CONSTRAINING THE EARLY EVOLUTION OF TERRESTRIAL PLANETS VIA NOBLE GAS ISOTOPE- AND K/U-RATIOS

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1st stage: Accretion within the gas disk phase $\Delta t < 10$ Myr (~2-5 Myr)

2nd stage: “Continuous” accretion after the nebular evaporated $\Delta t \leq 10 - 100$ Myr

3rd stage: Catastrophic outgassing of a steam atmosphere from final “deep” magma ocean

4th stage: Evolution of secondary atmospheres “N2” related to tectonics
**ATTEMPTS TO REPRODUCE THE PRESENT ATMOSPHERIC ISOTOPE RATIOS**

Mixtures between initial solar & impact related material

**Venus:** Atmospheric $^{36}\text{Ar}/^{38}\text{Ar}$, $^{20}\text{Ne}/^{22}\text{Ne}$ closer to solar

**Earth:** Atmospheric $^{36}\text{Ar}/^{38}\text{Ar}$, $^{20}\text{Ne}/^{22}\text{Ne}$, water, nitrogen, etc. a mixture of solar and carbonaceous chondrites

In addition: Reproduction of present-day K/U-ratio at Venus and Earth - abundance of $^{40}\text{K}$ important for heat production - implications for habitability!

- **Venus:** Measurements of crustal K/U by Vega and Venera landers
- **Earth:** Measurements of K/U in Bulk Silicate Earth (BSE)

Surface Temperature: $T=2000 - 2500$ K

- Global Magma ocean with depths: $\approx 200-1500$ km
- Moderately volatile Potassium will be in the atmosphere
- Some amount of CO2 nad H2O will be outgassed from the mantle, main part stays inside
Tu et al., A&A 2015; Lammer et al., AAR 2018

Nebula gas solar composition

Boil-off phase with high thermal hydrodynamic escape rates until envelope is gravitational bound

H major species, O major heavy and minors

\[ \text{Ne, Ar, Kr, Xe, K, Mg, Nd, Sm, Th, etc.} \]

EUV-driven hydrodynamic hydrogen escape

\[ \text{Ne, Ar, Kr, Xe, K, Mg, Nd, Sm, Th, etc.} \]

Classical approach energy-limited formula & hydrodynamic drag

H major species, O major heavy and minors

\( k = ^{36}\text{Ar, } ^{38}\text{Ar, } ^{20}\text{Ne, } ^{22}\text{Ne, K, CO}_2 \)

Escape flux of H atoms:

\[
F_H = \frac{\beta^2 \eta F_{\text{EUV}}}{4 \Delta \Phi \left( m_H + m_O f_{OxO} + \sum_{k=1}^{n} m_k f_k x_k \right)}
\]

Research carried out within an interdisciplinary Austrian research project „Pathways to Habitability – PATH), including international cooperators, PATH is led by M. Güdel Univ. Vienna

- Upper atmosphere hydrodynamic hydrogen escape & heavy isotopes/element dragging, including fractionation
- Losses and elemental fractionation as a function of different young Sun EUV radiation track evolution scenarios
- Hydrogen envelope radius – mass law
- Mass additions and gravity change form proto-planet mass to final planet
- Modification of isotope ratios by CC-material via impact-related mass additions →mixture of solar and CC
- Atmospheric mass loss by Moon- and Mars size impactors (mass loss is randomly between the low and max cases according to SPH model simulations)

**Aim:** Reproduction of **observed K/U** (Venus & Earth), and atmospheric **20Ne/22Ne, 36Ar/38Ar** (Venus & Earth)

- Initial ratios: solar (Genesis data vs. old solar wind as measured in the Kapoeta Howardite)
HYDROGEN ATMOSPHERE & ATMOSPHERIC LOSS

- Time-dependent hydrodynamic, radiative transport and convective energy transport H2-envelope atmosphere structure modelling
- Total atmosphere masses within the Hill radius as function of time
- Gas disk evaporates → short boil-off phase → photosphere radius shrinks until the gravity attracts the envelope → EUV-hydro-escape/fractionation

\[ f_{at} = \left[ \frac{\log(r_{ph}) + 0.07151}{1.14767} \right]^{3.1217} \]

\[ f_{at} = \frac{M_{at}}{M_{pl}} \]
SPH code & model description in Burger et al., CMDA [2018] in cooperation with Kley et al. Univ. Tübingen Institut für Astronomie & Astrophysik

Loss from moon-sized impactors ~1–10% depending on impact angle and velocity – for Mars-sized bodies ~5–30%

Removal of random atmospheric mass by impactors in our simulations

[Burger et al., CMDA 2018; IfA, Vienna: Smoothed Particle Hydrodynamic (SPH) model simulations)
## Impact Delivery of Chondrite Mixture

<table>
<thead>
<tr>
<th>Element</th>
<th>solar</th>
<th>chondritic</th>
<th>present-day Earth</th>
<th>present-day Venus</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{36}$Ar/$^{38}$Ar</td>
<td>5.50$^{12}$, 5.79$^{1,34}$</td>
<td>5.32$^{10}$</td>
<td>5.32 ± 0.033$^{10}$</td>
<td>5.45 ± 0.19</td>
</tr>
<tr>
<td>$^{20}$Ne/$^{22}$Ne</td>
<td>13.77$^{12}$, 13.69$^{1,34}$</td>
<td>8.50$^{10}$</td>
<td>9.8 ± 0.08$^{10}$</td>
<td>11.9 ± 0.79</td>
</tr>
<tr>
<td>$^{39}$K/$^{28}$U</td>
<td>394475$^{Lo}$</td>
<td>420636$^{Lo}$</td>
<td>84215.38$^{\pm15866.66}$</td>
<td>42913.23$^{\pm7445.13}$ (Vega 1, 2 &amp; Venera 9,10)</td>
</tr>
</tbody>
</table>

Abundance ratios (by number)

$^{110}$N$^{55}$S$^{72}$O$^{48}$Ne$^{21}$Ar$^{34}$U$^{20}$V$^{18}$

Miyamoto et al. 2012

### Added by impactors:

**Case 1**

- K (CI chondrites): $1.43 \times 10^{-5}$ mol/g [Lodders et al., Springer 2009]
- U (CI chondrites): $3.403 \times 10^{-11}$ mol/g [Lodders et al., Springer 2009]

**Case 2**

Mixture of 98% depleted dry material and 2% CI chondrites [Marty 2012]

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**Genesis data**

Ancient solar wind? (Kapoeta howardite) [e.g. Palma et al. GCA 2002]

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### References

- Anders and Crevese 1989
- Meshik et al. GCA 2014
- Palma et al. GCA 2002
- Marty 2012
- Wieler RMG 2002
- Davis et al. T Geo 2005
- Lodders et al., Springer 2009
- Arevalo et al., EPSL 2009
- ArArevalo et al., EPSL 2009
- Palma et al. GCA 2002
- Marty 2012
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REPRODUCTION OF $^{20}\text{Ne}/^{22}\text{Ne}$, $^{36}\text{Ar}/^{38}\text{Ar}$, K/U ON VENUS

0.93$M_{\text{Venus}}$ (0.75$M_{\text{Earth}}$)

Sun close to a slow rotator (EUV slightly higher than a slow rotator)

$^{36}\text{Ar}/^{38}\text{Ar}$ can only be reproduced with ancient solar wind $f_{\text{at}}=7.2 \times 10^{-4}$

$Lammer et al., under preparation 2018$
$0.75M_{\text{Earth}}$

$f^a = 4.8 \times 10^{-3}$

Sun a moderate rotator

[Lammer et al., under preparation 2018]
0.58M_{\text{Earth}}

f^{at}_{\text{H}} = 4.35 \times 10^{-5}

Sun close to a slow rotator (EUV slightly higher than a slow rotator)

K/U can only be reproduced if we assume depleted (Mars-like bulk-composition) delivery by impactors and only 2% CI-chondrites

In agreement with:
Hf – W chronometry of terrestrial rocks
[e.g., Wetherill, 1986; Harber and Jacobsen, 1996; Kleine et al., 2002; Yin et al. 2002; Ju and Jacobsen 2011]

[Lammer et al., under preparation 2018]
CHI^2 TESTS: VENUS & EARTH RUNS

Young Sun: slow to moderate rotating weakly active G-star

Initial core masses (~ 5 Myr):

- Venus: ~0.87 – 1.0M
- Earth: ~0.57 – 0.59M

[Tu et al., A&A 2015]

[Lammer et al., under preparation 2018]
CONCLUSION

- Initial (~2-5 Myr) core masses: $0.9 \pm 0.03 M_{\text{Venus}}$ or $\approx 0.73 M_{\text{Earth}}$ (Venus) and $0.58 \pm 0.01 M_{\text{Earth}}$ (Earth)

- A weakly active slow rotating young Sun reproduces the observed isotope (Ne, Ar) and K/U fractionation on Venus & Earth & Mars (K/U)

- Venus !!! Mission! Venus atmosphere may contain fingerprints of the early solar wind!

- K/U ratio on Earth was mainly delivered by impactors after its initial amount was lost
  K should be lost efficiently from fractionated planetary embryos (magma oceans)

- “Realistic” magma ocean related steam atmospheres cannot reproduce the K/U and noble gas isotope fractionations on Venus and Earth

- Stellar X-ray and EUV activity, impact history, accretion time and delivery of volatiles by carbonaceous chondrites set the initial stage for the evolution of Earth-like planet’s:
  - bulk composition,
  - geodynamics and
  - habitability, especially the evolution of long time geological active habitats (i.e., plate tectonics, outgassing, secondary atmosphere evolution, water, etc.)

- because of many different formation possibilities, one may expect that many terrestrial planets may have problems for developing long-time plate tectonics important for habitability and life as we know it
EVOLUTION OF EARLY VENUS & EARTH

[Lammer et al., under preparation 2018]
TERRESTRIAL PLANET EVOLUTION

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[Yu & Jacobsen, PNAS 2011]
EVIDENCE OF CAPTURED H2-ENVELOPES

A determination of the neon isotopic composition of the deep mantle

Reika Yokochi*, Bernard Marty

Abstract

The neon isotopic composition of the deep mantle, which allows to investigate formation processes of the Earth, is subject to debate. We have analyzed Ne trapped in fluid inclusions from plume-related Devonian rocks from the Kola Peninsula, Russia. The lower limit for pristine neon in the deep mantle is set at 20 Ne/22 Ne ≥ 13.0 ± 0.2, close to the solar wind (SW) value. We interpret this similarity as evidence that mantle light noble gases were directly incorporated from the solar nebula rather than derived from implanted meteoritic solar component, possibly through gravitational capture of a proto-atmosphere. This constraint is consistent with geochemical observations of rapid accretion of a major part of the growing Earth within the inferred lifetime of the solar nebula. If depleted mantle neon admits an upper limit of 12.5, then the occurrence of plume type neon with 20 Ne/22 Ne ≥ 13.0 ± 0.2 may indicate a primordial Ne heterogeneity in the mantle. The 3He/4He ratios of terrestrial mantle reservoirs sampled by MORB and plumes vary with the degree of volatile element depletion of the mantle. This correlation was possibly established during magmatic events having led to the chemical characteristics of the depleted mantle reservoir.

Keywords: mantle; neon; solar

H2O in envelope ≤ 30 bar
CO2 in envelope ≤ 5 bar
The main fraction of H2O, CO2 remain in the magma ocean until solidification

[Stolper and Holloway, EPSL 1988; Gillmann et al., EPSL 2009]

T = 2000 – 2500 K
Magma ocean depths: ≈ 200–1500 km

Modelled by the group of Doris Breuer
DLR Berlin (N. Tosi & A. Nikolaou)

[Lammer et al., in preparation 2018]
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**Earth:** Atmospheric $^{36}\text{Ar}/^{38}\text{Ar}$, $^{20}\text{Ne}/^{22}\text{Ne}$, water, nitrogen, etc. a mixture of solar and carbonaceous chondrites  
[e.g., Marty, EPSL 2012]

**Mars:** Atmospheric $^{36}\text{Ar}/^{38}\text{Ar}$, $^{20}\text{Ne}/^{22}\text{Ne}$, Xe, Kr  
[e.g., Becker et al., SSR 2003]

During the past decades several previous attempts have been carried out for reproducing the observations  

What was badly known until a few years ago?

- Interaction between possible captured H2–envelopes during the accretion of protoplanets against losses, drag and fractionation after envelope evaporates
- The EUV–evolution track(s) of the young Sun (G–stars)
- Interaction between atmosphere–losses / fractionation vs. impact delivered material
Time-dependent hydrodynamic, radiative transport and convective energy transport H2-envelope atmosphere structure modelling

Total atmosphere masses within the Hill radius as function of time

Gas disk evaporates → short boil-off phase → photosphere radius shrinks until the gravity attracts the envelope → EUV-hydro-escape/fractionation
Potassium (K) IS DEPLETED ON EVERY PLANET

Experimental evidence that potassium is a substantial radioactive heat source in planetary cores

V. Rama Murthy*, Wim van Westrenen† & Yingwei Fei†

[Murthy et al., Nature 2003]

K: condensation temperature ~1000 K

One further trace element of potential importance to the core is potassium, because radioactive decay of this element can help drive a long-lived dynamo and influences the long-term temperature evolution of the core [e.g., Nimmo, 2015]. K does not appear to partition efficiently

[Mimmo and Kleine, 2015]