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

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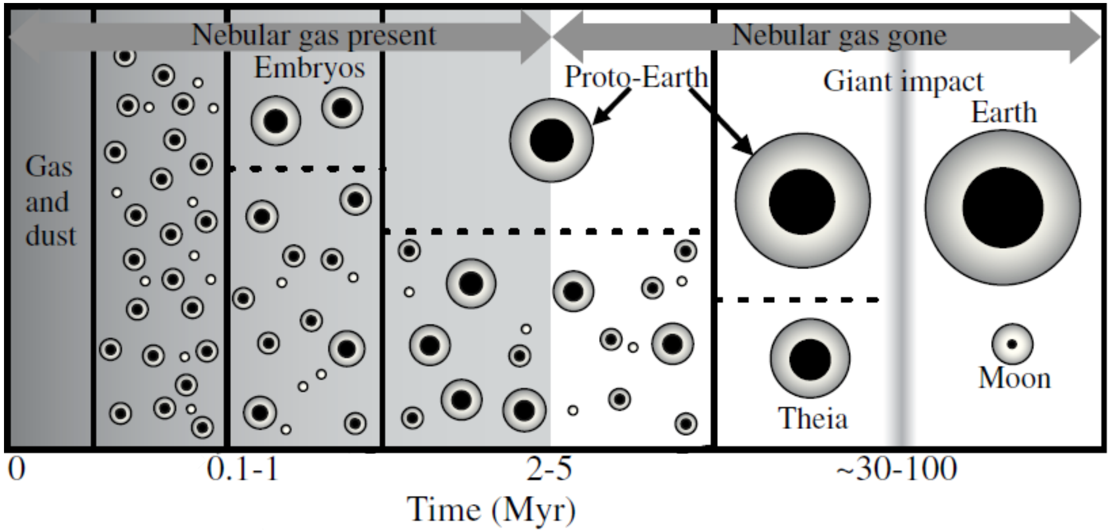
TERRESTRIAL PLANET EVOLUTION

- 1st stage: Accretion within the gas disk phase Δt < 10 Myr (~2-5 Myr)
- 2nd stage: "Continuous" accretion after the nebular evaporated Δt ≤ 10 – 100 Myr



[Yu & Jacobsen, PNAS 2011]

- 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 $^{36}Ar/^{38}Ar$, $^{20}Ne/^{22}Ne$ closer to solar [e.g., Wieler 2002]

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

Orgueil

Murchison

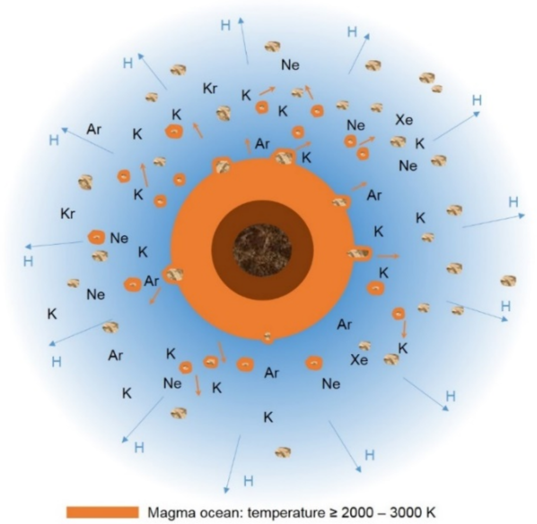
In addition: Reproduction of present-day K/U-ratio at Venus and Earth – abundance of ^{40}K important for heat production – implications for habitability!

- **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: ≈ 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

Venus & Earth



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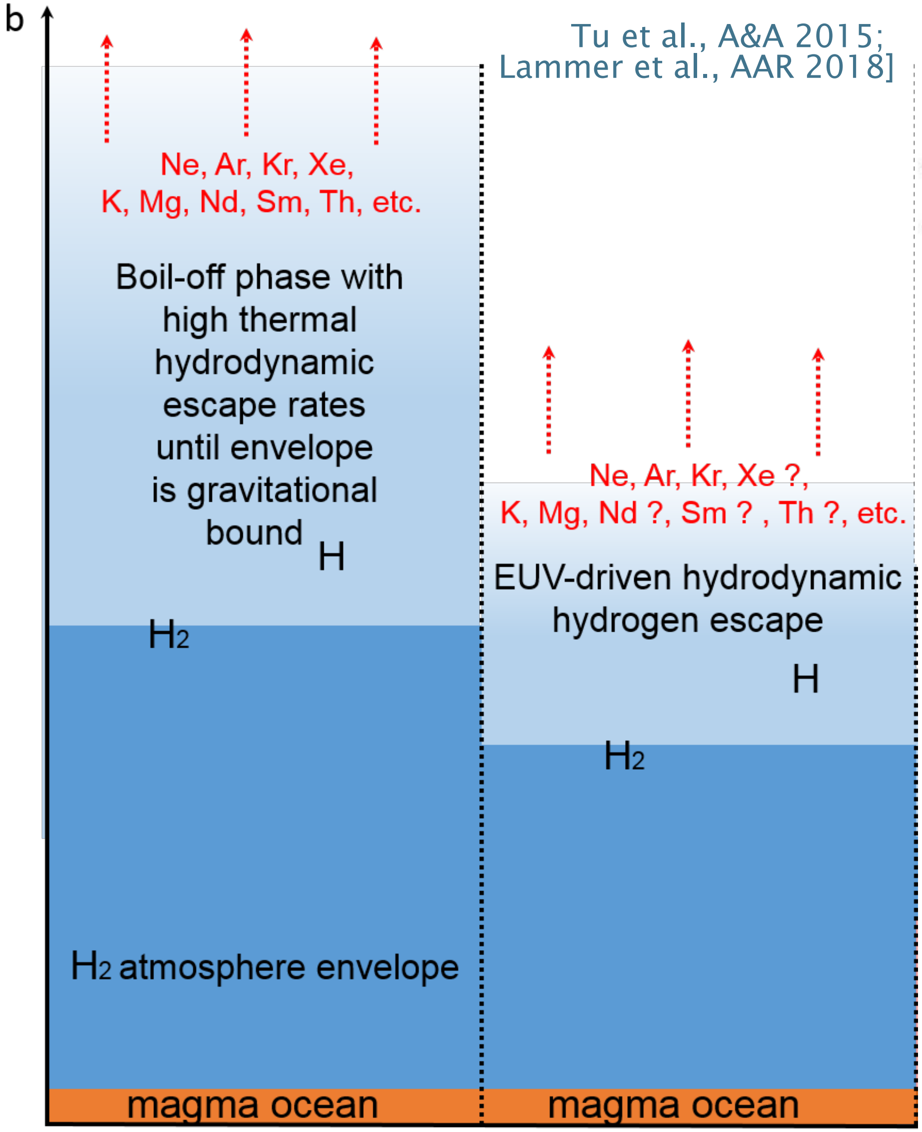

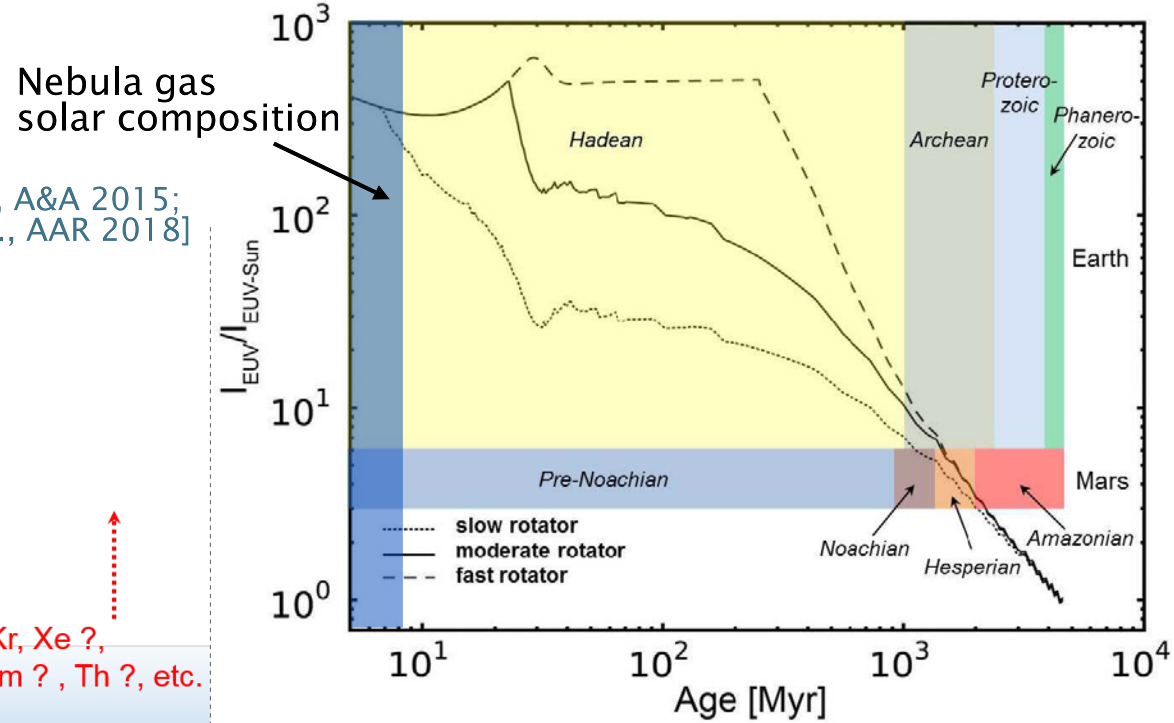

Classical approach energy-limited formula & hydrodynamic drag

H major species, O major heavy and minors

$$(k = {}^{36}Ar,\ {}^{38}Ar,\ {}^{20}Ne,\ {}^{22}Ne,\ K,\ CO_2)$$

Escape flux of H atoms:

$$F_H = \frac{\beta^2 \eta F_{EUV}}{4\Delta\Phi \left(m_H + m_O f_O x_O + \sum_{k=1}^{n} m_k f_k x_k\right)}$$

[e.g., Hunten, JAS 1973; Icarus 1987; Zahnle et al., Icarus 1990; Pepin, Icarus 1991; Nature 1998; SSR 2000; Odert et al., Icarus 2017]

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MODELLING (SHOULD) INCLUDE

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)

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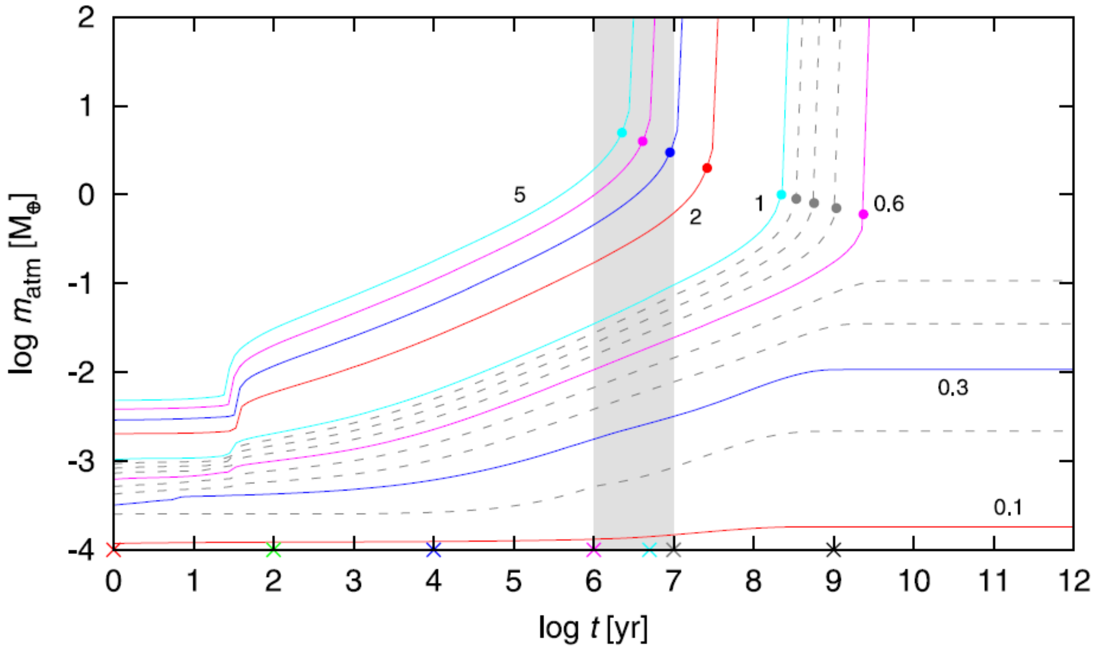
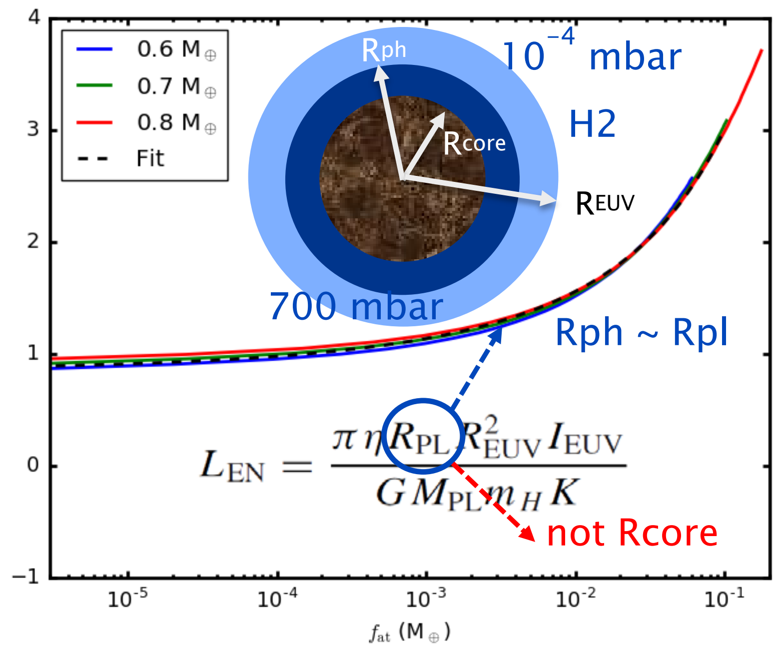
HYDROGEN ATMOSPHERE & ATMOSPHERIC LOSS



[Stökl et al., ApJ 2016]



[Lammer et al., in preparation 2018]

- 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

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

$$f_{at} = M_{at}/M_{pl}$$

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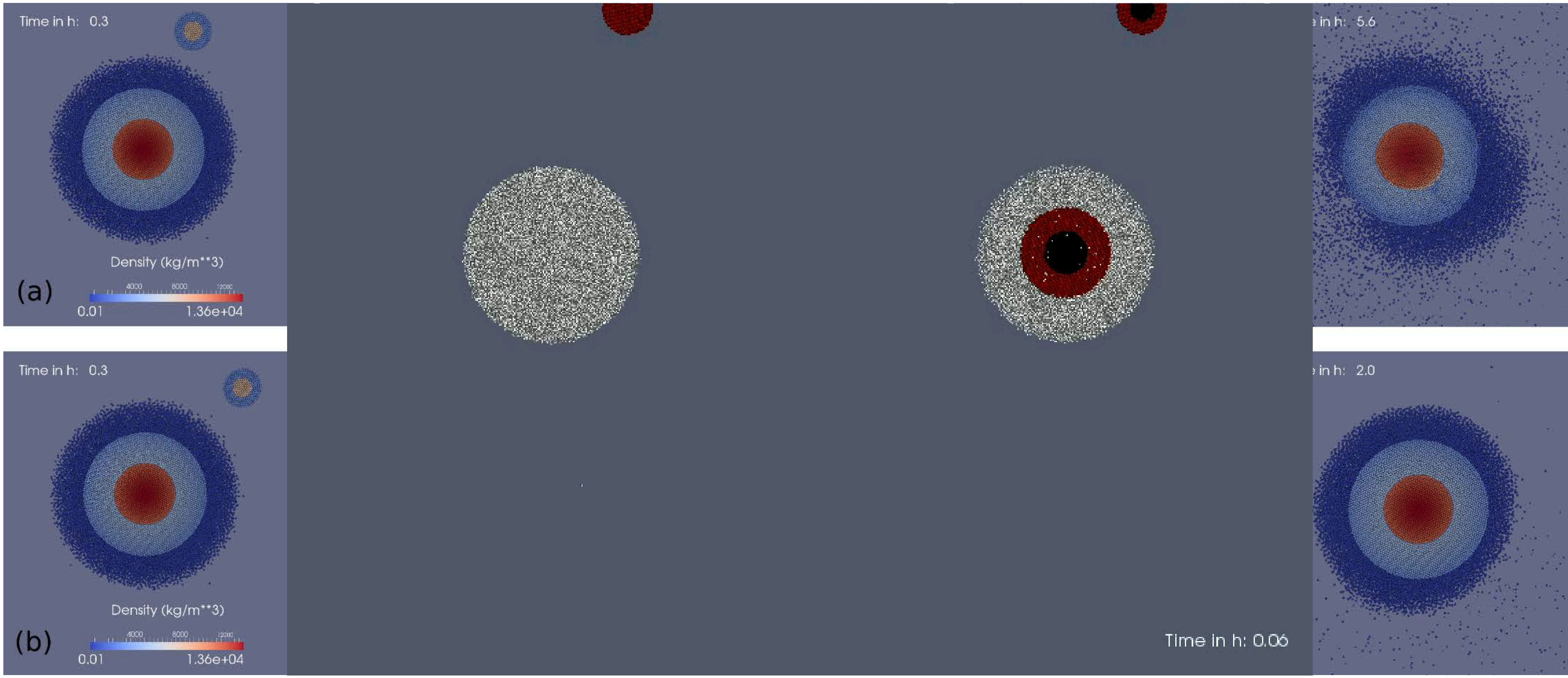
IMPACTS

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)]

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IMPACT DELIVERY OF CHONDRITE MIXTURE

Genesis data

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

Element	solar	chondritic	present-day Earth	present-day Venus
$^{36}Ar/^{38}Ar$	5.50[12], 5.79[1,34]	5.32[10]	5.32 ± 0.033[10]	5.45 ± 0.1[9]
$^{20}Ne/^{22}Ne$	13.77[12], 13.69[1,34]	8.50[10]	9.8 ± 0.08[10]	11.9 ± 0.7[9]
$^{39}K/^{238}U$	394475[Lo]	420636[Lo]	$84215.38^{\pm 15866.66}$[Ar]	$42913.23^{\pm 7445.13}$ (Vega 1, 2 & Venera 9,10)[20]
				$110955.72^{\pm 48521.97}$ (Venera 8)[20]

Abundance ratios (by number)

[[1]Anders and Crevese 1989; [12]Meshik et al. GCA 2014; [34]Palma et al. GCA 2002; [10]Marty 2012; [9]Wieler RMG 2002; [20]Davis et al. T Geo 2005; [Lo]Lodders et al., Springer 2009; [Ar]Arevalo et al., EPSL 2009]

Added by impactors:

Case 1

K (CI chondrites): 1.43×10^{-5} mol/g [Lodders et al., Springer 2009]

U (CI chondrites): 3.403×10^{-11} mol/g [Lodders et al., Springer 2009]

Case 2

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

	Solar (mol/g)	CC (mol/g)	+/−	ATM (mol/g)	DM (mol/g)	+/−	BM (mol/g)	+/−	Bulk Earth (ppm)	+/−	Bulk Earth/ (CC)
^{12}C	8.60E-11	2.94E-03	5.31E-04	1.29E-06	1.67E-06	6.67E-07	6.38E-05	2.5E-05	526	206	1.49%
^{14}N	1.78E-11	1.09E-04	1.63E-05	5.98E-08	6.43E-09	3.57E-09	9.0E-08	4.6E-08	1.68	0.85	0.11%
H_2O	1.17E-10	6.60E-03	2.10E-03	1.48E-05	8.33E-06	2.78E-06	2.0E-04	9.6E-05	2699	1347	2.27%
^{22}Ne	2.13E-12	1.62E-12	4.33E-13	2.27E-14	3.42E-16	1.71E-16	5.8E-15	3.2E-15			1.64%
^{36}Ar	6.31E-13	3.47E-11	2.78E-12	9.58E-13	2.72E-15	1.88E-15	7.8E-14	4.3E-14			2.91%
^{84}Kr	3.15E-16	4.25E-13	1.79E-14	1.98E-14	1.51E-16	7.57E-17	1.9E-15	1.1E-15			4.95%
^{130}Xe	7.88E-18	5.38E-14	1.46E-14	1.08E-16	2.84E-18	1.95E-18	2.6E-17	6.8E-18			0.23%

[Marty, EPSL 2012]

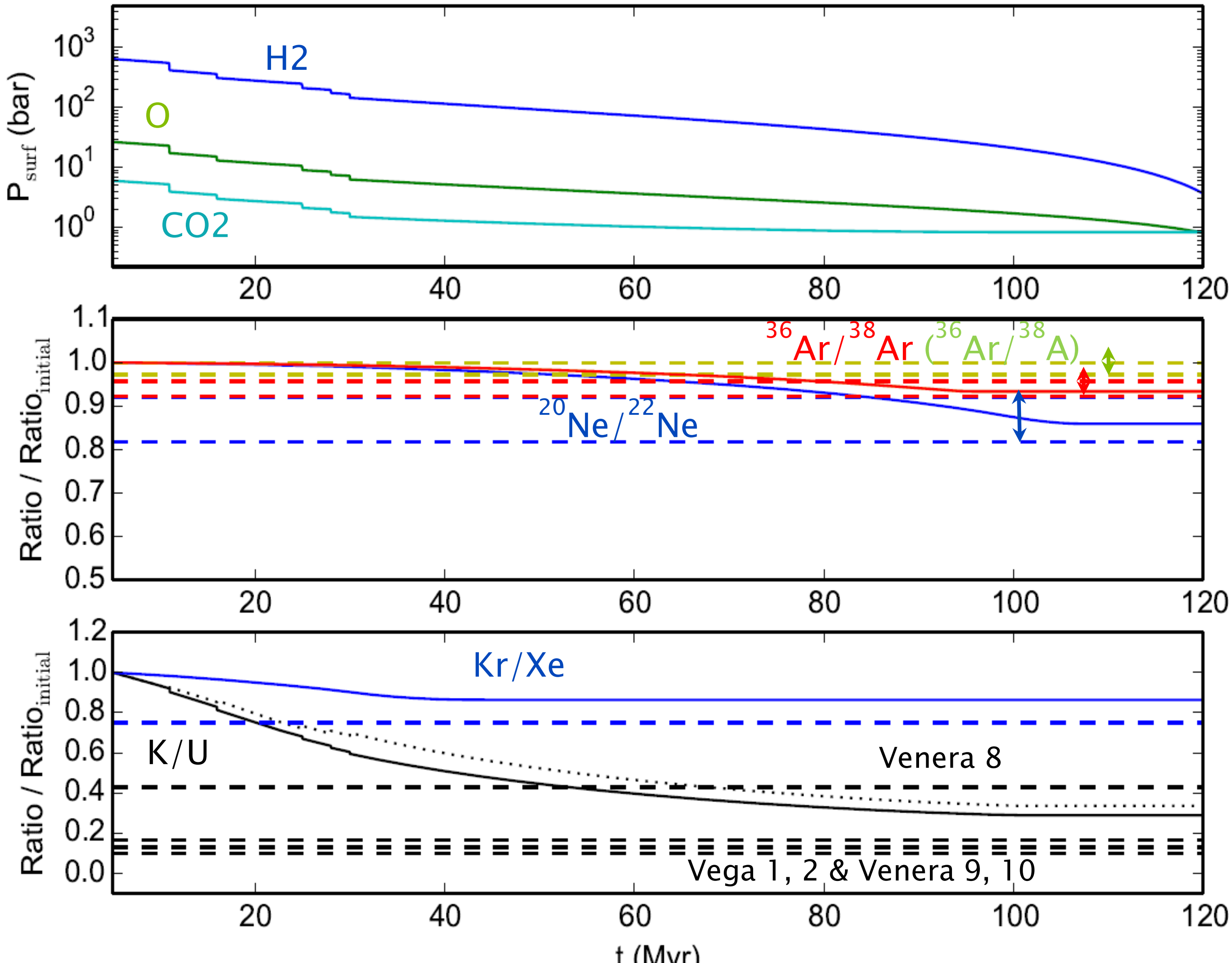
REPRODUCTION OF ^{20}NE/^{22}NE, ^{36}AR/^{38}AR, K/U ON VENUS

0.93M^{Venus} (0.75M^{Earth})

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

^{36}Ar/^{38}Ar can only be reproduced with ancient solar wind

$f_{at} = 7.2 \times 10^{-4}$



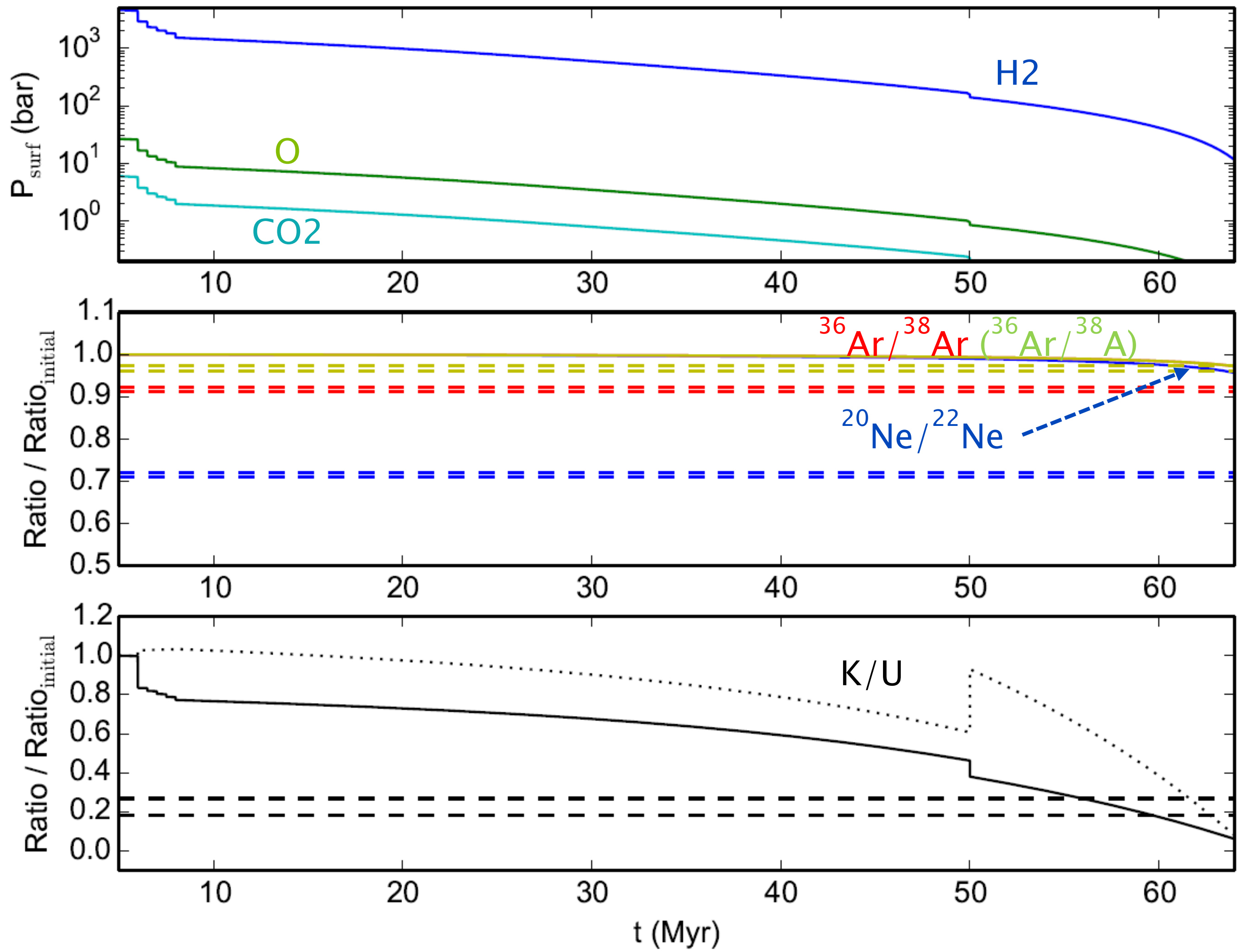
[Lammer et al., under preparation 2018]

REPRODUCTION ATTEMPT ON EARTH

$0.75M^{Earth}$

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

Sun a moderate rotator



[Lammer et al., under preparation 2018]

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REPRODUCTION OF ^{20}NE/^{22}NE, ^{36}AR/^{38}AR, K/U ON EARTH

$0.58 M^{Earth}$

$f^{at} = 4.35 \times 10^{-5}$

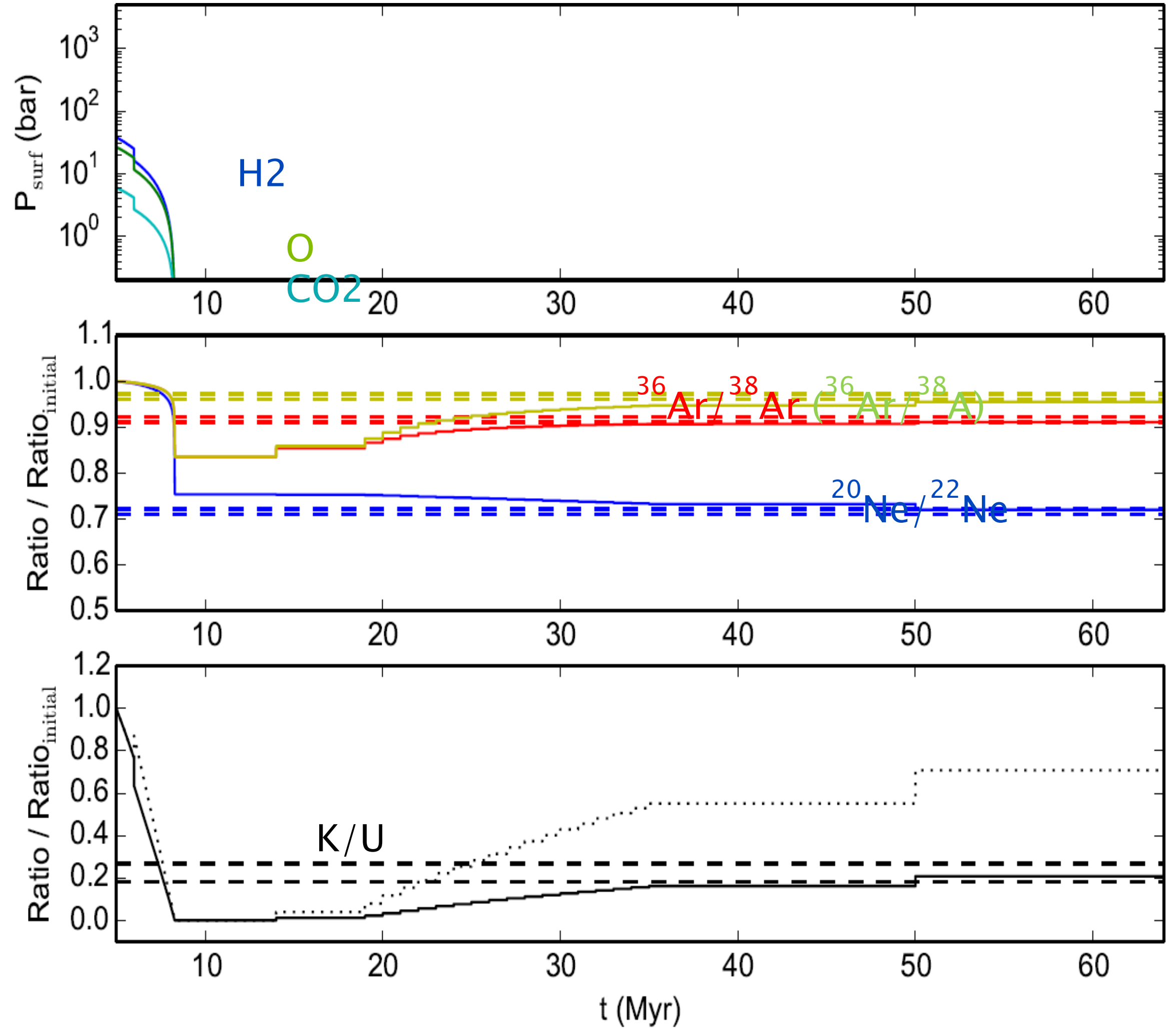
Sun close to a slow rotator (EUV slightly higher than a slow rotator)

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]

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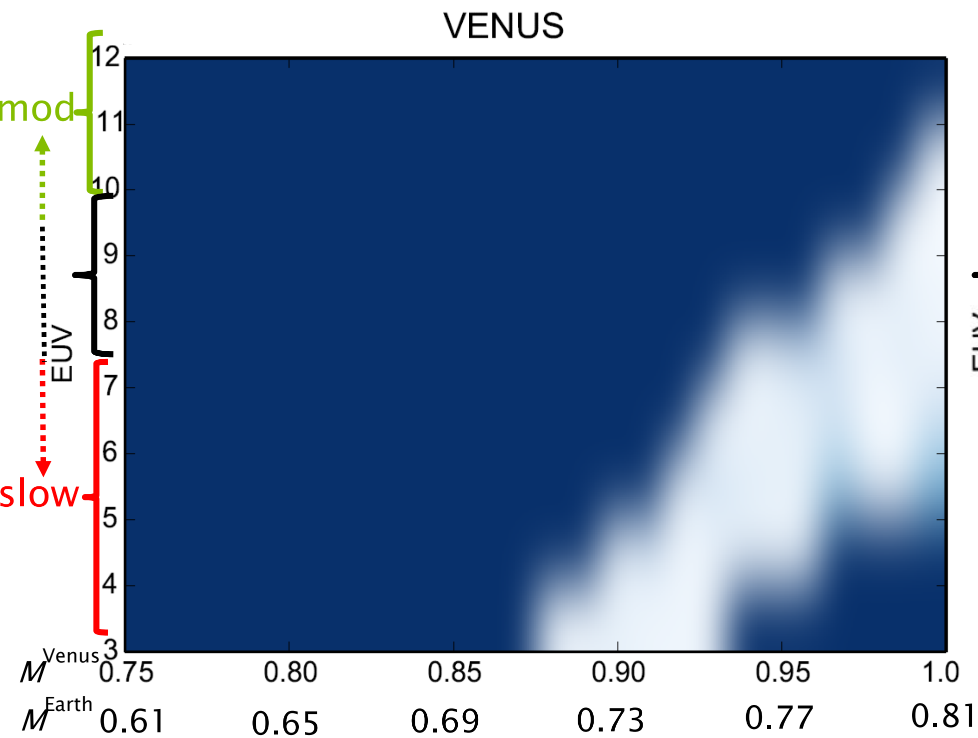
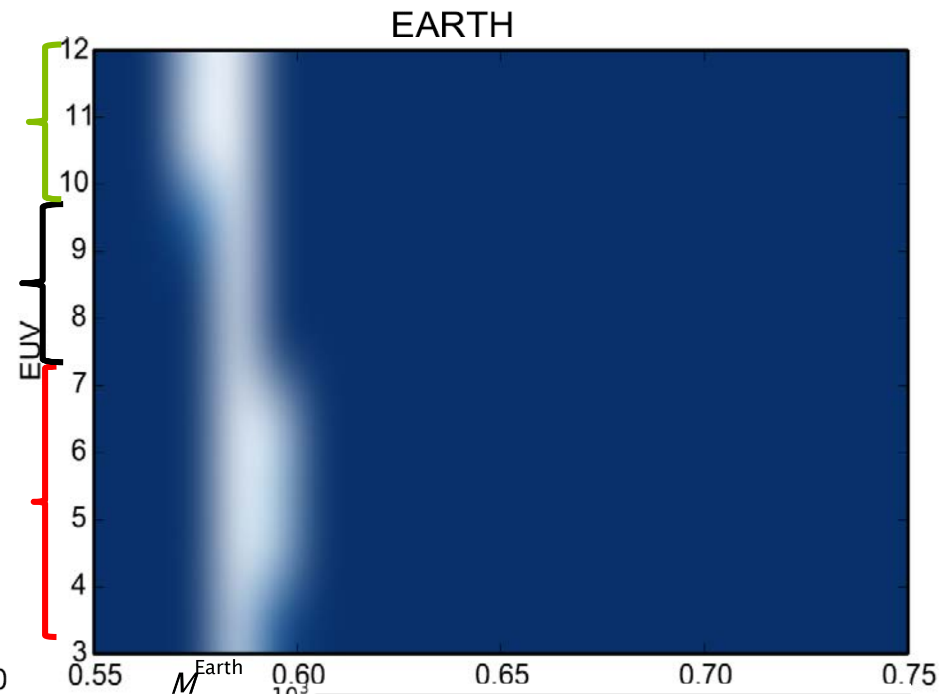
CHI^2 TESTS: VENUS & EARTH RUNS



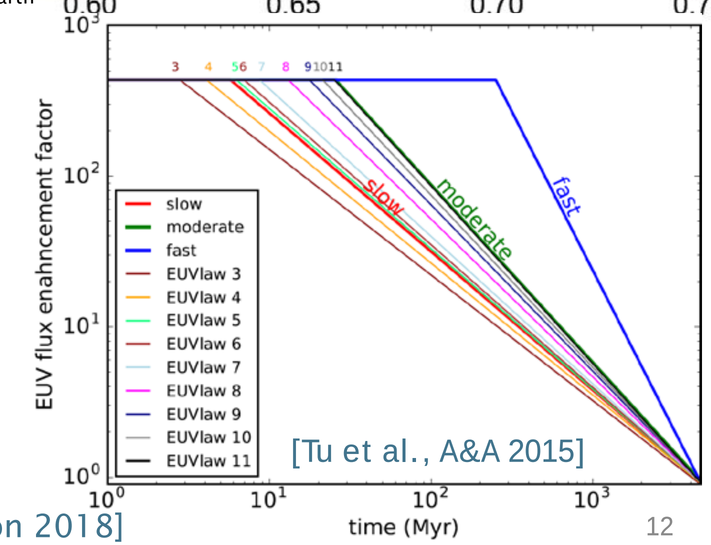


Young Sun: slow to moderate rotating weakly active G-star

Initial core masses (~ 5 Myr):

Venus: ~0.87 – 1.0 M^{Venus}

Earth: ~0.57 – 0.59 M^{Earth}



[Tu et al., A&A 2015]

[Lammer et al., under preparation 2018]

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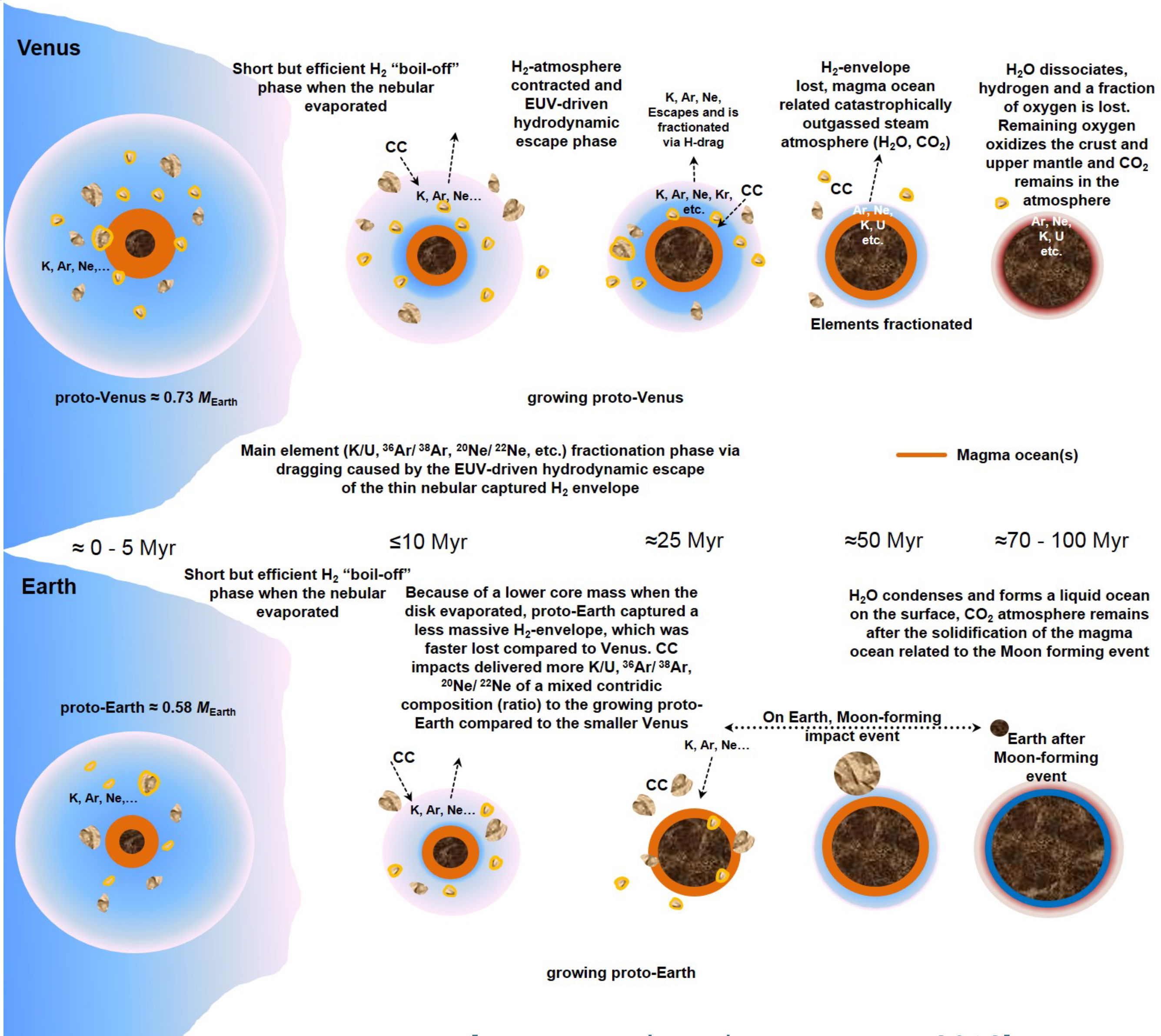
CONCLUSION

- Initial (~2-5 Myr) core masses: 0.9±0.03M_{Venus} or ≈0.73M_{Earth} (Venus) and 0.58±0.01M_{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]

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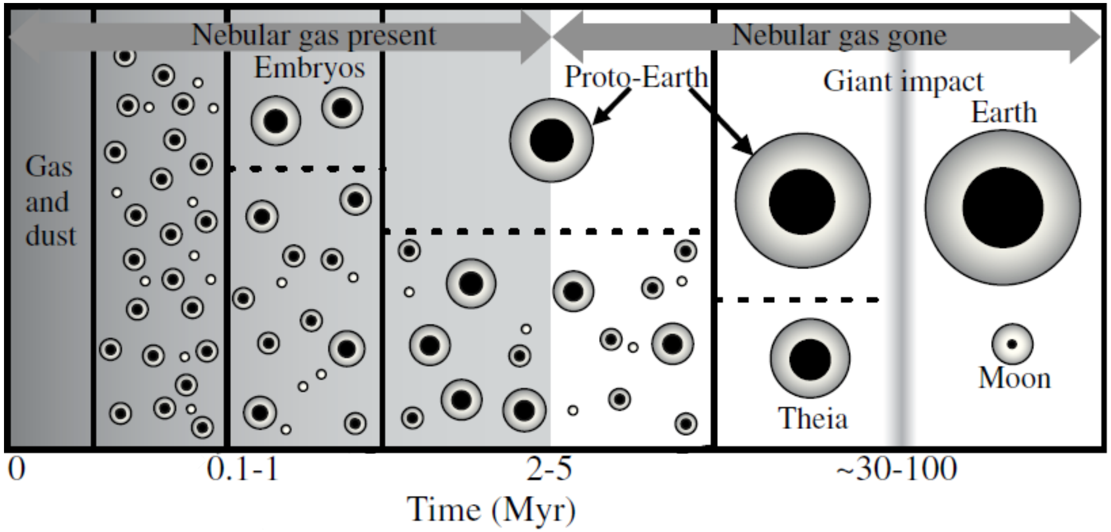
TERRESTRIAL PLANET EVOLUTION

- 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



[Yu & Jacobsen, PNAS 2011]

- 3rd stage: Catastrophic outgassing of a steam atmosphere from final "deep" magma ocean
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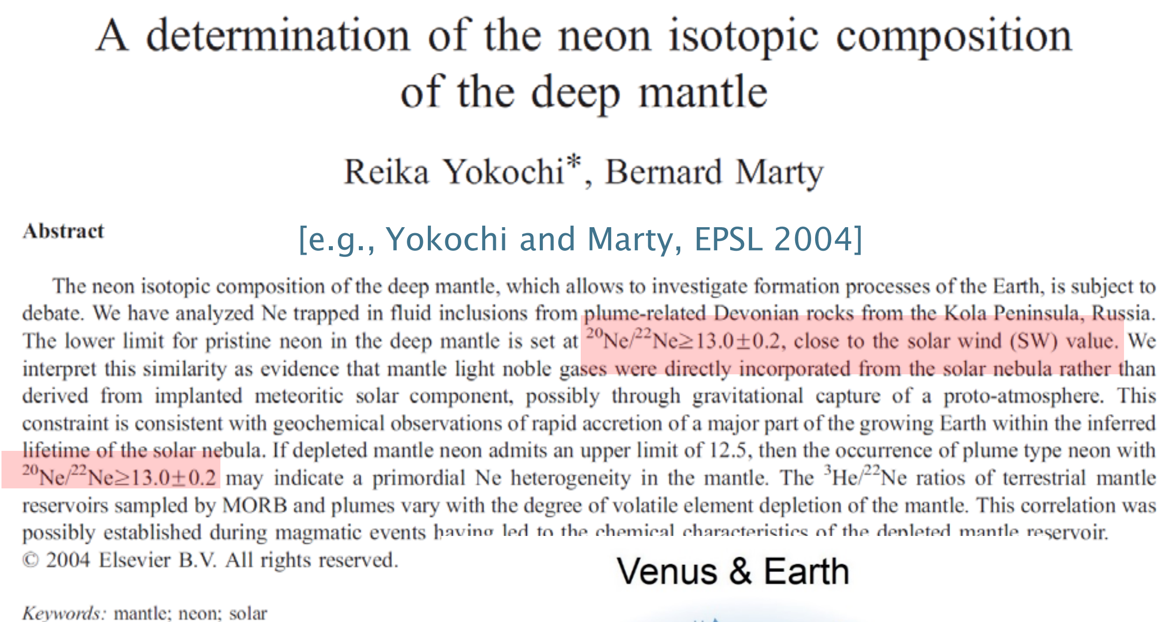
EVIDENCE OF CAPTURED H2-ENVELOPES



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 $^{20}Ne/^{22}Ne \geq 13.0 \pm 0.2$, 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 $^{20}Ne/^{22}Ne \geq 13.0 \pm 0.2$ may indicate a primordial Ne heterogeneity in the mantle. The $^{3}He/^{22}Ne$ 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.

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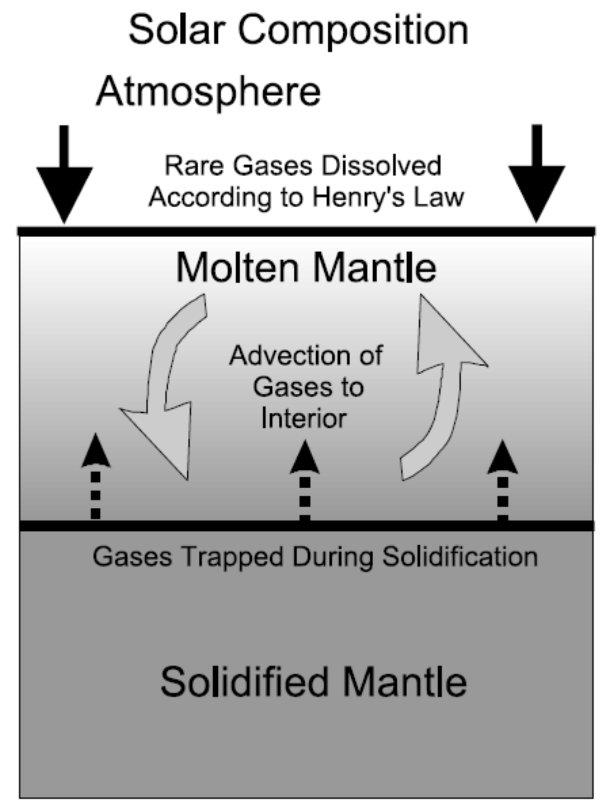
Keywords: mantle; neon; solar

[e.g., Yokochi and Marty, EPSL 2004]



[Porcelli et al., EPSL 2001]

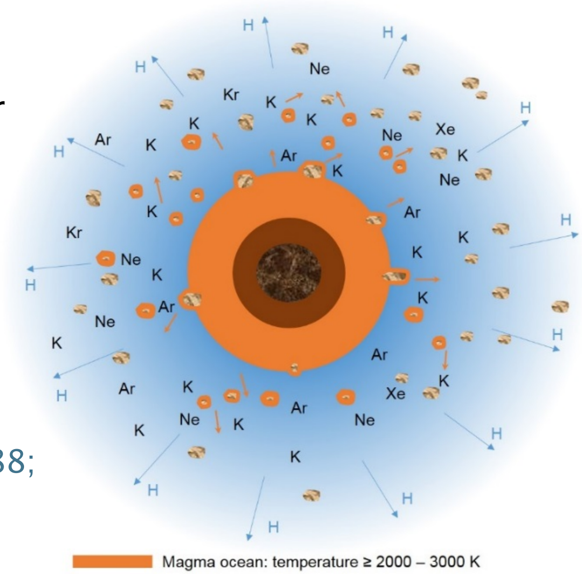
H_2O in envelope ≤ 30 bar

CO_2 in envelope ≤ 5 bar

The main fraction of H_2O, CO_2 remain in the magma ocean until solidification

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

Venus & Earth



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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Mixtures between initial solar & impact related material

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

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

[e.g., Zahnle and Kasting, Icarus 1986; Hunten et al., Icarus 1987; Zahnle et al. Icarus, 1990; Pepin, Icarus 1991; Nature 1998; SSR 2000; Jakosky et al., Icarus 1994; 1997; Porcelli and Pepin, 2000; Gillmann et al., EPSCL 2009; Odert et al., Icarus 2018]

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

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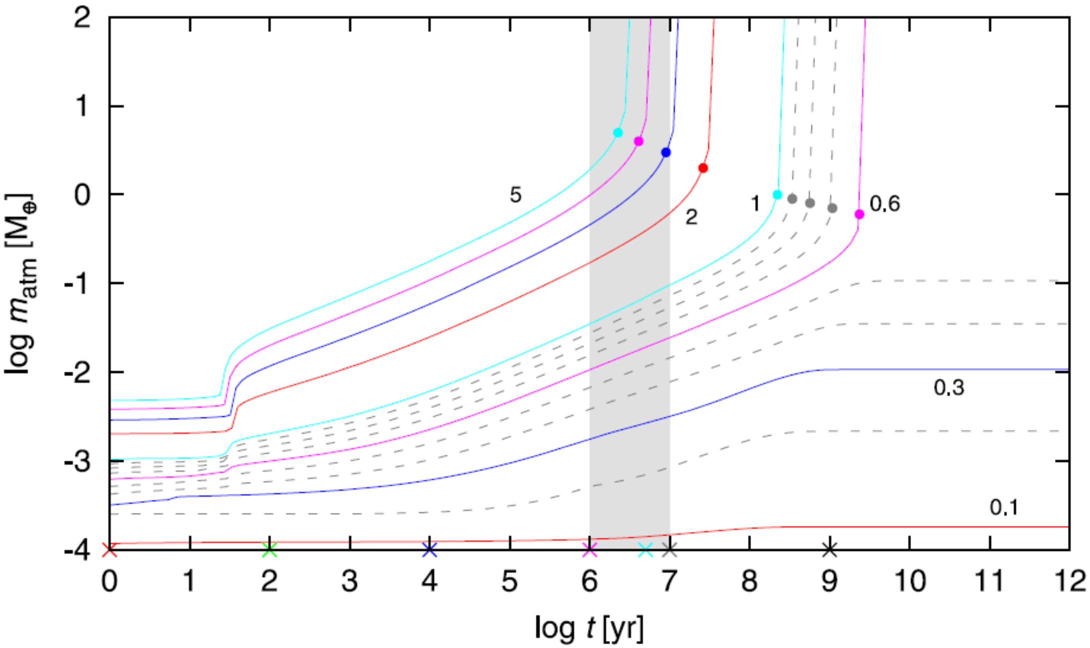
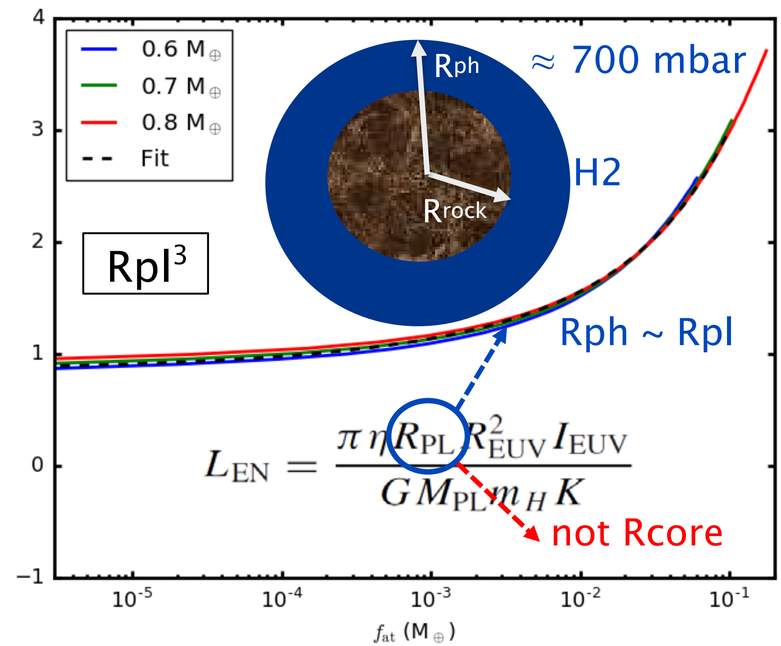
CORE RADIUS VS. PHOTOSPHERE RADIUS



[Stökl et al., ApJ 2016]



[Lammer et al., in preparation 2018]

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

$$f_{at} = M_{at}/M_{pl}$$

- 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

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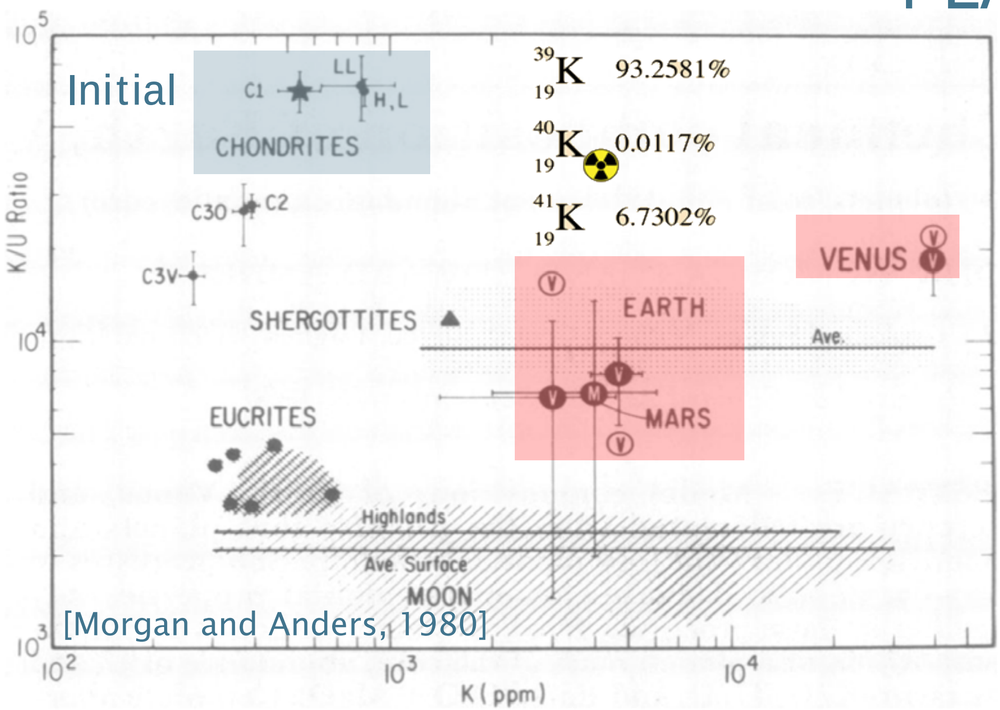
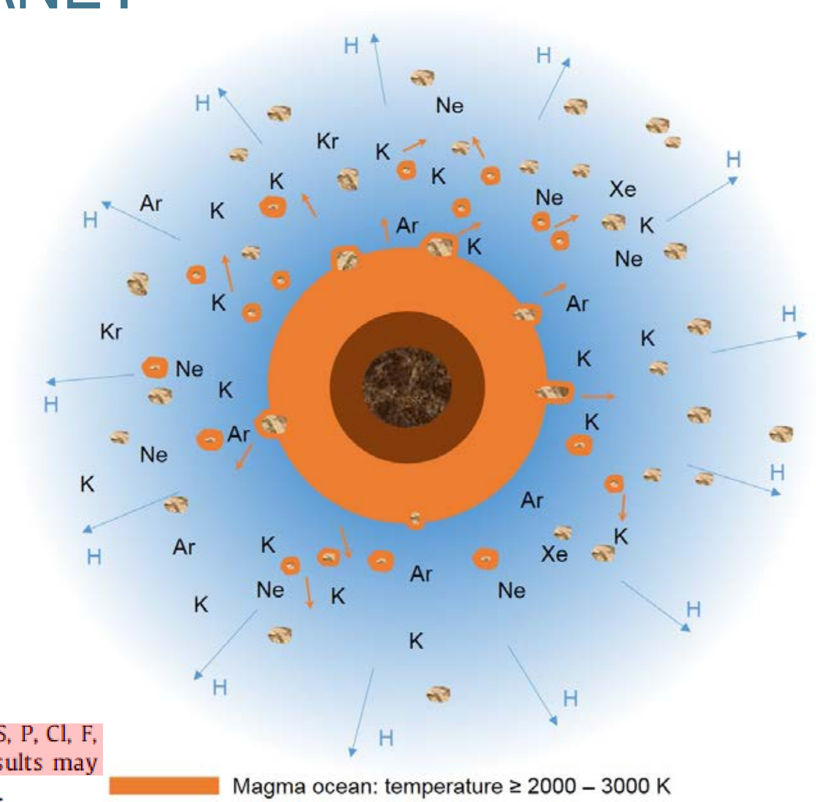
Potassium (K) IS DEPLETED ON EVERY PLANET



[Morgan and Anders, 1980]

nantly *CI* and *CM* carbonaceous chondritic material. We also predict significant amounts of S, P, Cl, F, Na, and K in accretionary atmospheres at high temperatures (1500–2500 K). Finally, our results may be useful for interpreting spectroscopic observations of accreting extrasolar terrestrial planets.

[Schaefer and Fegley Jr., Icarus 2010]



[Lammer et al., under preparation 2018]

K: condensation temperature ~1000 K

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]

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

[Nimmo and Kleine, 2015]