Understanding Noble Gases in the context of Mantle Dynamics:

The influence of the K/U ratio and melting in TERRA simulations

Nicolas Récalde, J.Huw Davies, James Panton, Don Porcelli, Morten Andersen

Introduction:

- Noble gases provide constraints on Earth thermal evolution that current geodynamical models struggle to fit.
- He and Ar are produced by main Heat Producing Elements (HPEs), significant elements in mantle dynamics.
- Numerical simulations help us generate various geodynamical contexts and allow us to better understand how Noble gases experience mantle dynamics. Noble gases being excellent tracers with strong geochemical affinities.
- We first focus on the melting process and how it is driven within TERRA simulations.
- We also vary amounts of K and U in the mantle from published models to test the influence on the dynamics, as these elements are part of main HPEs, but also to analyse how the simulation predicts the outputs of their decaying for the K-Ar system.

Method:

- We use the code TERRA to simulate mantle convection in a 3D spherical shell (**Baumgardner**), in the Boussinesq approximation, with particle tracking allowing us to simulate bulk composition and isotopic concentrations. Bulk composition is influencing buoyancy in our calculations with density variations between a Harzburgitic depleted component and basaltic enriched one.
- Internal heating is driven by particles isotopic amounts, it is then composition dependent.
- Melting is implemented with a composition dependent solidus (**van Heck**).
- We present two different categories of models here, mantle convection and mantle circulation models. **Convection models** are free-slip on top and bottom boundary layers whereas **circulation models** have imposed surface velocities from plate motion reconstructions.

Simulations:

Table 1: Presented Models

Models	Ar09	MS95	A95	LK07	L04
K (ppm)	280	240	267.5	190	172.5
U (ppb)	20	20.3	21.25	17.3	21
K/U ratio (x 10^3)	14	11.82	12.59	10.98	8.21
Reference	Arevalo et al	McDonough and Sun	Allègre et al	Lyubetskaya and Korenaga	Lassiter

The reference model is highlighted in grey (Ar09)
The suffix **cv** is used for mantle **convection models**
The suffix **crcl** is used for mantle **circulation models**

Results:

Melting analysis in TERRA simulations

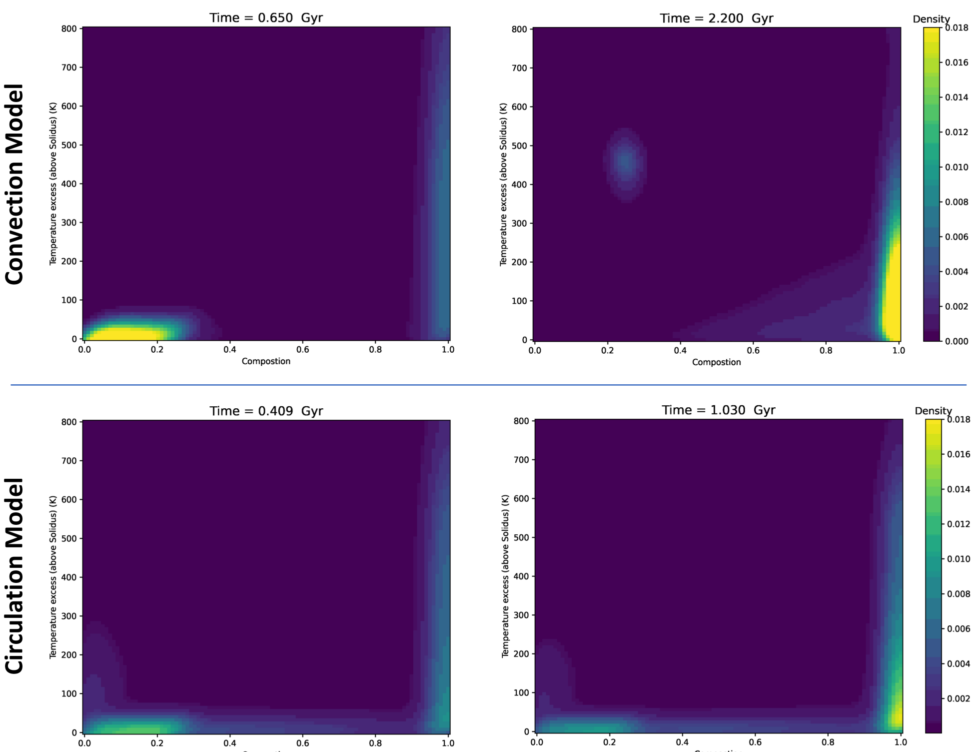

Figure 1:
Density plot showing the temperature excess, i.e. the difference between the particle temperature and the solidus temperature (for the given particle composition), depending on the composition, 1 for the enriched composition and 0 the depleted one. Results for reference model (**Table 1**). **Scan QR code to see whole simulation animations.**

Animations Fig.1

- The melting process, as it contributes to heat transfer and creates compositional heterogeneities, seems to be key to better understand mantle dynamics. Melting also drives outgassing, which could significantly impact noble gases ratios. **Figure 1** shows how melting is driven in simulations.
- Convection models can melt depleted particles at the beginning of the simulation for about 500 Myr, but then process only enriched compositions with a wide variety of temperature excesses for the rest of the simulation. We can observe a small patch of particles that have ambient mantle composition and high temperature excess also maintained for the rest of the simulation.

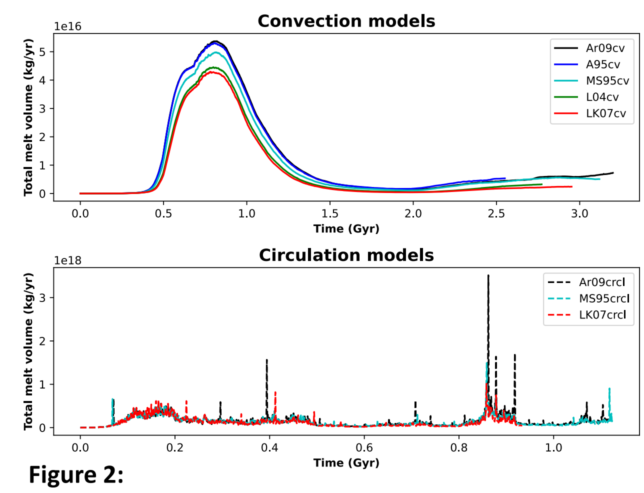

Figure 2:
Amount of melt produced over time for convection and circulation models.

- Circulation models are producing much more melt than classic convection models (about 2 orders of magnitude).
- The top boundary condition of circulation models favour melt production.

- Mantle circulation models process two categories of material, depleted low temperature particles and enriched particles with various temperature excesses. The first one is due to surface velocity conditions, forcing melting at low temperature excess, for all kinds of compositions. It is thus reproducing a more Earth-like behaviour regarding melting. A more quantitative analysis is however needed to determine which material category is preferentially processed. Prefering depleted material melting could be significant regarding the preservation of high He ratios and Ar outgassing.

K/U ratio impact on atmospheric Argon

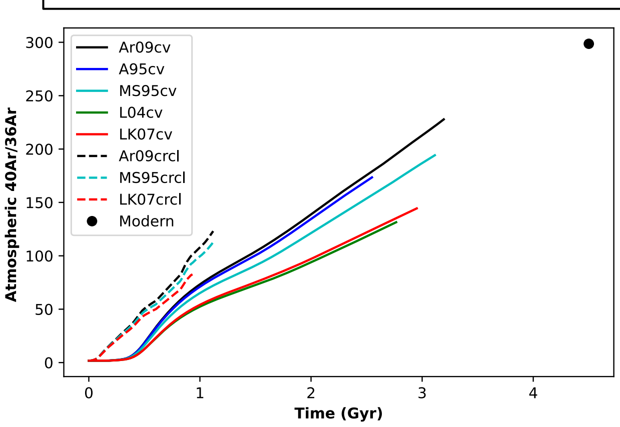

Figure 3:
Temporal evolution of Atmospheric 40Ar/36Ar ratio in simulations.

- Variation between convection and circulation models is due to melting differences (**Figure 2**).
- Convection models show a greater variation between various K/U ratios models.

K/U ratio impact on heat transfer

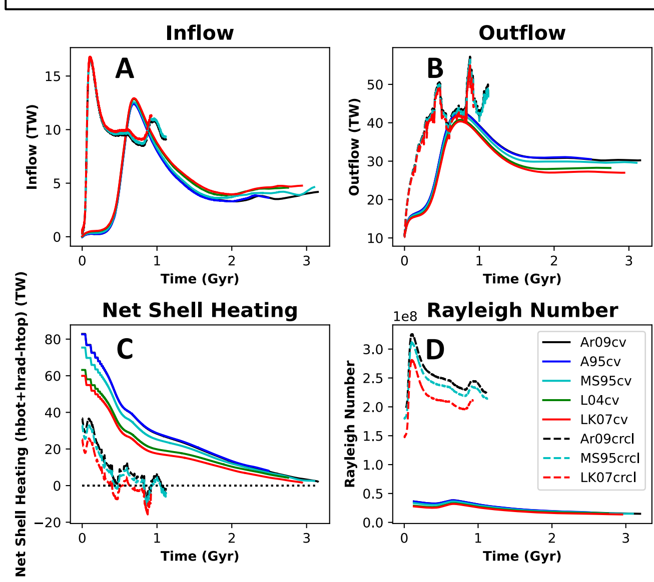

Figure 4:
Impact of various K and U concentrations (Table 1) on heat transfer.

- **A:** With imposed velocities on the surface, circulation models show a different pattern, as cold material reach the CMB faster than in convection models
- **B:** Convection models show a small variation on outflows after 1.5 Gyr, because of different radiogenic heating imposed by K and U concentrations (Table 1).
- **C:** Radioactive heating controls heat balance trend.
- **D:** Circulation models have a more vigorous convection, explaining the differences in quantity of processed material (**Figure 2**). Various K/U ratios do not seem to have a strong impact on convection vigor.

Conclusion and Future Work

- Melting in simulations
  - Dependent on the convection vigor, the melting process does not operate the same way depending on the type of model (convection vs circulation).
  - If circulation models seem to have a more Earth-like behaviour, it processes too much material to have a realistic outgassing rate of Ar.
  - The type of material that is processed in simulations is key as it drives compositional diversity and transfer to the atmosphere. Models need to tend to a more Earth-like melting.
- K/U ratio:
  - The preliminary results presented here seem to show that various K/U ratios do not affect convection but could have a greater significance in noble gases outputs
- Outgassing
  - The outgassing process is very simply implemented currently and poorly constrained. In a context where intrusive magmatism is also poorly constrained, we propose to implement a depth-dependent outgassing rate, going from very efficient at the surface to inefficient in depth.
- Tracking High He ratios:
  - Tracking these ratios in the convecting mantle is important to evaluate what parameters influence their generation and/or preservation.

References

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