature set by heating due to ^{26}Al decay. The accretion time is varied randomly from 0 to 2 Myr after CAI and the peak temperature is calculated accordingly, based on a decay constant of 0.99 Myr^{-1} and a temperature at 1 Myr of 1486 K. Mass loss for each body is then calculated assuming this initial temperature and an isothermal atmosphere. For the isotopic calculations a constant fractionation factor of α=0.99913 is assumed.

N-body Results:

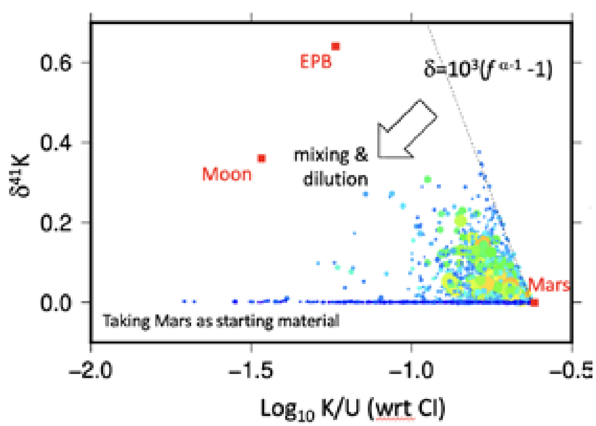
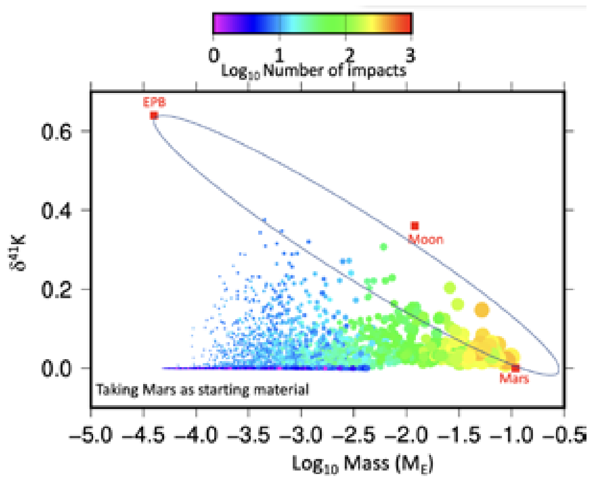


Figure 2. Potassium isotope anomaly vs. K/U ratio for bodies growing by collision according to [7]. Dot size is proportional to final mass; color indicates number of collisions. EPB=eucrite parent body. The dotted line indicates the expected results for pure Rayleigh fractionation.

Figure 2 shows the calculated $\delta^{41/39}K$ against the K/U ratio of the final objects, where the colors indicate the number of impacts. Bodies that suffer no impacts follow the Rayleigh fractionation line (dotted), where more significant K loss results in larger isotopic anomalies. Larger bodies typically show more subdued isotopic anomalies due to mixing and dilution.

Figure 3. Potassium isotope anomaly as a function of final body mass. Color scheme as for Figure 2.

Figure 3 shows the calculated $\delta^{41/39}K$ against the mass of the final objects. The upper envelope of possibilities shows a rough inverse correlation (ellipse) between $\delta^{41/39}K$ and mass, similar to the trend observed by [6]. Initial mass loss and fractionation is easier for



smaller bodies, and smaller bodies are also less subject to subsequent dilution and mixing by later impacts. Thus, the trend observed by [6] does not necessarily imply that evaporative mass loss had to take place after accretion had finished; this signature could instead be a result of early evaporative loss followed by accretion, mixing and dilution.

Future Work: Rather than simply specifying an initial temperature, a more realistic approach would be to track the internal temperature evolution due to the combined effects of ^{26}Al heating, mass loss and radiative cooling. Tracking additional MVEs, such as Zn, would provide additional constraints. Experimental determination of the relevant α values is desirable.

Conclusions: Small, initially molten bodies develop large potassium anomalies via evaporative loss (Fig 1). Subsequent mixing and dilution during accretion can retain an inverse correlation between body mass and isotope anomaly (Fig 3), as observed.

References: [1] Norris, C.A. and Wood, B.J. (2017) *Nature 549*, 507-510. [2] Sengupta D. et al. (2020) *DPS 52*, 504.01. [3] Hin R.C. et al. (2017) *Nature 549*, 511-515. [4] Young E.D. et al. (2019) *Icarus 323*, 1-15. [5] Day J.M.D. and Moynier F. (2014) *PTRS A372*, 20130259. [6] Tian Z. et al. (2021) *PNAS 118*, e2101155118. [7] Carter P.J. et al. (2015) *AJ 813*, 72. [8] Sossi P.A. et al. (2022) *Nature Astron.* 6, 951-960. [9] Zahnle K. J. and Catling D.C. (2017) *AJ 843*, 122. [10] Zahnle K.J. and Kasting J.F. (1986) *Icarus 68*, 462.