EVOLUTION OF ATMOSPHERES

OUTGASSING HISTORY, AND WATER INVENTORIES OF TERRESTRIAL PLANETS

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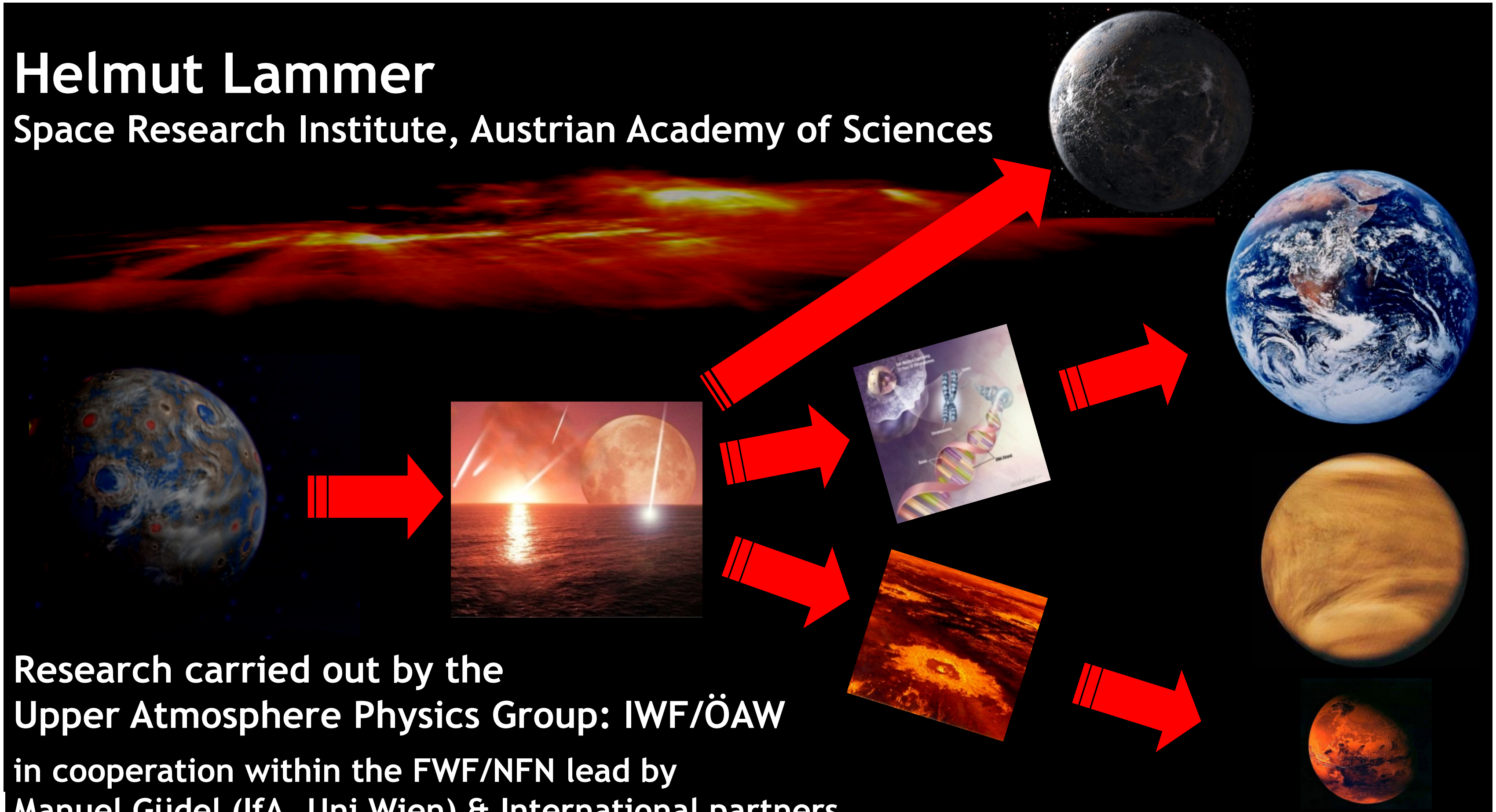

Research carried out by the
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in cooperation within the FWF/NFN lead by
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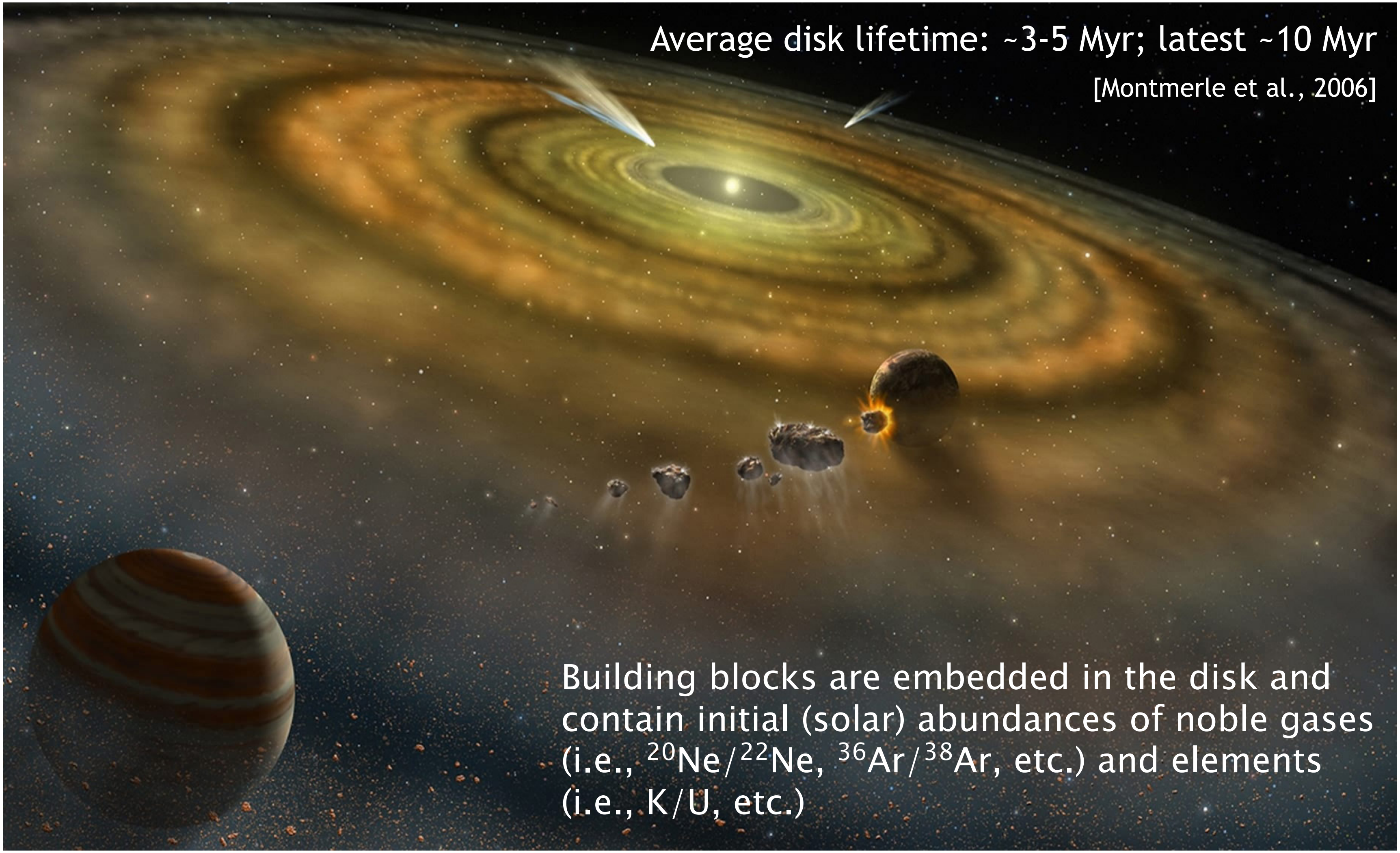
THE INITIAL FORMATION PHASE



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FAST OR SLOW(ER) ACCRETION?

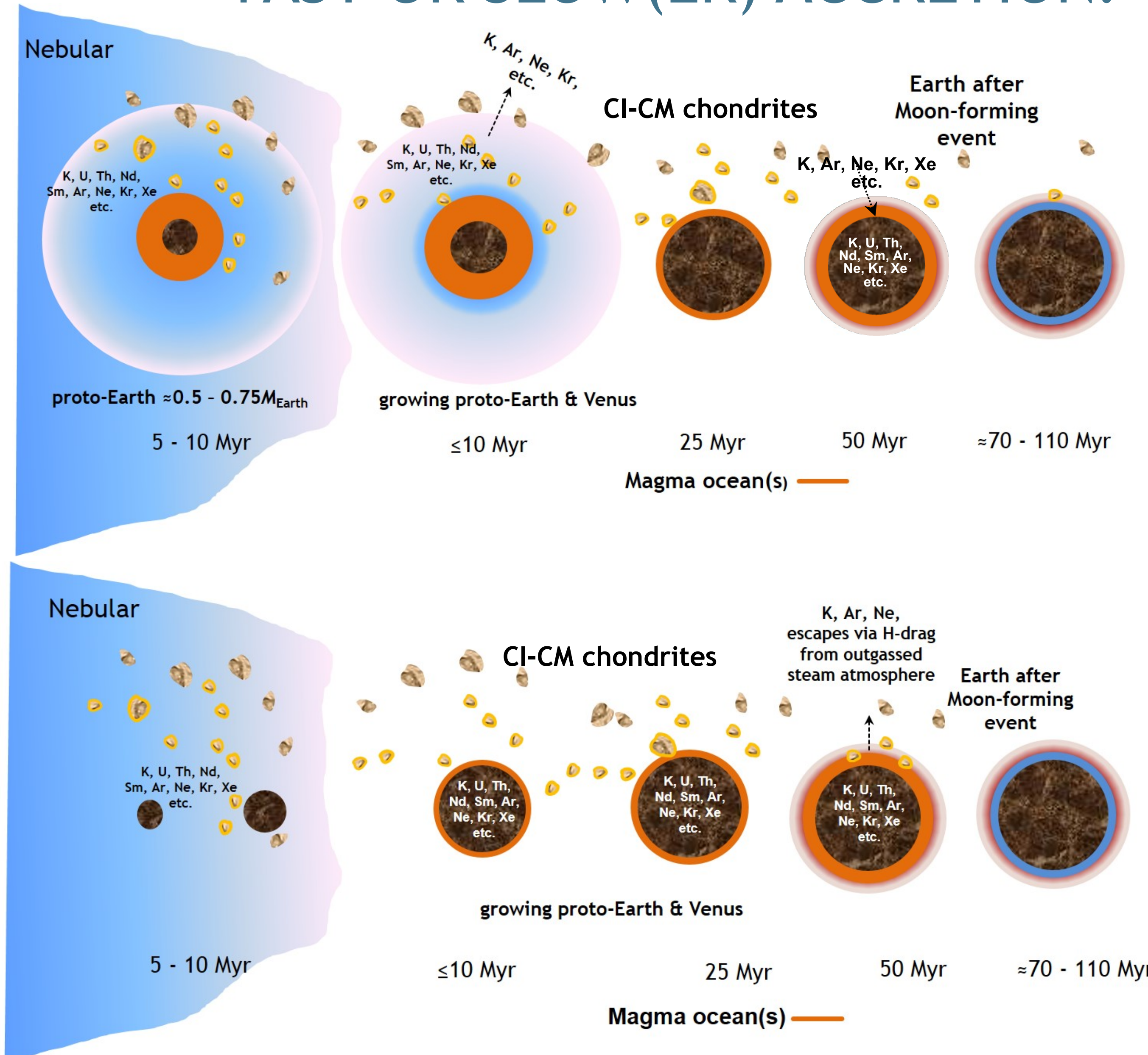
Venus: Atmospheric $^{36}Ar/^{38}Ar$, $^{20}Ne/^{22}Ne$ closer to solar

Earth: Atmospheric $^{36}Ar/^{38}Ar$, $^{20}Ne/^{22}Ne$ a mixture of solar and **CI-CM chondrites**

Orgueil

Murchison

Mars: Atmospheric $^{36}Ar/^{38}Ar$, $^{20}Ne/^{22}Ne$, Xe, Kr closer to solar



[Lammer et al., under preparation 2017]

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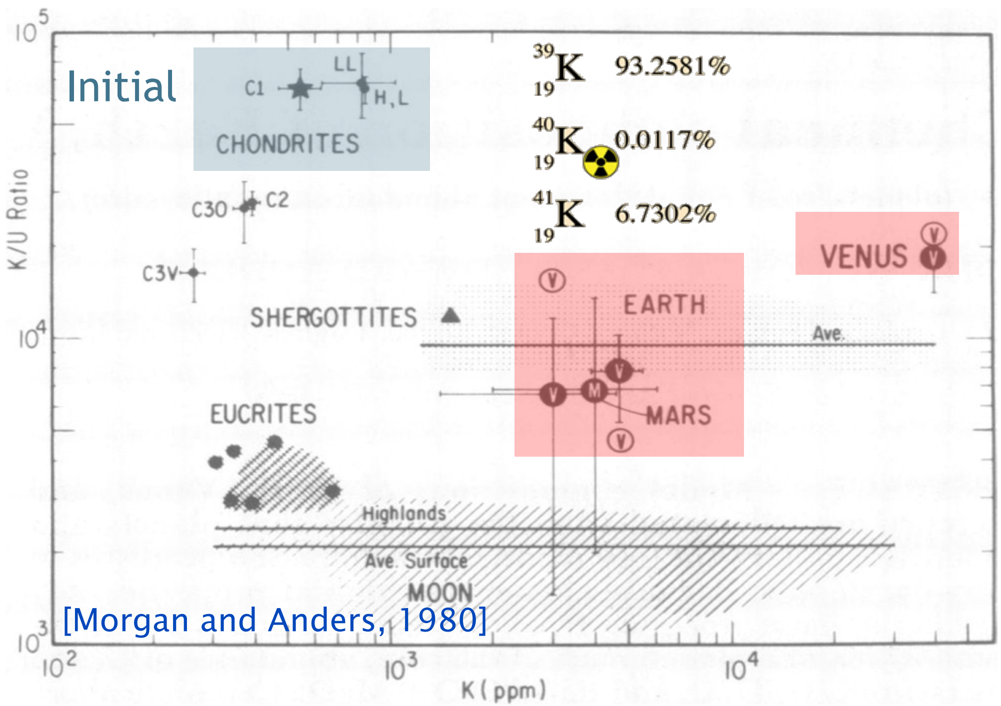
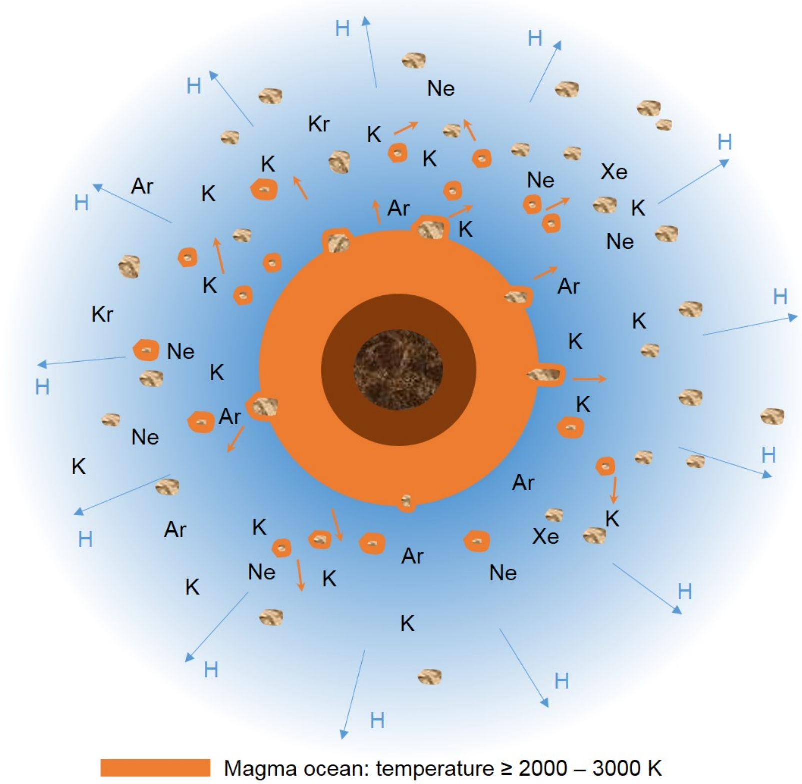
Potassium (K) IS DEPLETED ON EVERY PLANET



[Morgan and Anders, 1980]

K: condensation temperature ~1000 K



[Lammer et al., under preparation 2017]

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

[Nimo and Kleine, 2015]

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MODEL

- Hydrodynamic hydrogen escape & heavy isotopes/element dragging, including fractionation
- Losses and elemental fractionation as a function of different young Sun XUV radiation track evolution scenarios
- Hydrogen envelope radius – mass law
- Mass additions and gravity change form proto-planet core to final planet
- Atmospheric mass loss by Moon and Mars size impactors (mass loss is randomly between the low and max cases according to SPH model simulations)
- Initial ratios: solar
- Chondritic (CC) ratios are added by impactors when mass is added

Aim: Reproduction of **observed K/U** (Venus, Earth & Mars), and atmospheric $^{20}Ne/^{22}Ne$, $^{36}Ar/^{38}Ar$ (Venus & Earth) and $^{84}Kr/^{130}Xe$ (Venus)

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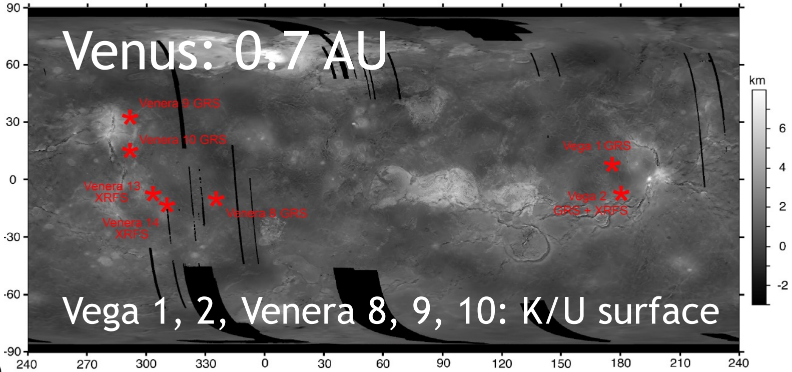
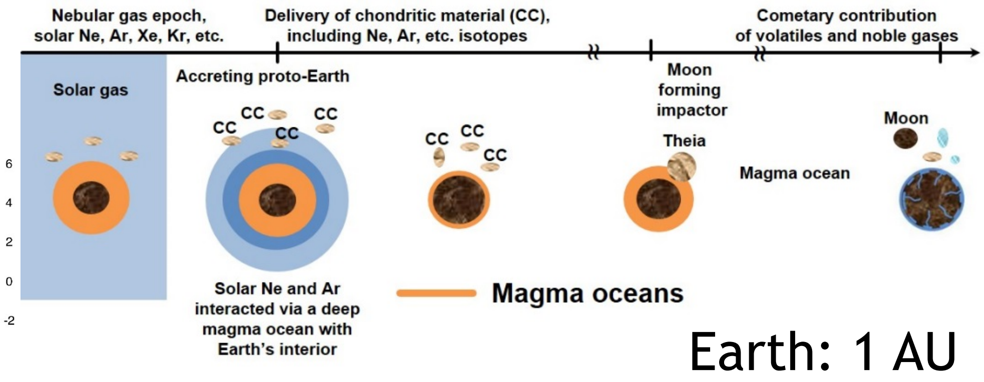
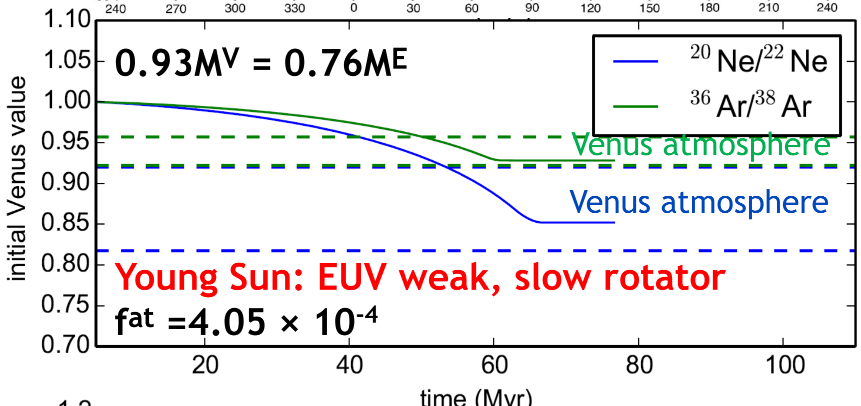
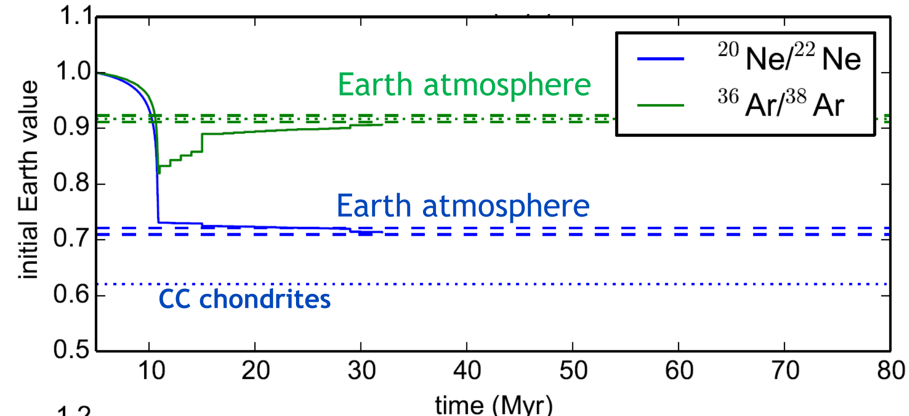
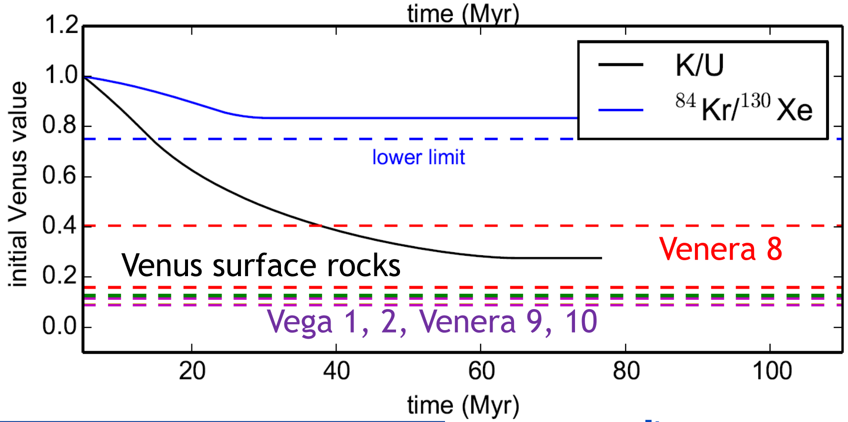
REPRODUCTION OF ^{20}NE/^{22}NE, ^{36}AR/^{38}AR, K/U

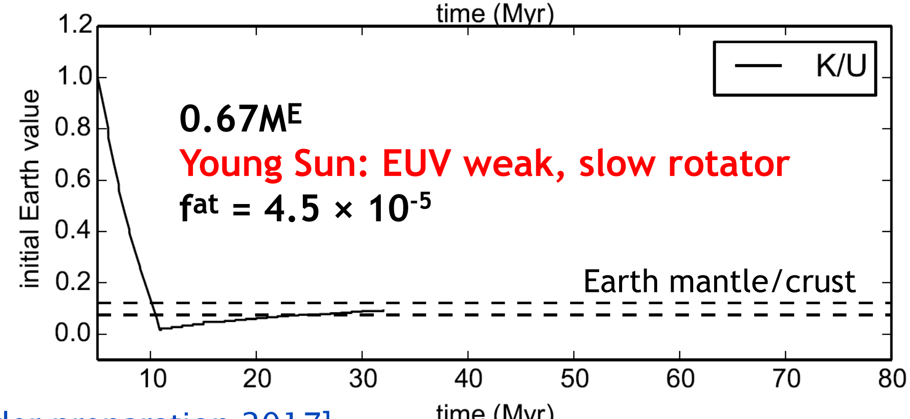












[Lammer et al., under preparation 2017]

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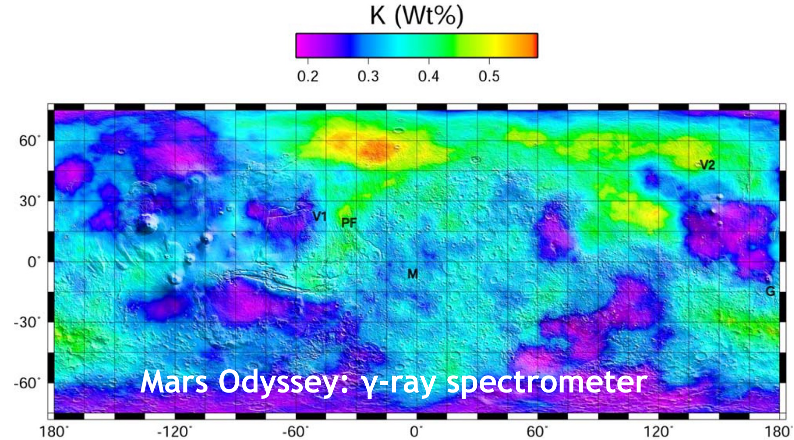
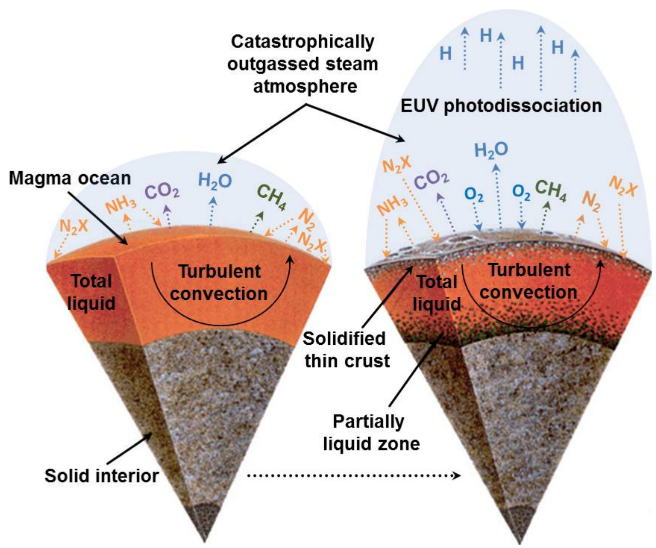
MARS: REPRODUCTION OF K/U RATIO

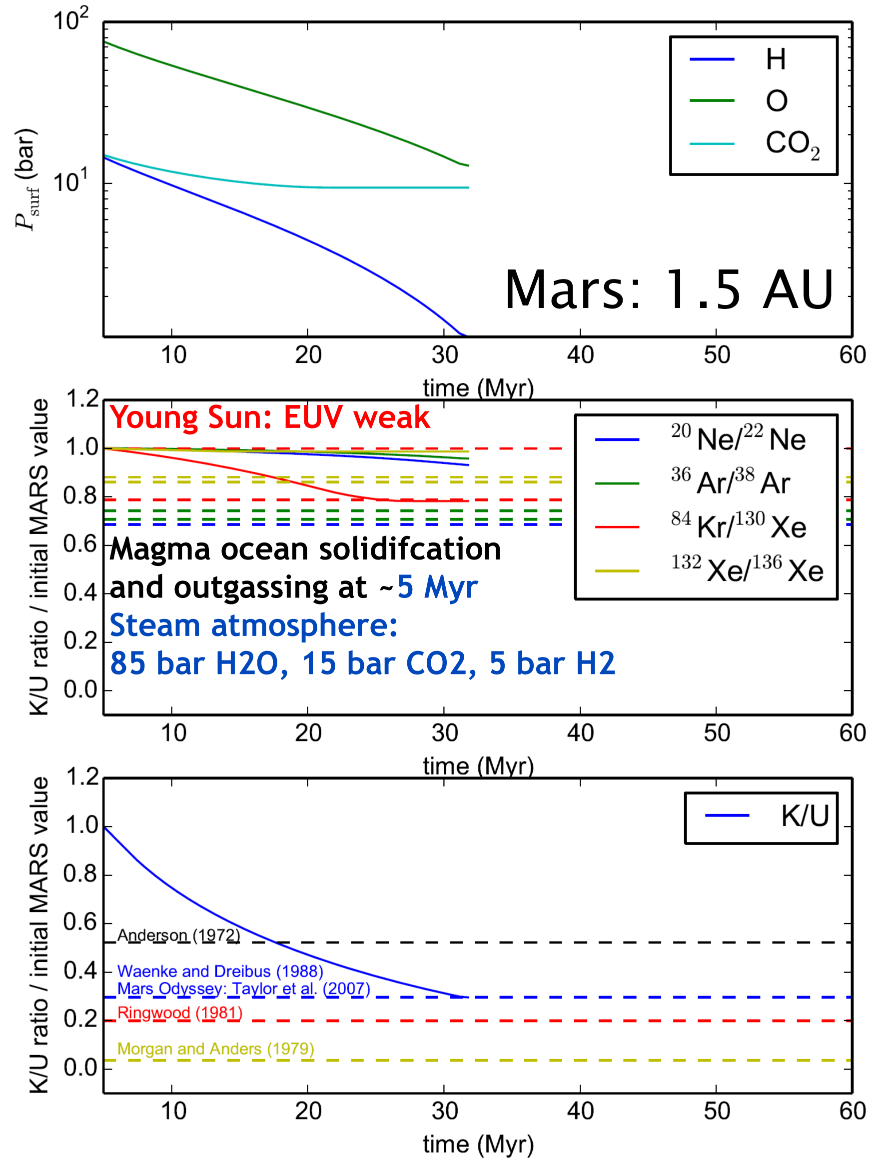


[Taylor et al., 2007]



Coupled ^{142}Nd–^{143}Nd evidence for a protracted magma ocean in Mars

[Debaille et al., 2007]



[Lammer et al., under preparation 2017]

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THE SOLAR SYSTEM

- Initial core masses (~ 5 Myr):
  Venus: ~0.93M_V (~0.76M_E)
  Earth: ~0.67 M_E
- Earth formed within ≤ 30 Myr

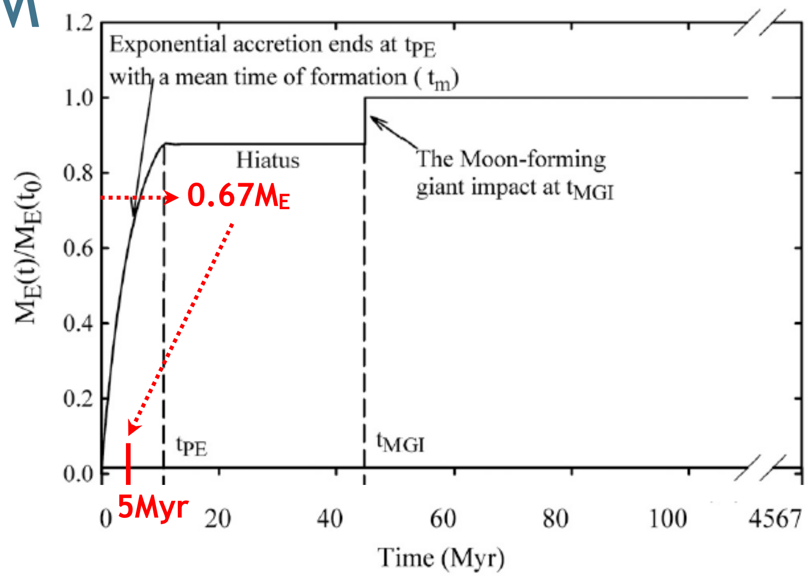
In agreement with:

^{182}Hf - ^{182}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],

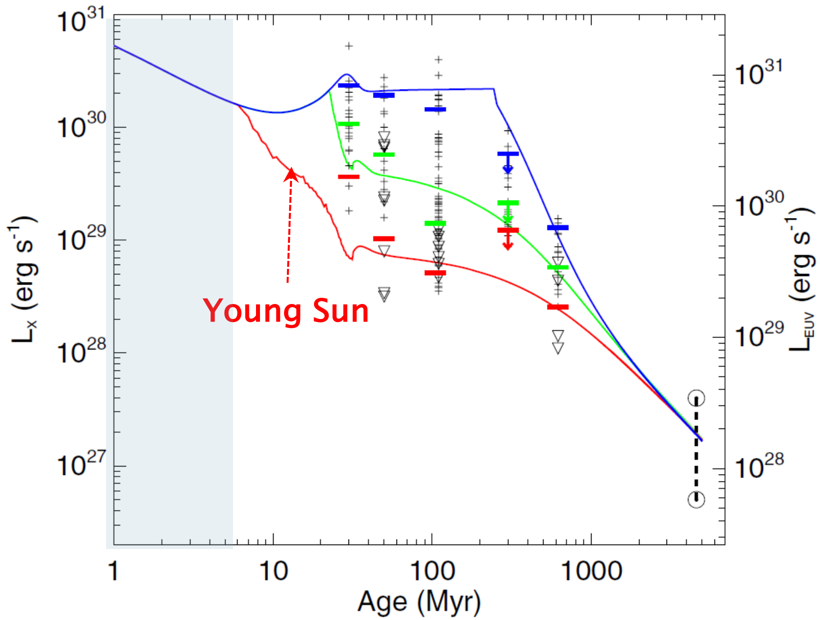
Ar and Ne isotope analysis
[Porcelli et al. 2001; Yokochi and Marty 2004; Marty 2012;],
and the

Grand Tack formation scenario
[e.g., O`Brien et al. 2014]

- Only a slow rotating weakly active young Sun reproduces the observations



[Ju and Jacobsen, 2011]



[Tu et al., 2015]

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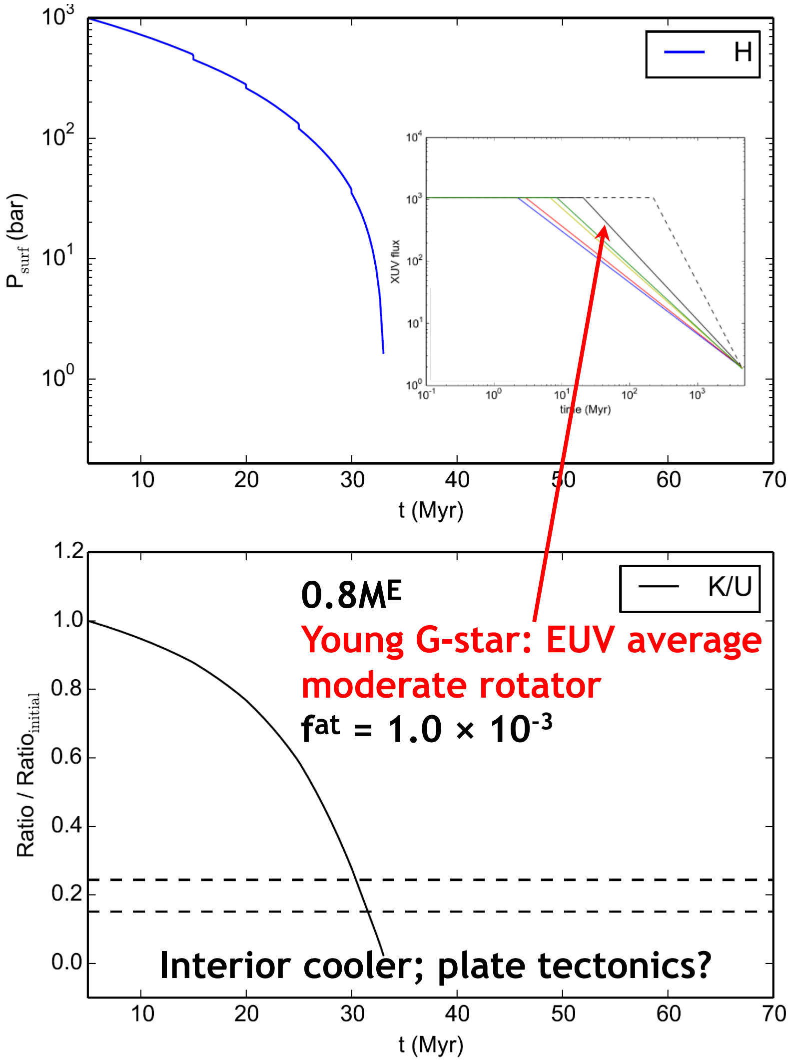
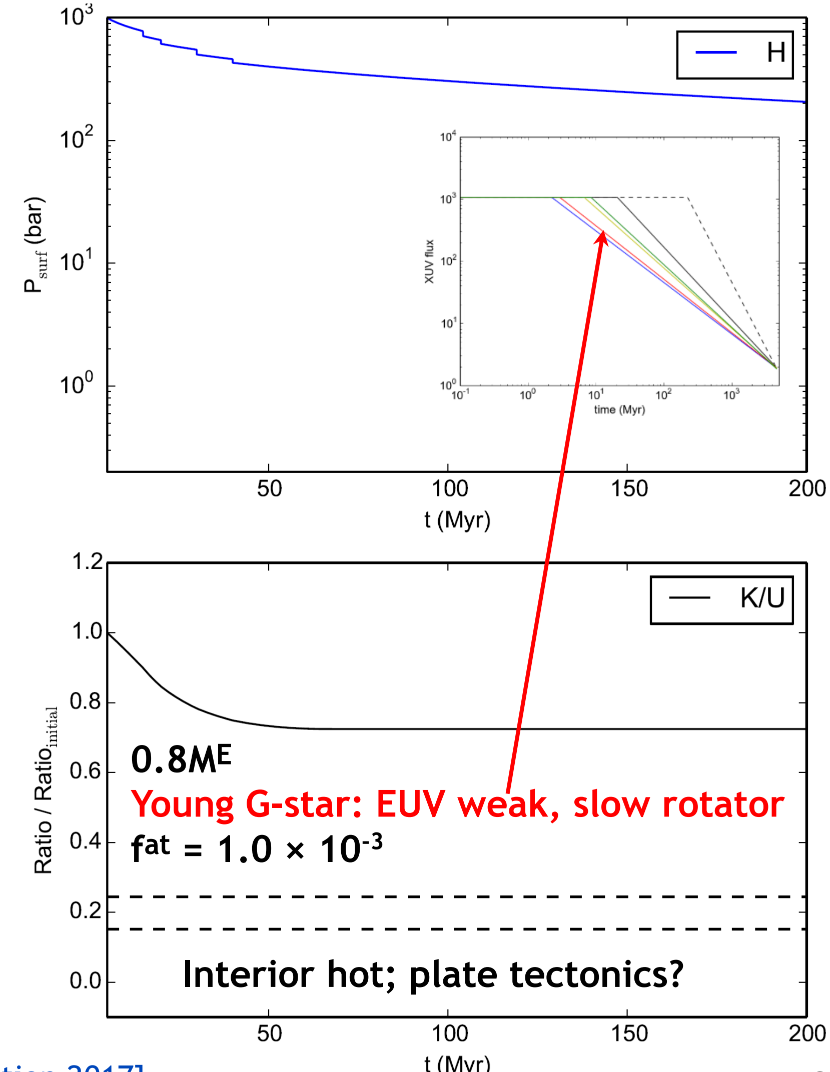
K/U RATIO ON HYPOTHETICAL EXO-EARTH´S INSIDE THE HABITABLE ZONE

- **The temperature profile of the planetary mantles will vary to a great extent**
- **Strong connections: bulk composition, geodynamics and habitability of Earth-like planets**





[under preparation 2017]

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CONCLUSION

- Initial (~5 Myr) core masses: 0.93 M_{Venus} 0.76 M_{Earth} (Venus) and 0.67 M_{Earth} (Earth)
- A weakly active young Sun reproduces the observed isotope (Ne, Ar) and K/U fractionation on Venus & Earth & Mars (K/U)
- A fast formation scenario is favoured and magma ocean related steam atmospheres can not reproduce the K/U and noble gas isotope fractionations on Venus and Earth
- Magma ocean related outgassed steam atmospheres between 80 – 120 bar H_2O, 8 - 15 bar CO_2 and about 5 bar H_2 can reproduce the observed K/U ratio which agrees with the Mars Odyssey data and the Wänke and Dreibus (1988) silicate bulk Mars model
- 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 evolve to

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MULTISPECIES UPPER ATMOSPHERE HYDRODYNAMIC MODELS

Multi-species hydrodynamic code & modified energy-limited formula & hydrodynamic drag

The equations describing the properties of a multi-component gas correspond, in the most simple case, to the 5-moment approximation of the Boltzmann equation. The system of equations in spherical coordinates for species i, including external forces and heating terms, reads

$$\frac{\partial(\rho_i r^2)}{\partial t} + \frac{\partial(\rho_i u_i r^2)}{\partial r} = 0,$$

$$\frac{\partial(\rho_i u_i r^2)}{\partial t} + \frac{\partial[(\rho_i u_i^2 + p_i) r^2]}{\partial r} = f_{\rm ext}\rho_i r^2 + 2p_i r + \sum_j \rho_i r^2 \nu_{ij}(u_j - u_i),$$

$$\frac{\partial(E_i r^2)}{\partial t} + \frac{\partial[(E_i + p_i)u_i r^2 + h_i r^2]}{\partial r} = f_{\rm ext}\rho_i u_i r^2 + q_i r^2 + \sum_j \rho_i u_i r^2 \nu_{ij}(u_j - u_i) + \sum_j \frac{\rho_i r^2 \nu_{ij}}{m_i + m_j}\left[3k(T_j - T_i) + m_j(u_j - u_i)^2\right],$$

$$E = \frac{3}{2}(n_{\rm H} + n_{\rm H^+}) + \frac{5}{2}(n_{\rm H_2} + n_{\rm H_2^+}),\quad U = \frac{GM_{\rm pl}}{R_0}\left(1 - \frac{R_0}{R}\right),$$

$$Q_{\rm EUV} = \eta \sum_i n_i(r) \sum_\lambda \sigma_i(\lambda) \frac{1}{4\pi} \int_0^{\pi/2+\arccos(1/r)} J_0(r,\theta,\lambda) e^{-\sum_i \sigma_i(\lambda)\int_r^\infty n_i(r,\theta)\,dr} 2\pi \sin\theta\, d\theta,$$

H escape

$$F_i = \frac{\beta^2 \eta F_{\rm EUV}}{4\Delta\Phi\,(m_i + m_j f_j x_j + m_k f_k x_k)}$$

Escape of dragged particles

$$F_{j,k} = F_i f_{j,k} x_{j,k}$$

Mixing ratios

$$f_{j,k} = N_{j,k}/N_i$$

Fractionation factors

$$x_j = 1 - \frac{g\,(m_j - m_i)\, b_{i,j}}{F_i k_{\rm B} T\,(1 + f_j)}$$

$$x_k = \frac{1 - \frac{g(m_k - m_i) b_{i,k}}{F_i k_{\rm B} T} + \frac{b_{i,k}}{b_{i,j}} f_j\,(1 - x_j) + \frac{b_{i,k}}{b_{j,k}} f_j x_j}{1 + \frac{b_{i,k}}{b_{j,k}} f_j}$$

[in test phase at the IWF/ÖAW]

[e.g., Hunten, JAS 1973; Icarus 1987; Zahnle et al., Icarus 1990; Odert et al., Icarus 2017]