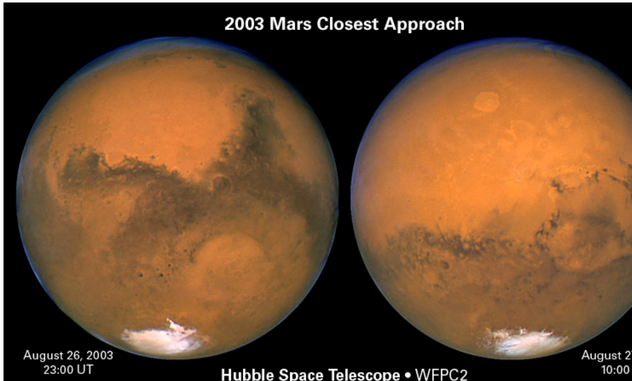
Martian evolution based on noble gas and other trace elements

Sho Sasaki

(University of Tokyo)



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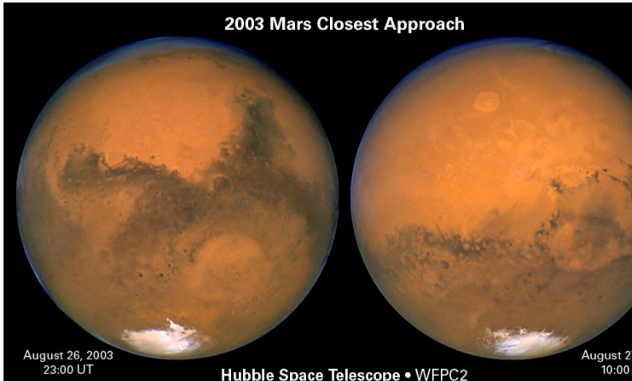
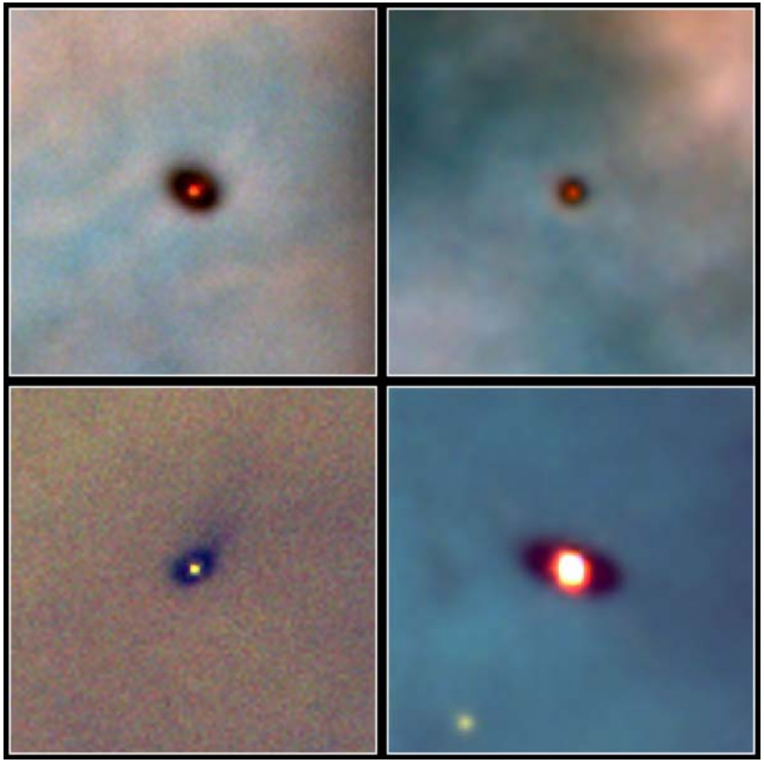


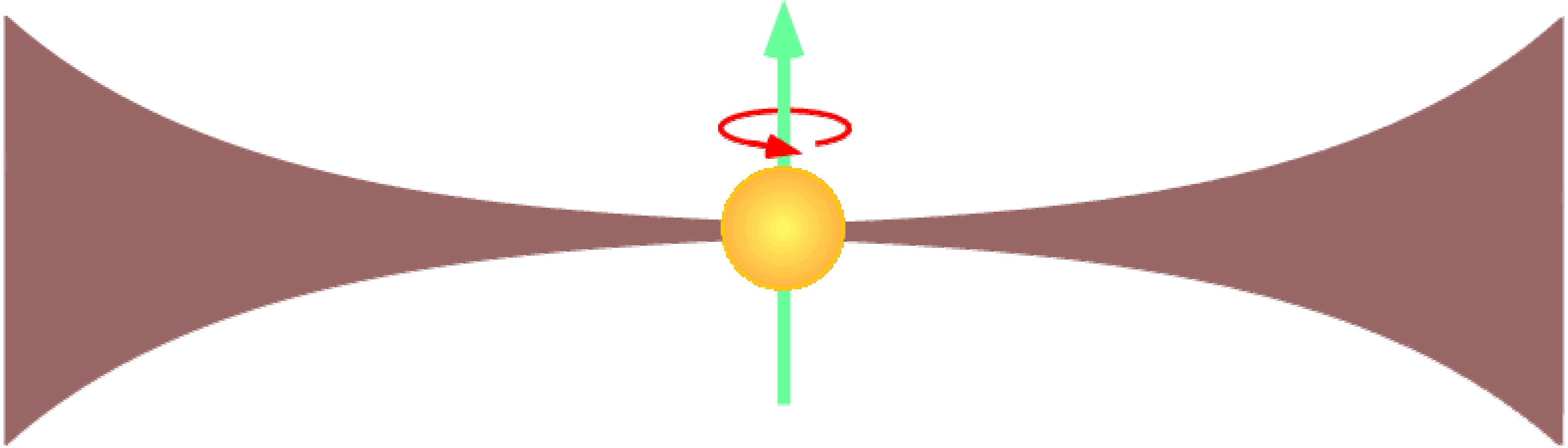
4500000000 yr

Events on the Early Mars

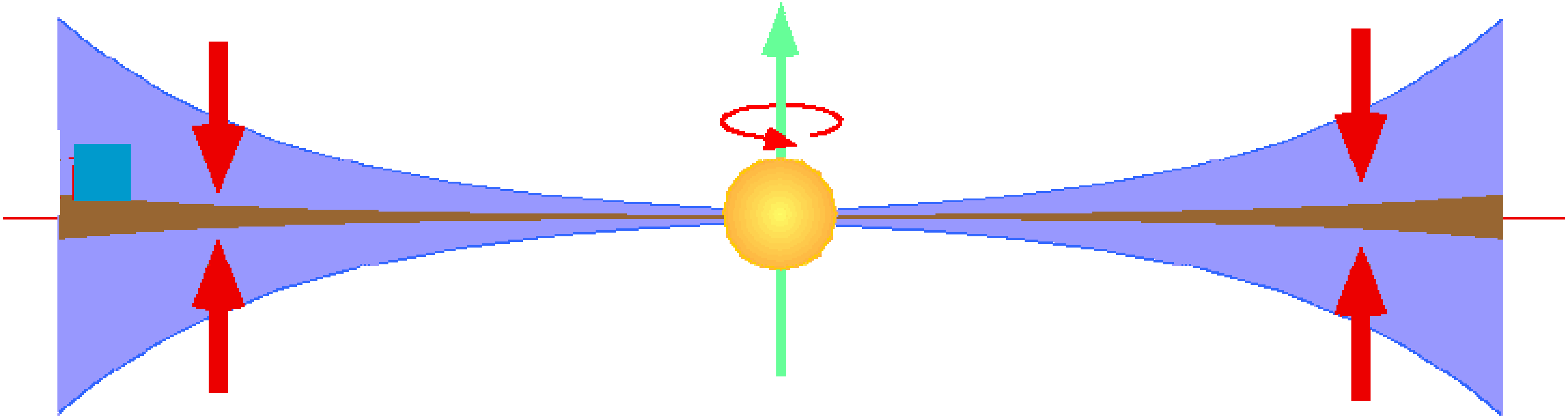
- Formation by successive accretion of planetesimals
- Heating by the blanketing effect of the atmosphere
- Formation of “magma ocean”
- Metal-silicate segregation and formation of metallic core
- Giant impact(s) ?
- Cooling of magma ocean

A central star
and
a surrounding
gas-dust disk



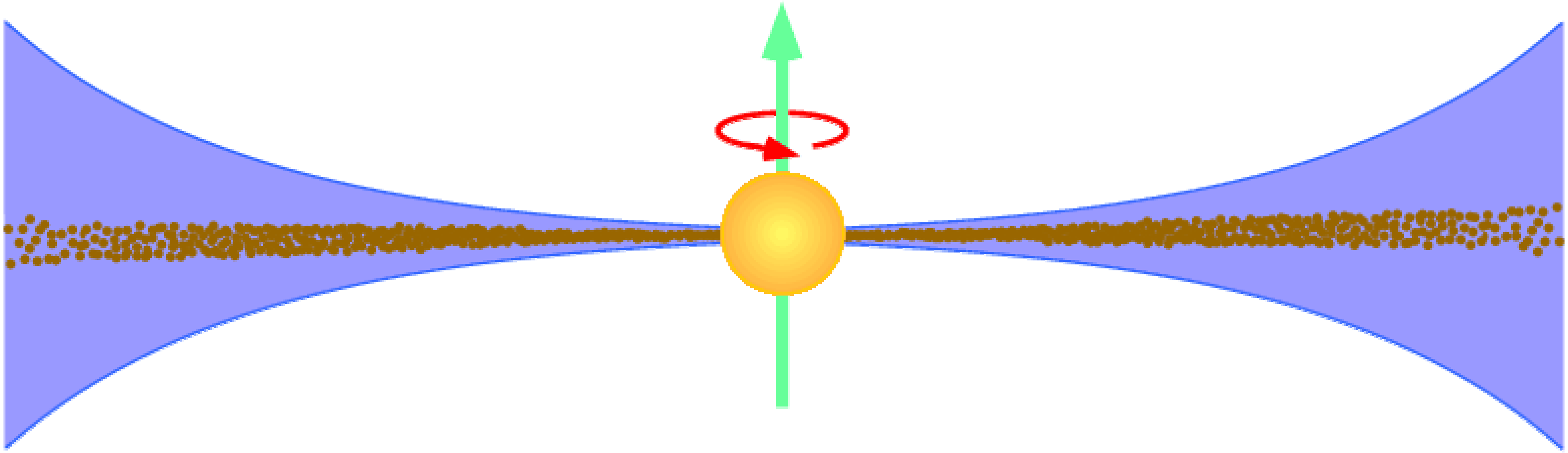


Dust formation and sedimentation



Formation of planetesimals

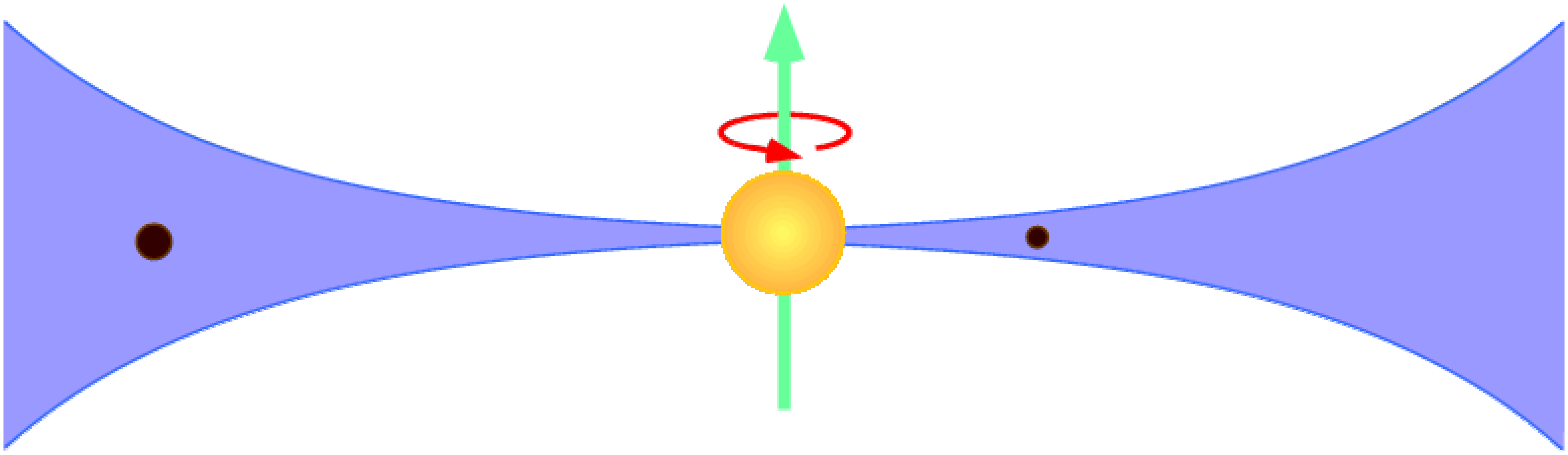
Gravitational instability of the dust-rich layer



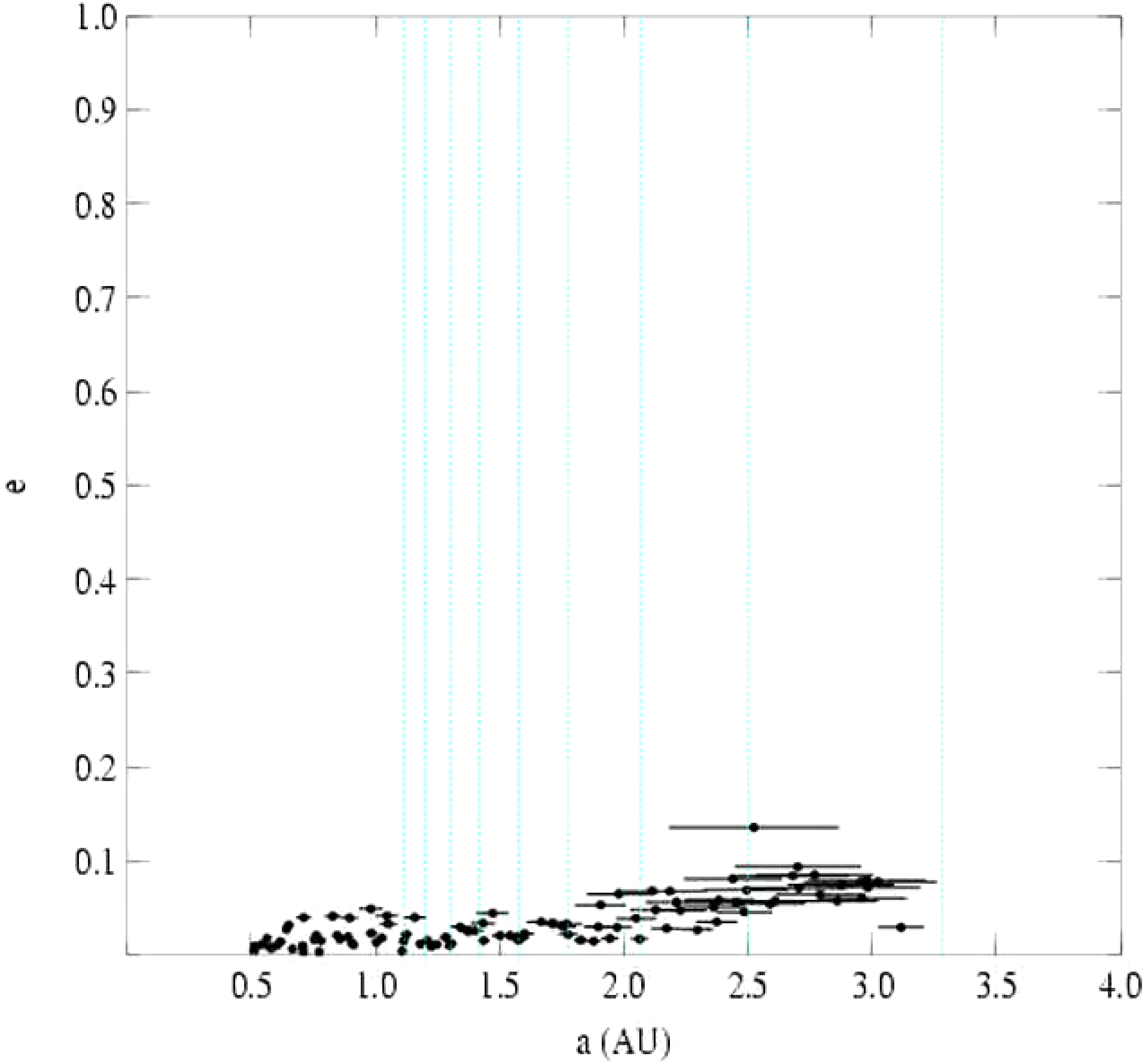
10-100km in size

10^{10-11}

Collisions of planetesimals => protoplanets => planets



Dissipation of the gas disk

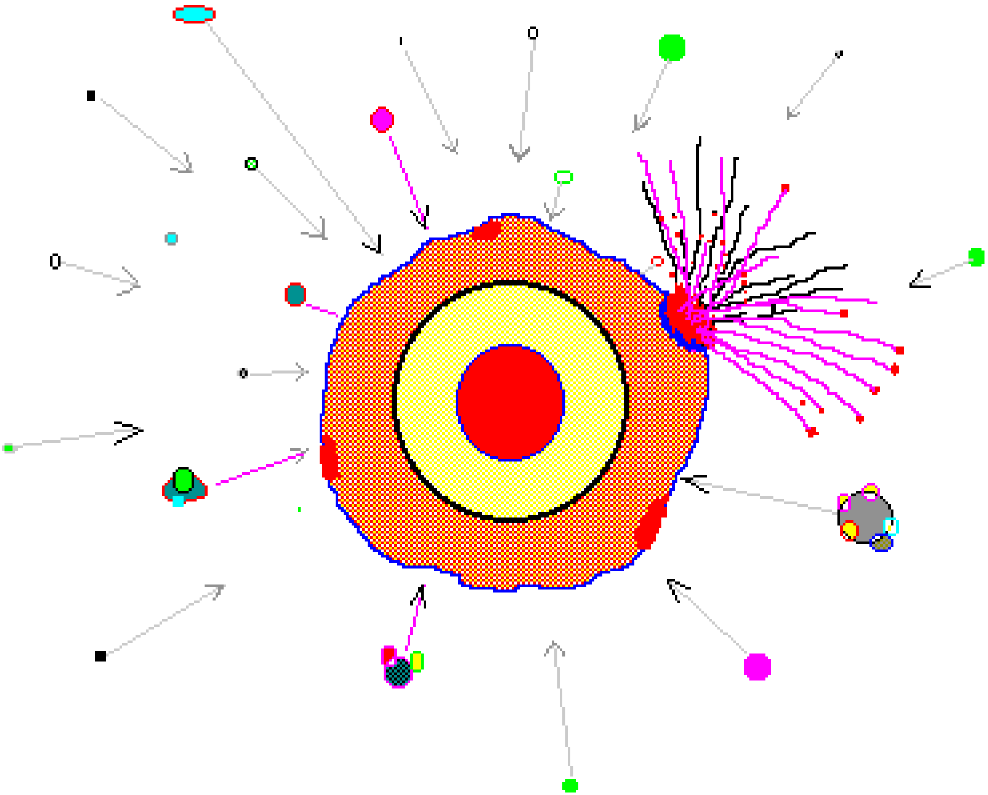


SS t=0

Planetesimal accretion

A Growing Planet

Accretion



Actual collision frequency -- 1 in 10000 yr for 500km bodies

1 in 100yr for 100km bodies

Impact degassing => atmosphere

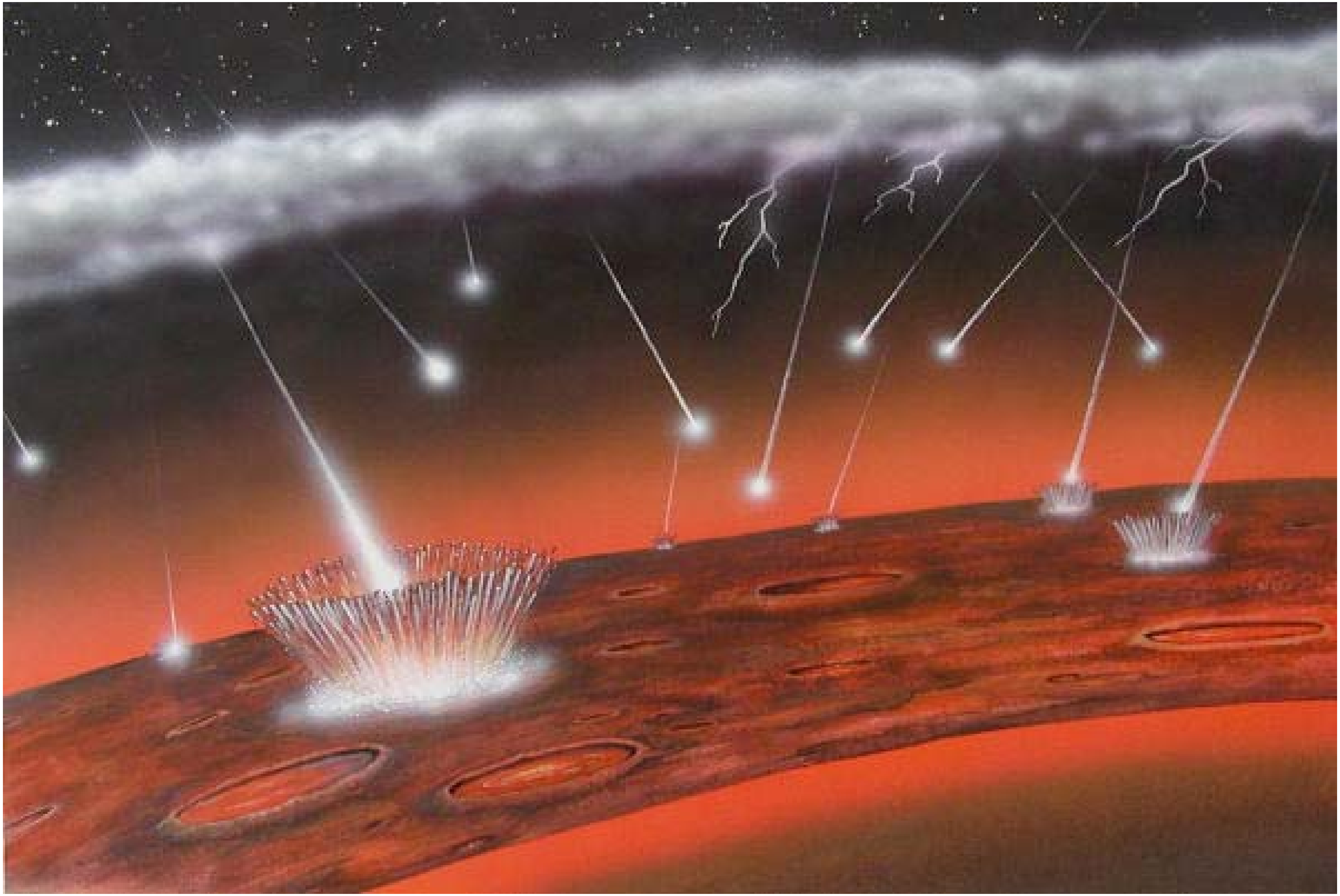
Trap of accretional energy

- $\Sigma\, 1/2\, mv^2 \sim 3/5\, GM^2/R$

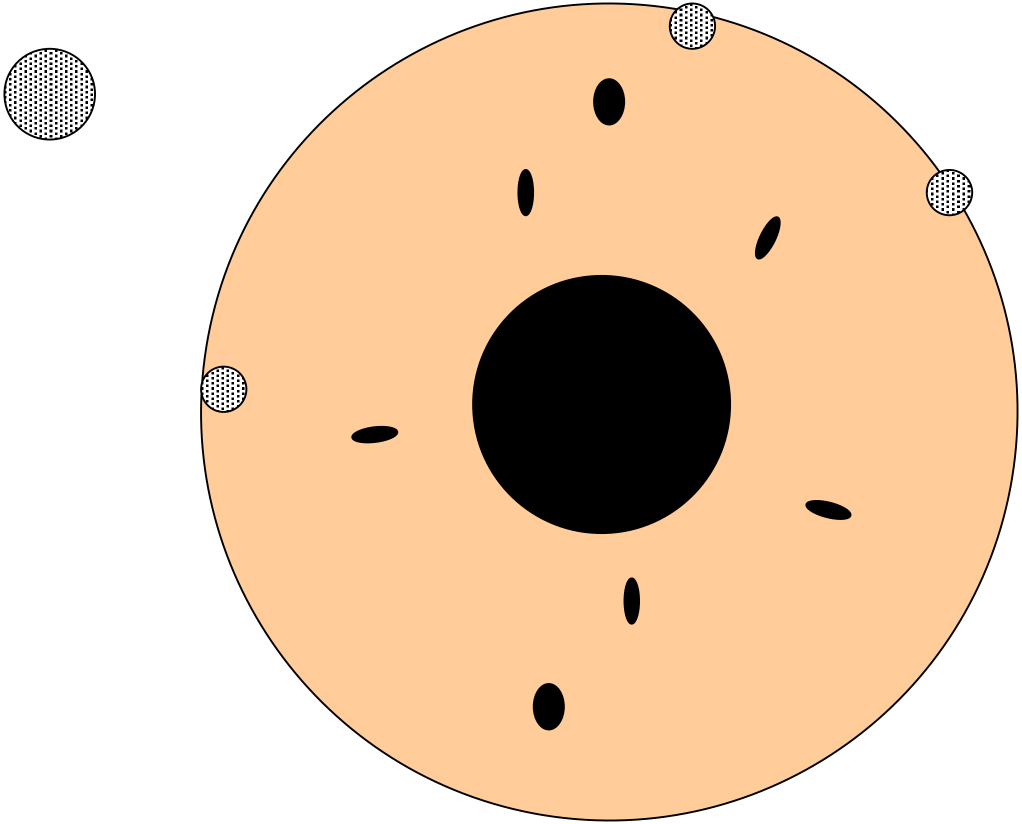
- If the gravitational energy is captured completely, Mars mean $T \sim 25000$K.
- But heat is easily lost by radiation.
- Blanketing effect of atmosphere should suppress heat escape.

  => Enhance surface T
- $T > T_m$ around $M \sim M_{Mars}$

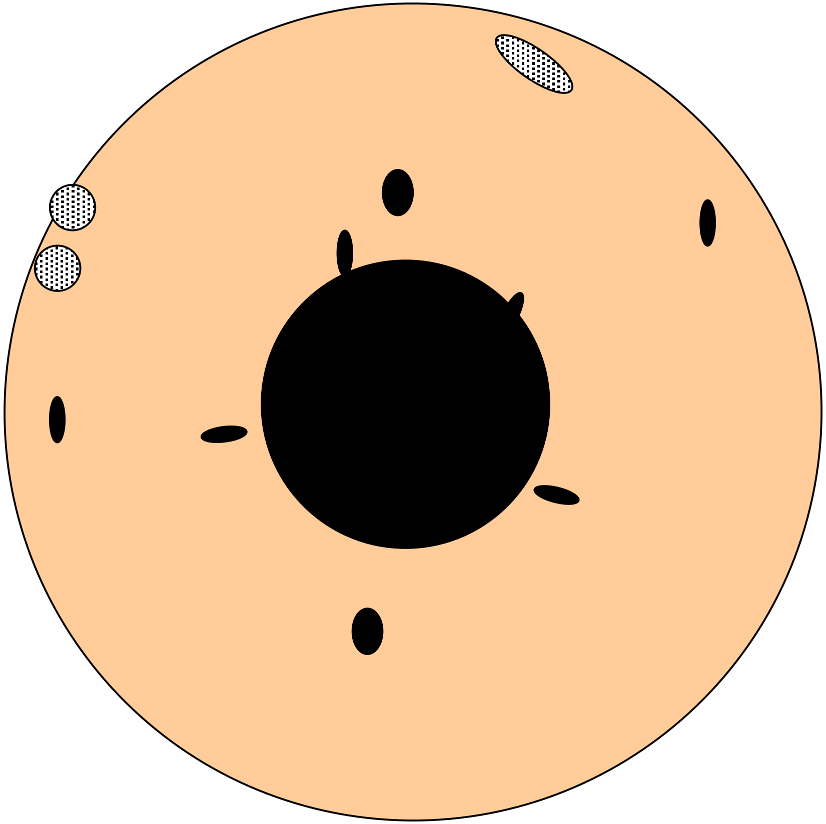
Blanketing effect of the atmosphere
Formation of “magma ocean”



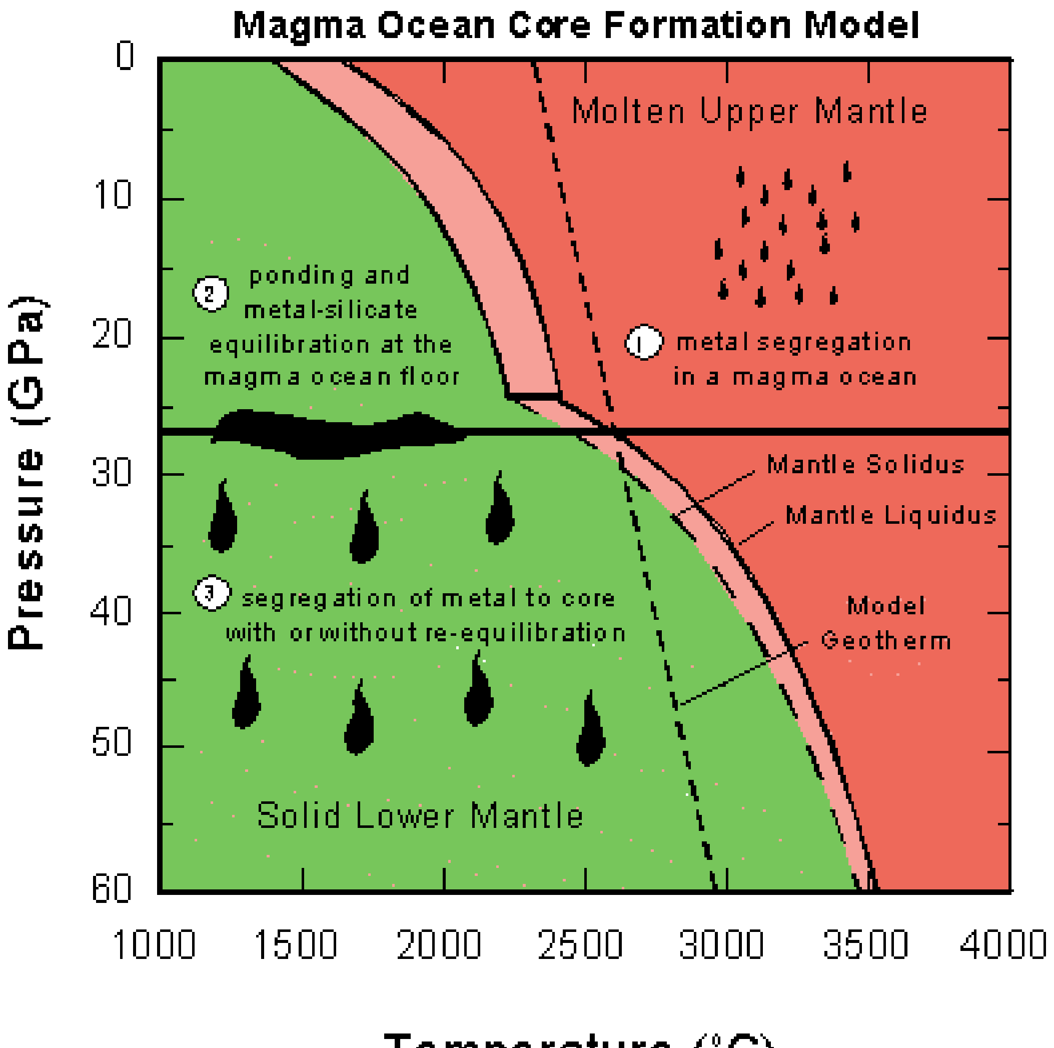
Metal-silicate differentiation in the magma ocean => core formation



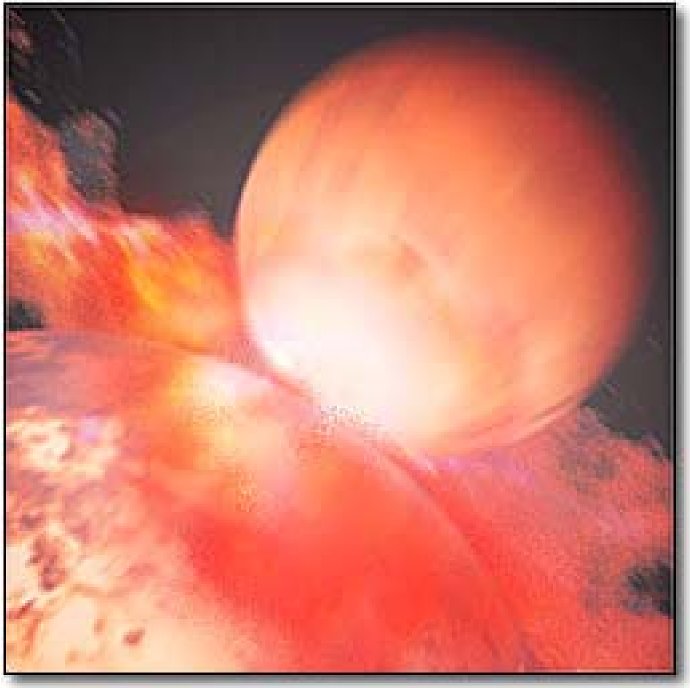
Metal-silicate differentiation in the magma ocean => core formation



Metal-silicate differentiation in the magma ocean => core formation



Giant Impacts?



Re-melting, mixing, degassing, etc….

Origin and evolution of the Martian atmosphere

Primary atmosphere from the protoplanetary gas disk?

Degassed atmosphere from impacts

Impact erosion of the atmosphere

Degassing through solidification of magma ocean

Thick atmosphere of CO_2 (a few bar)

Later evolution of the atmosphere:

- Volcanic supply / cometary supply
- trapped into the interior / escape to the space

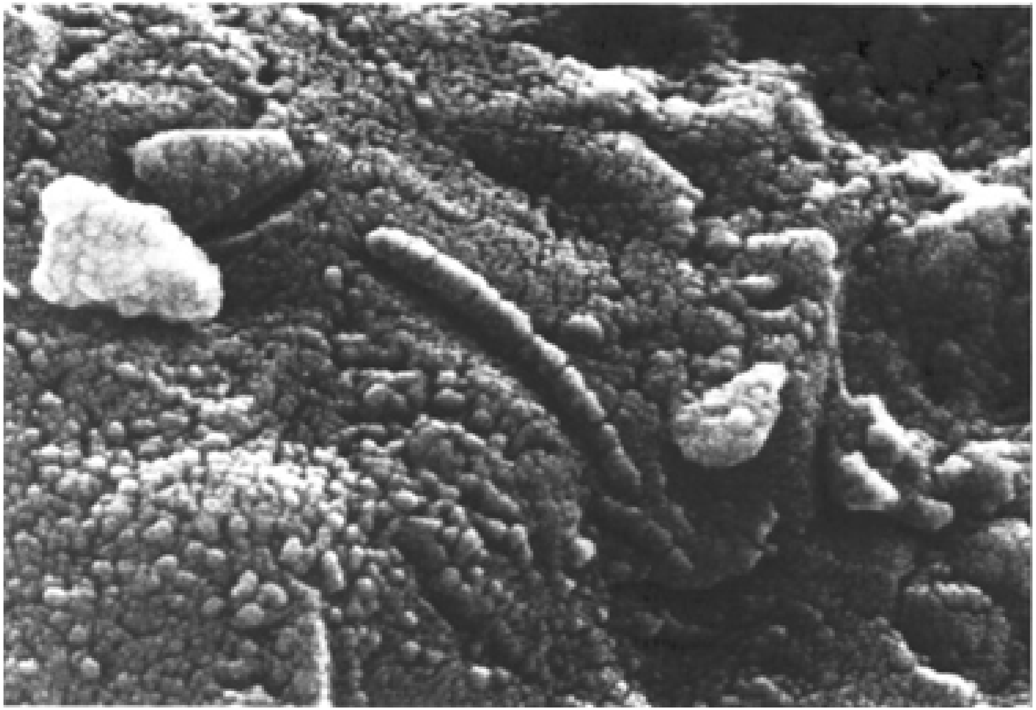
Key compositional data

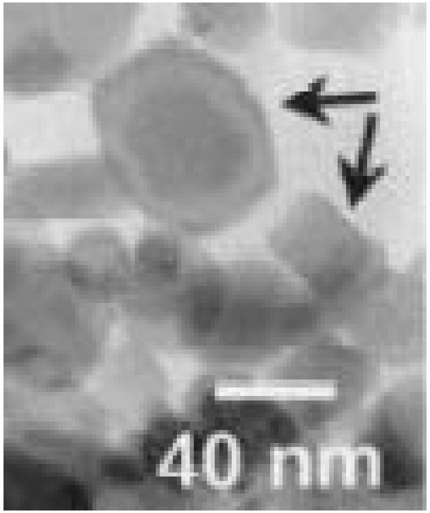
- Martian atmosphere data by Viking landers (1976)
- Meteorites from Mars

Meteorites from Mars

- Young age mostly $< 1.3 \times 10^9$ yr
- Close to terrestrial basalts and volcanic rock
  - Volcanisms of a large body?
- Different isotopic compositions from terrestrial rocks and other meteorites
  - e.g. Oxygen isotopes
- Composition of trapped gas – similar to atmospheric composition taken by Viking lander

ALH84001 Life?



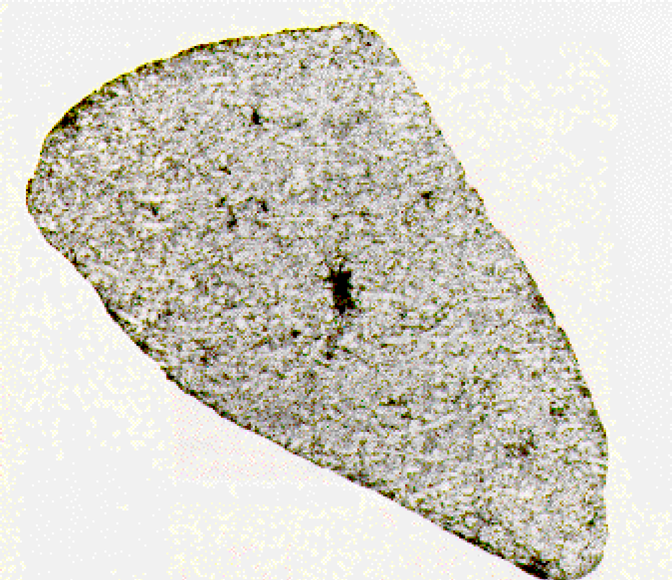

40 nm

SNC meteorites

Nakhla

Chassigny

Shergotty

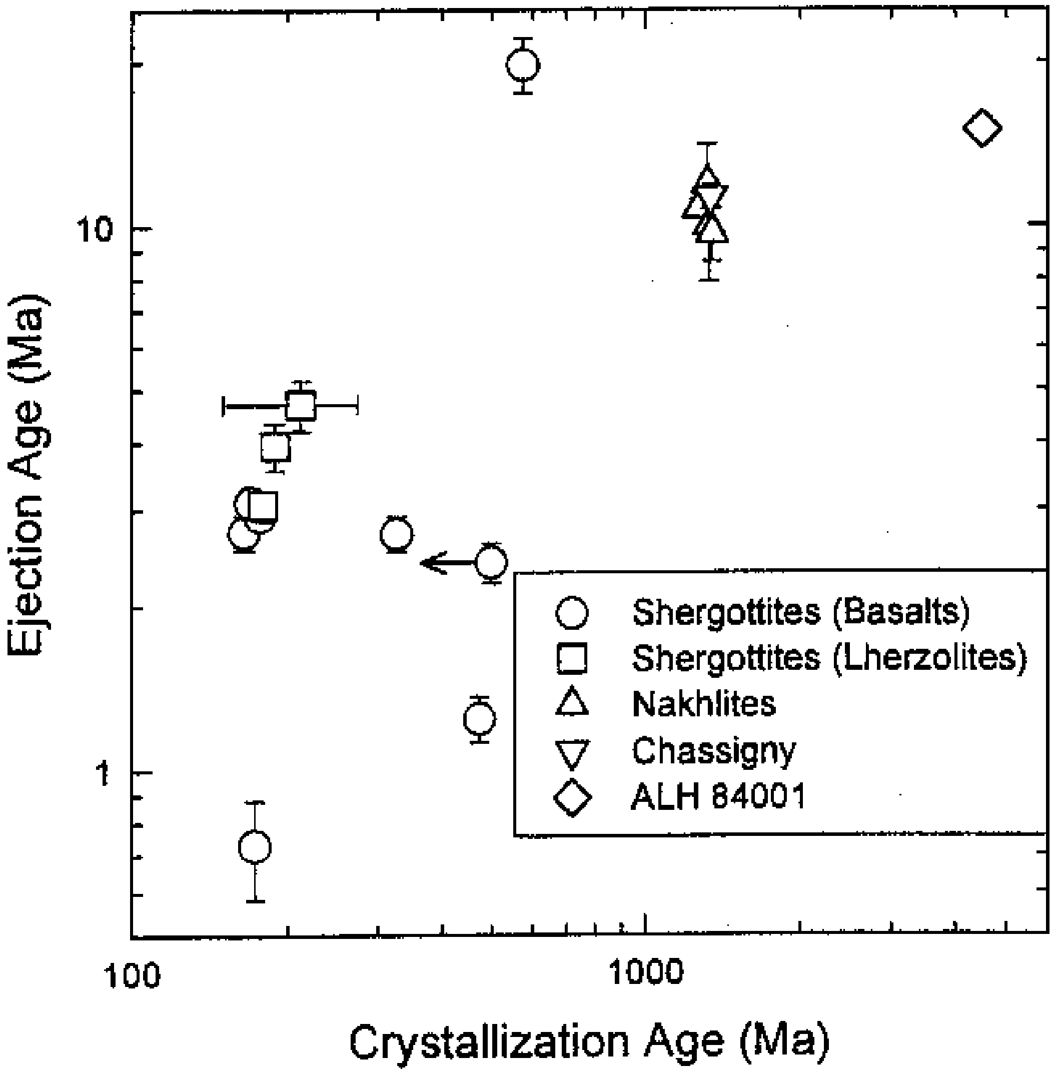


Zagami

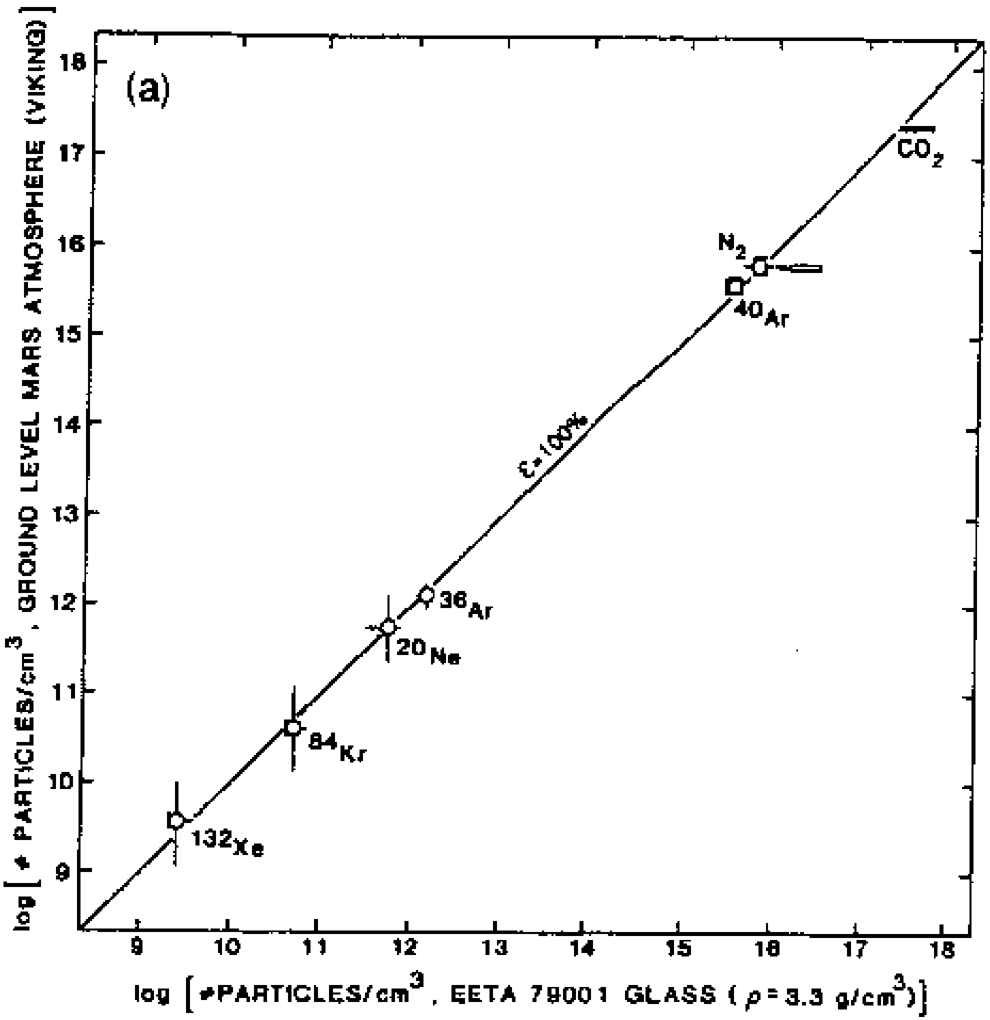
Table 1. Martian meteorites.

Name (associated meteorites)	*Year found*	*Crystallization age (Ma)*	*Ejection age (Ma)*
Shergottites (basalts)			
Dar al Gani 476 (489, 670, 735, 876)	2000	474(11)	1.24(12)
Dhofar 019	2000	575(5)	19.8(2.3)
Elephant Moraine 79001	1979	173(3)	0.73(15)
Los Angeles	1999	170(8)	3.10(20)
Northwest Africa 480	2000	<500	2.4(2)
Queen Alexandra Range 94201	1994	327(10)	2.71(20)
Sayh al Uhaymir 008 (008, 051, 094)	1999		1.5(3)
Shergotty	1865*	165(4)	2.73(20)
Zagami	1962*	177(3)	2.92(15)
Shergottites (lherzolites)			
Allan Hills 77005	1977	179(5)	3.06(20)
Lewis Cliffs 88516	1988	178(8)	3.94(40)
Yamato 793605	1979	212(62)	4.70(50)
Nakhlites (clinopyroxenites)			
Governador Valadares	1958	1330(10)	10.0(2.1)
Lafayette	1931	1320(20)	11.9(2.2)
Nakhla	1911*	1270(10)	10.75(40)
Northwest Africa 817	2000	1350(?)	9.7(1.1)
Other			
Chassigny *(dunite)*	1815*	1340(50)	11.3(6)
Allan Hills 84001 *(orthopyroxenite)*	1984	4510(110)	15.0(8)

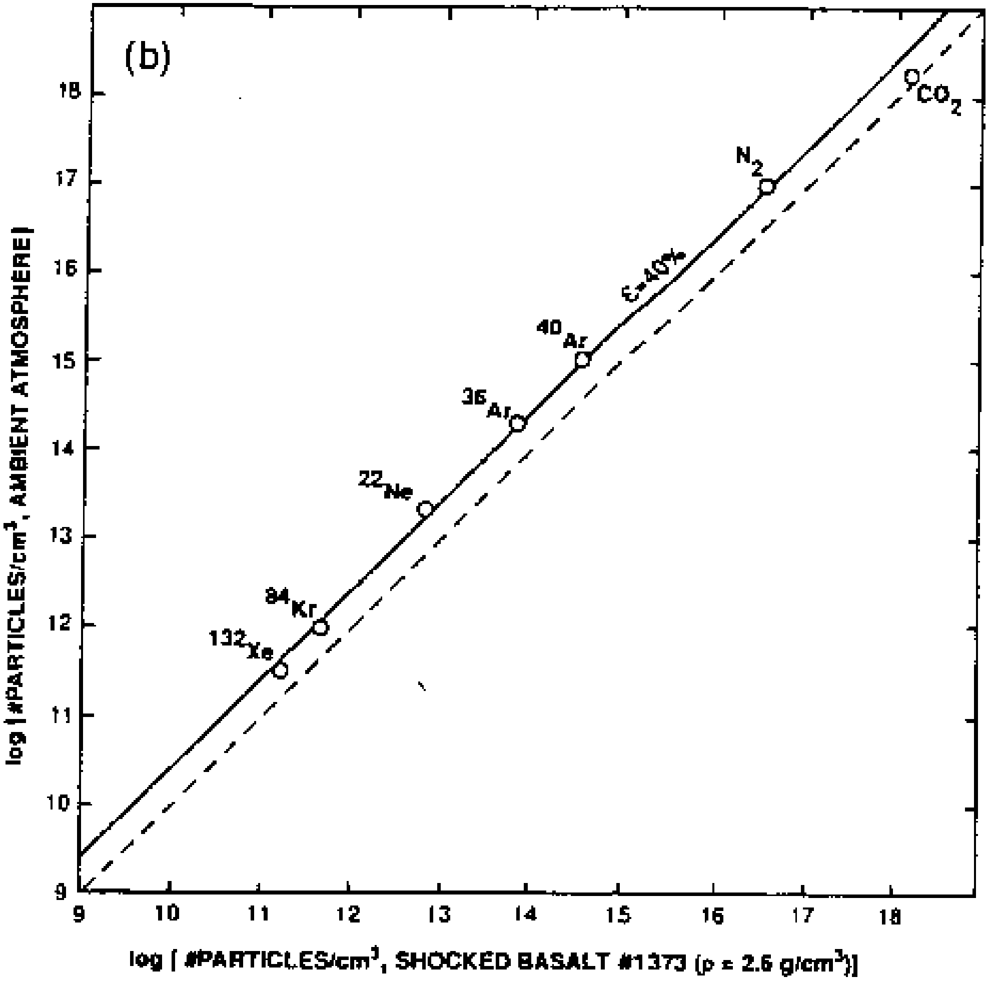
Martian meteorite age

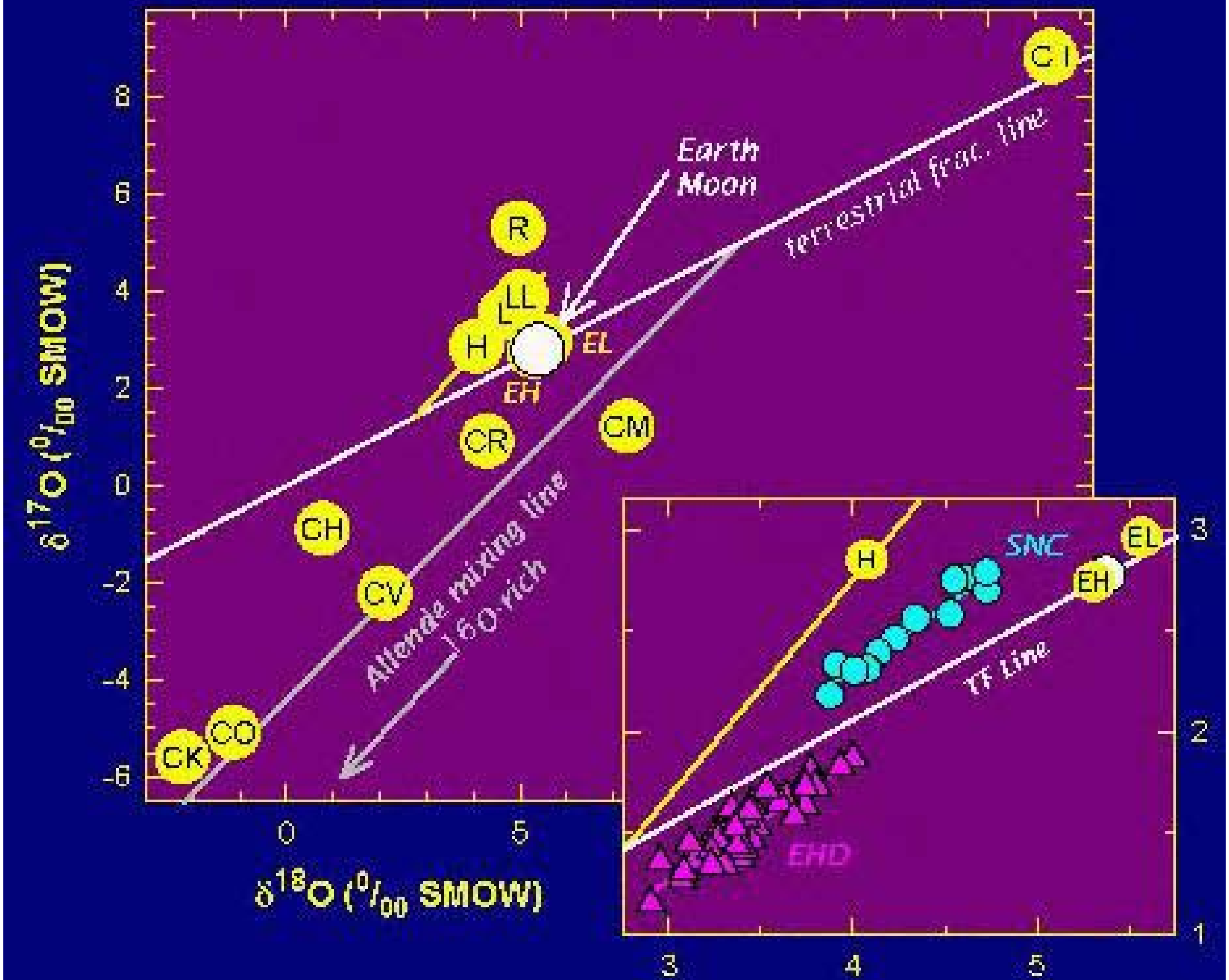


Meteorite gas vs Viking atmosphere measurements



Gas in shocked basalt vs atmosphere



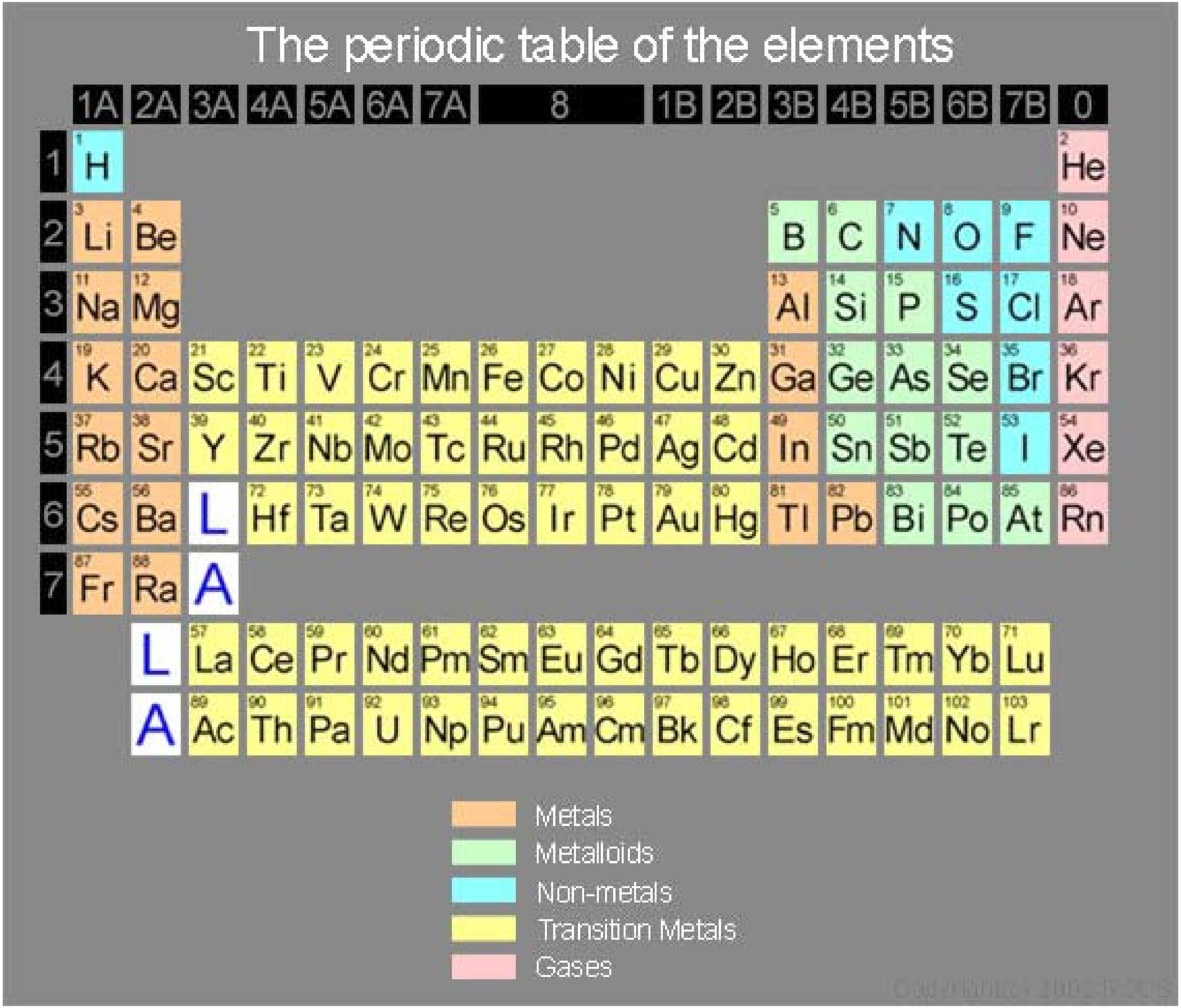


meteorite oxygen isotope systematics

Noble gas: He, Ne, Ar, Kr, Xe and their isotopes

- Evidence of physical / chemical processes - dissolution, partition, and degassing
- Rich in the solar gas but trapped amounts in solids are small
- Radiogenic noble gas isotopes and chronology
- Martian noble gas data: Viking measurements and Martian meteorites

Periodic table

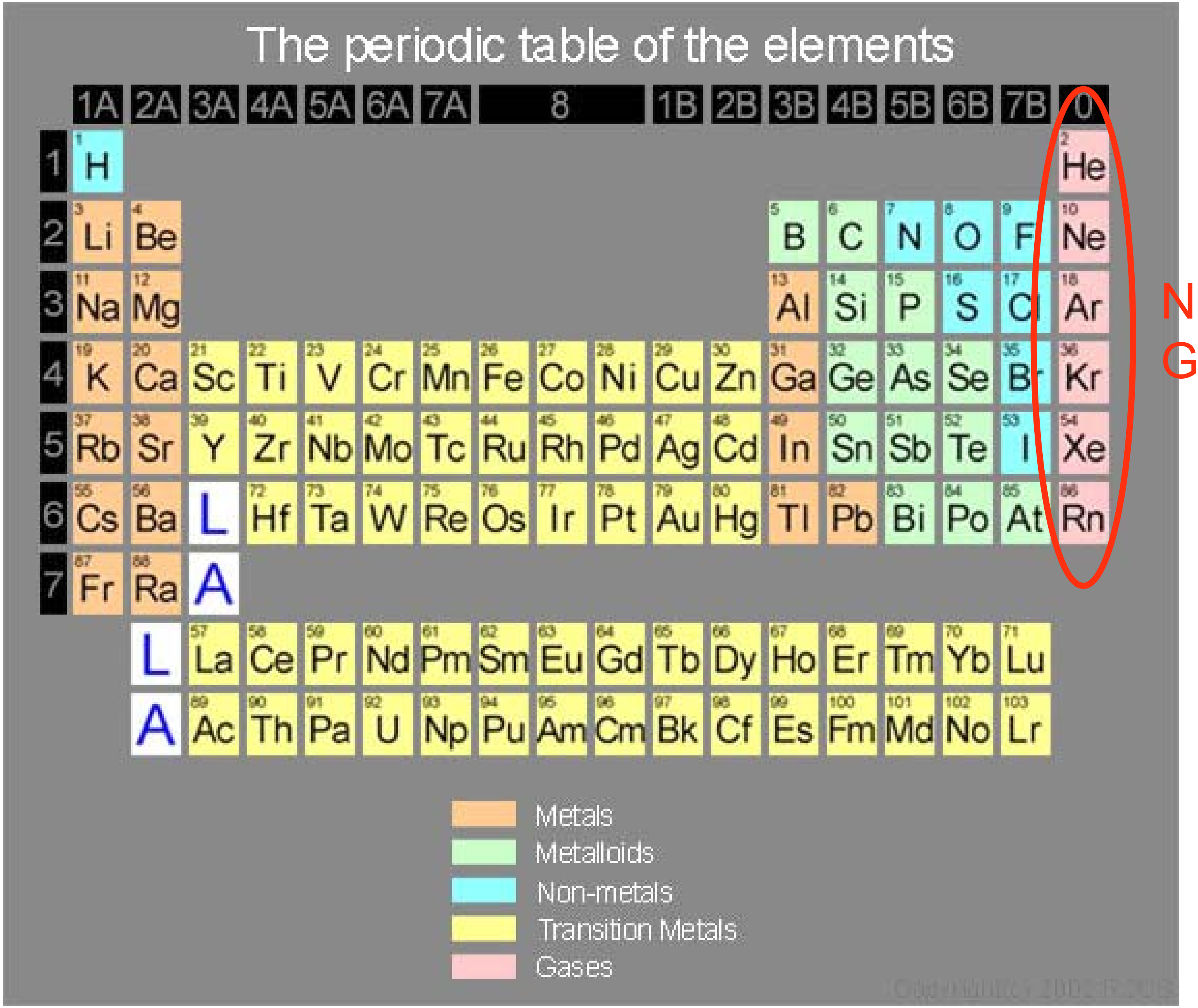


The periodic table of the elements

	1A	2A	3A	4A	5A	6A	7A	8			1B	2B	3B	4B	5B	6B	7B	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	L	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	A															
		L	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		A	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

🟧 Metals
🟩 Metalloids
🟦 Non-metals
🟨 Transition Metals
🟥 Gases

Periodic table



The periodic table of the elements

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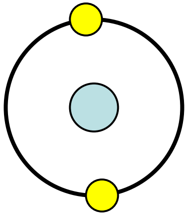
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	L	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	A															
		L	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		A	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

🟧 Metals
🟩 Metalloids
🟦 Non-metals
🟨 Transition Metals
🟥 Gases

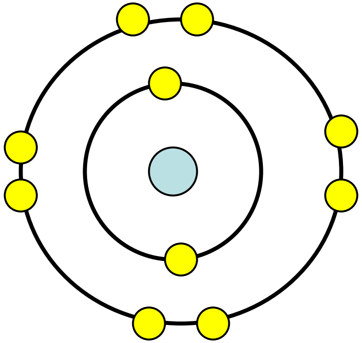
Noble Gas

Noble gas atomic structures

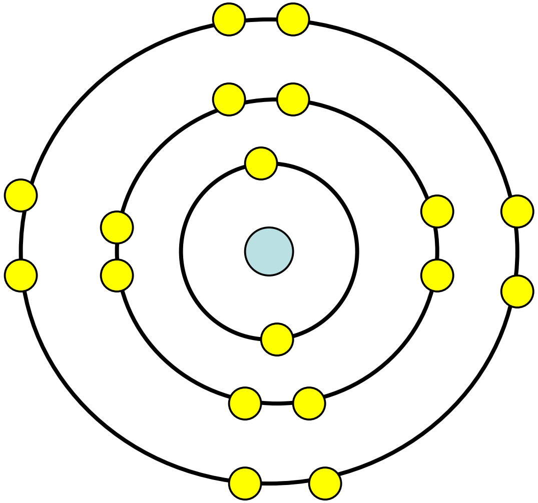
He



Ne



Ar



Mass spectrometer

Noble gas stable isotopes

Species	Mass number of isotopes
• He	3, 4
• Ne	20, 21, 22
• Ar	36, 38, 40
• Kr	80, 82, 83, 84, 86
• Xe	124, 126, 128, 129, 130, 131, 132, 134, 136
• Rn	All are unstable

Noble gas

- No chemical reaction
- Changed mostly by physical processes
- Especially isotopic ratios are changed by radiogenic processes or by physical processes such as mass fractionation.
- Favor in melt and gas phases

➔ Degassing ➔ atmosphere (➔ escape)

Noble gas in the atmosphere

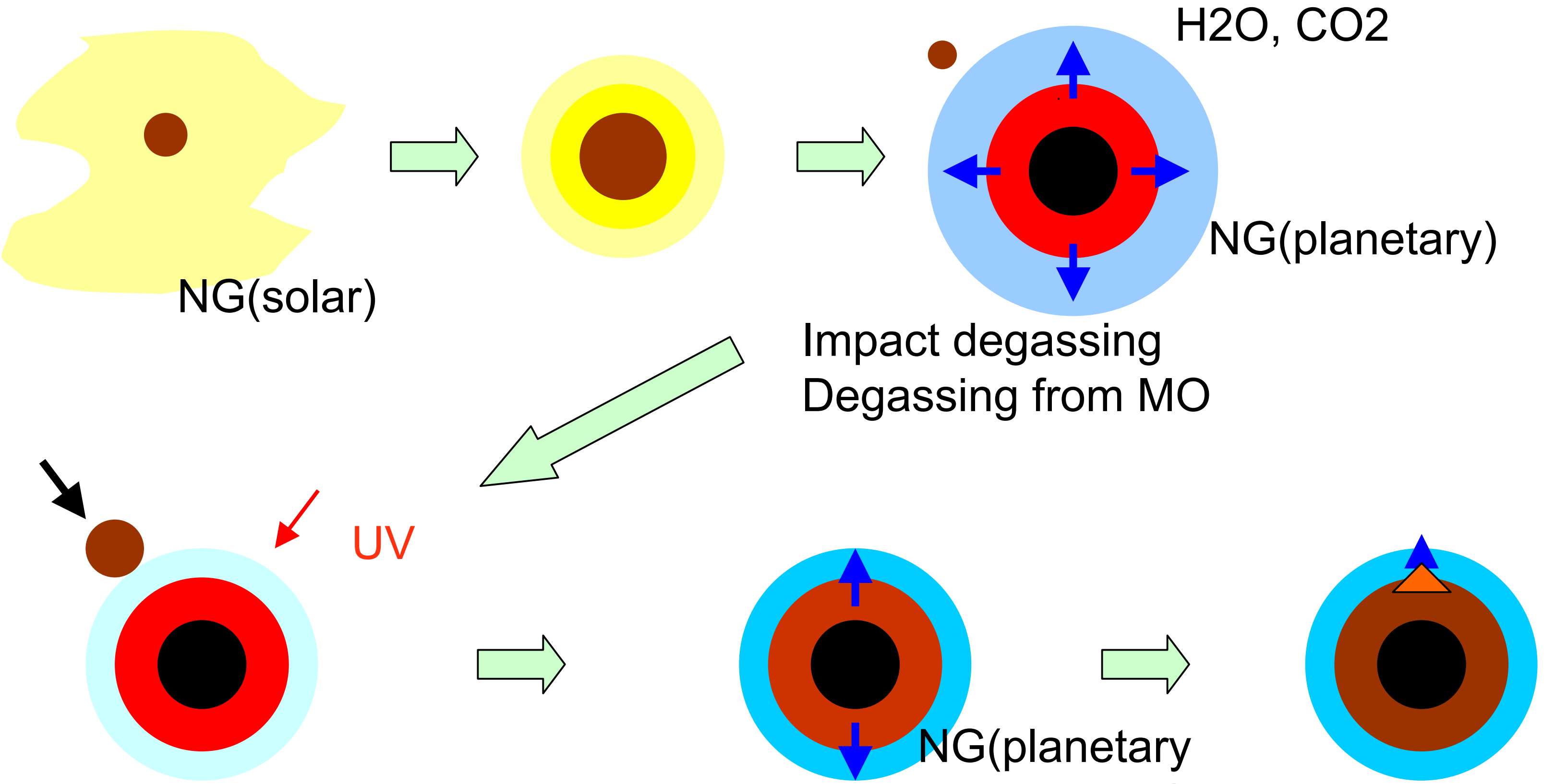
- No chemical reaction with the surface
- Little adsorption onto the surface

- NG in the atmosphere

= Remnant of early atmosphere
+ Accumulated degassed component
(- escaped component)

- NG ➔ story of atmosphere evolution

Noble gas in the course of a model of the atmosphere evolution



NG(solar)

H2O, CO2

NG(planetary)

Impact degassing
Degassing from MO

UV

NG(planetary
+ radiogenic)

Loss of atmosphere by
large impacts and
hydrodynamic escape

Degassing
through the
cooling of MO

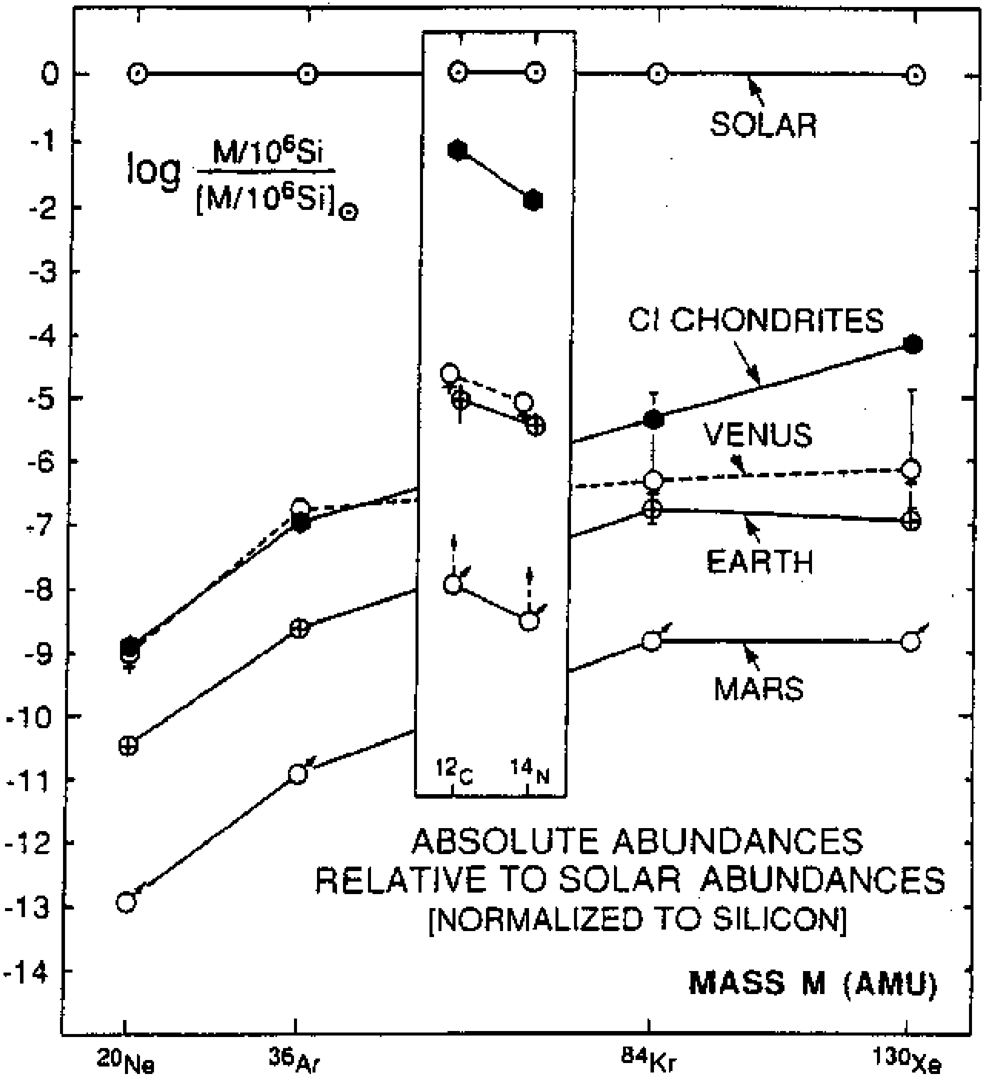
Volcanic degassing

Noble gas

- Significant fractionation from the gas in the protoplanetary gas disk (which was enriched in noble gas species).
- Solar elemental composition

- ➔ Planetary elemental composition
- Venus >> Earth >> Mars

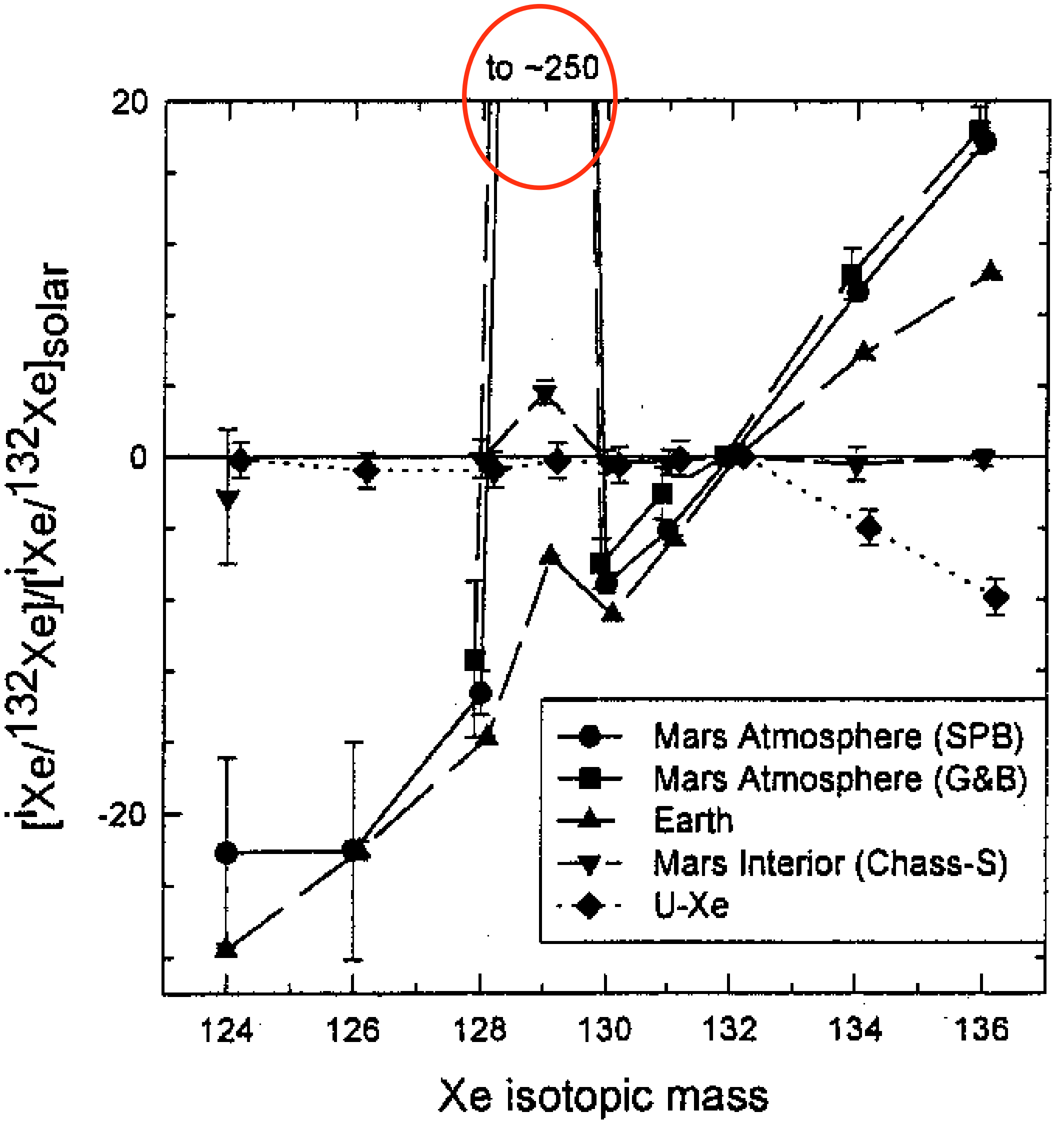
Noble gas abundance



“Planetary” noble gas

- Trapped from the nebular gas
  - Elemental fractionated pattern ≠ solar
  - Q phase in meteorites
- Difference among Mars, Earth, Venus?
  - Earth and Mars
  - Difference of atmospheric loss during / just after accretion
  - Venus: primary atmosphere of nebular gas?

Xe isotopic pattern



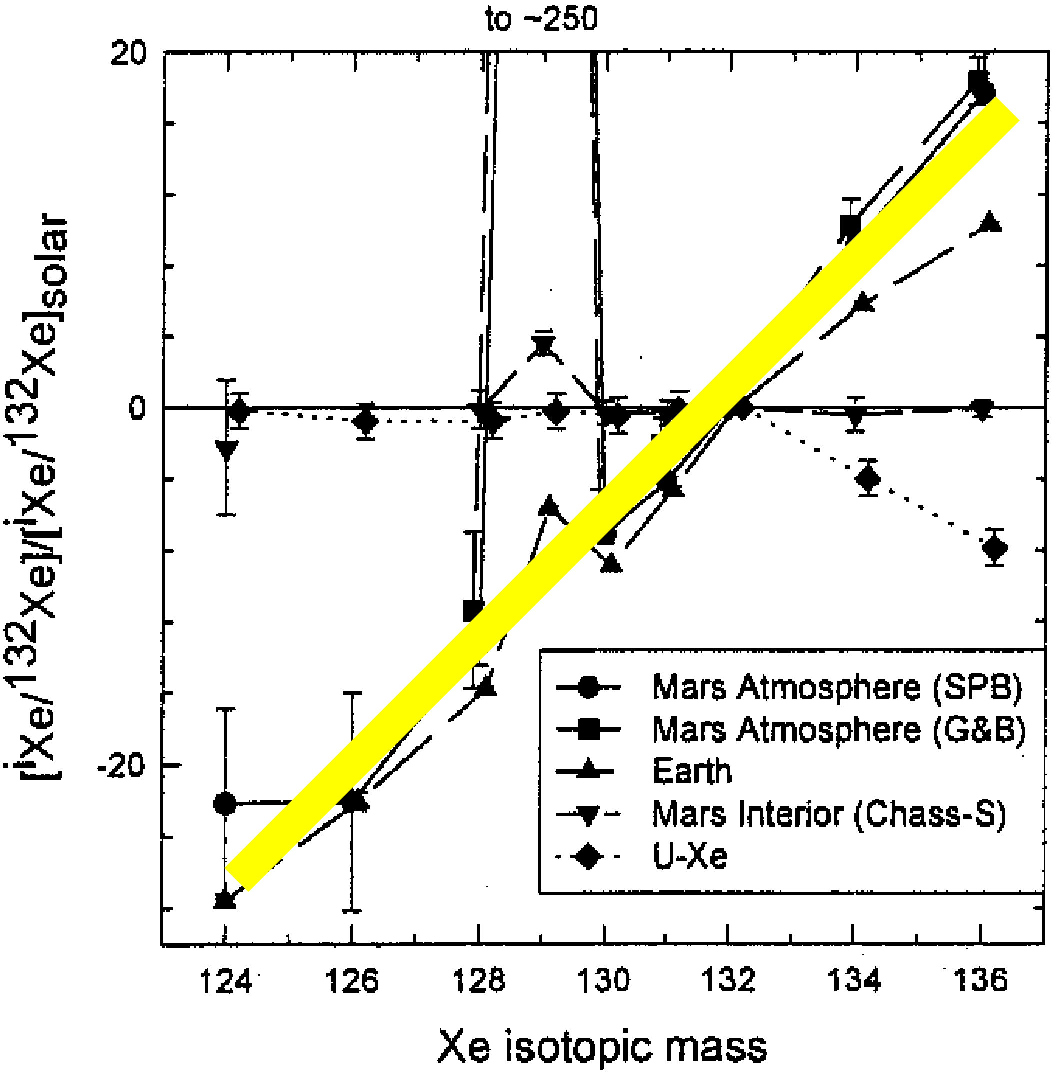
Enriched in ^{129}Xe

Overall fracitonation
Enriched in heavier isotopes

Mass fractionation through
early hydrodynamic escape

=> Decrease in “planetary”
noble gas

Xe isotopic pattern



Enriched in ^{129}Xe

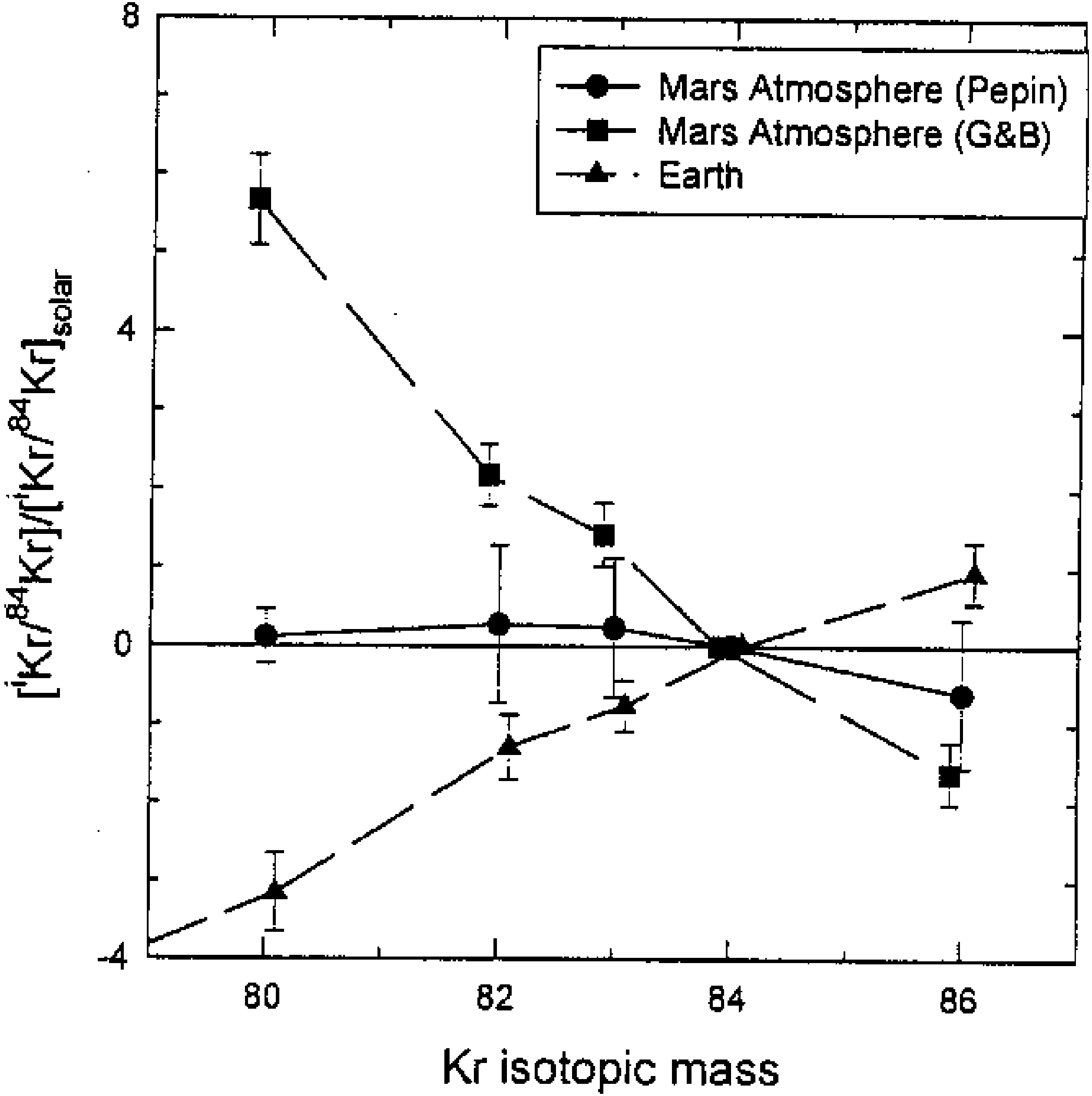
Overall fracitonation
Enriched in heavier isotopes

Mass fractionation through
early hydrodynamic escape

=> Decrease in “planetary”
noble gas

?

Kr


Mars Atmosphere (Pepin)
Mars Atmosphere (G&B)
Earth
8
4
0
-4
80
82
84
86
$[^{i}Kr/^{84}Kr]/[^{i}Kr/^{84}Kr]_{solar}$
Kr isotopic mass

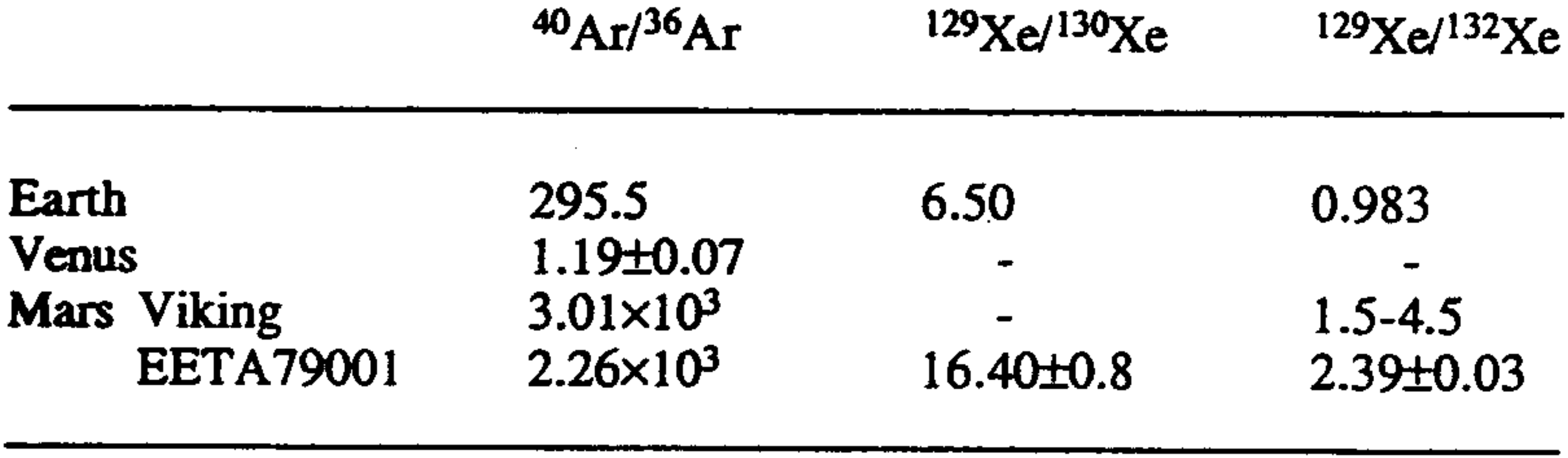
Radiogenic noble gas and Martian degassing history

- Difference between the Earth and Mars
- Constraints on Martian platetectonics – efficient degassing process
- Contribution from long-term volcanism

Estimate of Mars degassing from radiogenic noble gas species

$^{40}K \Rightarrow {}^{40}Ar$ half life 1.25×10^{9}yr

$^{129}I \Rightarrow {}^{129}Xe$ half life 1.57×10^{7}yr

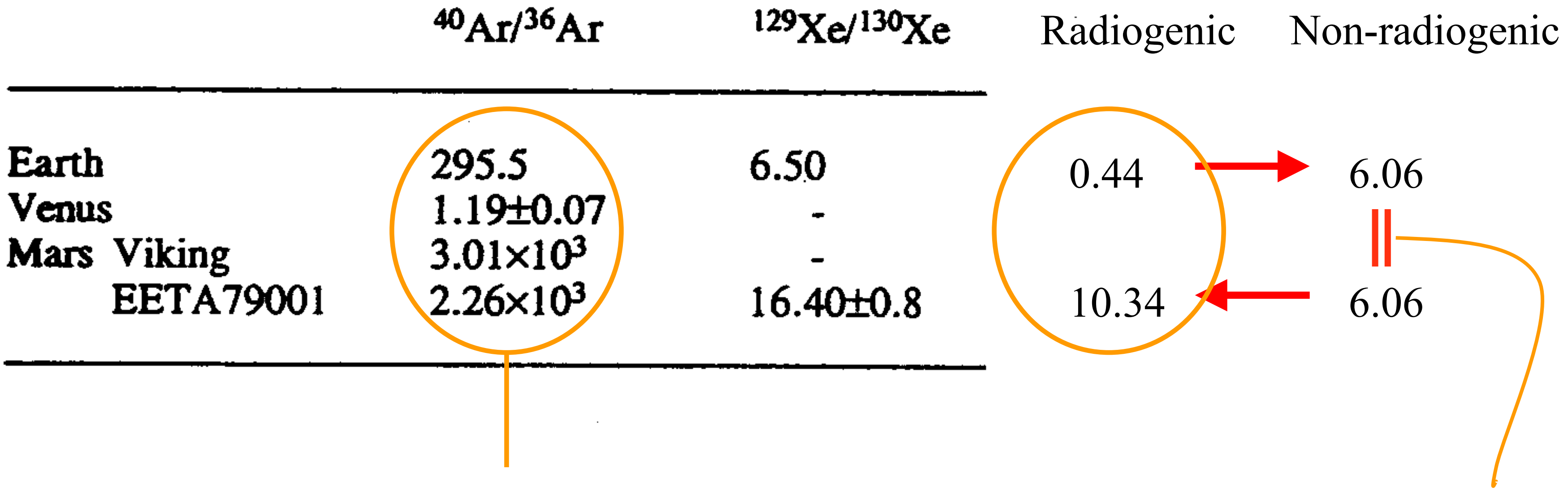


	$^{40}Ar/^{36}Ar$	$^{129}Xe/^{130}Xe$	$^{129}Xe/^{132}Xe$
Earth	295.5	6.50	0.983
Venus	1.19±0.07	-	-
Mars Viking	3.01×10^3	-	1.5-4.5
EETA79001	2.26×10^3	16.40±0.8	2.39±0.03

Radiogenic species

$^{40}K \Rightarrow {}^{40}Ar$ half life 1.25×10^{9}yr

$^{129}I \Rightarrow {}^{129}Xe$ half life 1.57×10^{7}yr



	$^{40}Ar/^{36}Ar$	$^{129}Xe/^{130}Xe$	Radiogenic	Non-radiogenic
Earth	295.5	6.50	0.44	6.06
Venus	1.19±0.07	-		
Mars Viking	3.01×10^3	-		
EETA79001	2.26×10^3	16.40±0.8	10.34	6.06

Mostly radiogenic ^{40}Ar

Same initial ratio is assumed between the Earth and Mars

Estimate of Mars degassing from radiogenic noble gas species

R(X) : Relative X abundance in the atmosphere
[kg / planetary mass]

$$\frac{R\left({}^{129}\mathrm{Xe}^*\right)_{\mathrm{Mars}}}{R\left({}^{129}\mathrm{Xe}^*\right)_{\mathrm{Earth}}} = \frac{R\left({}^{130}\mathrm{Xe}\right)_{\mathrm{Mars}} \times 10.34 \times \frac{129}{130}}{R\left({}^{130}\mathrm{Xe}\right)_{\mathrm{Earth}} \times 0.44 \times \frac{129}{130}} = 0.353.$$

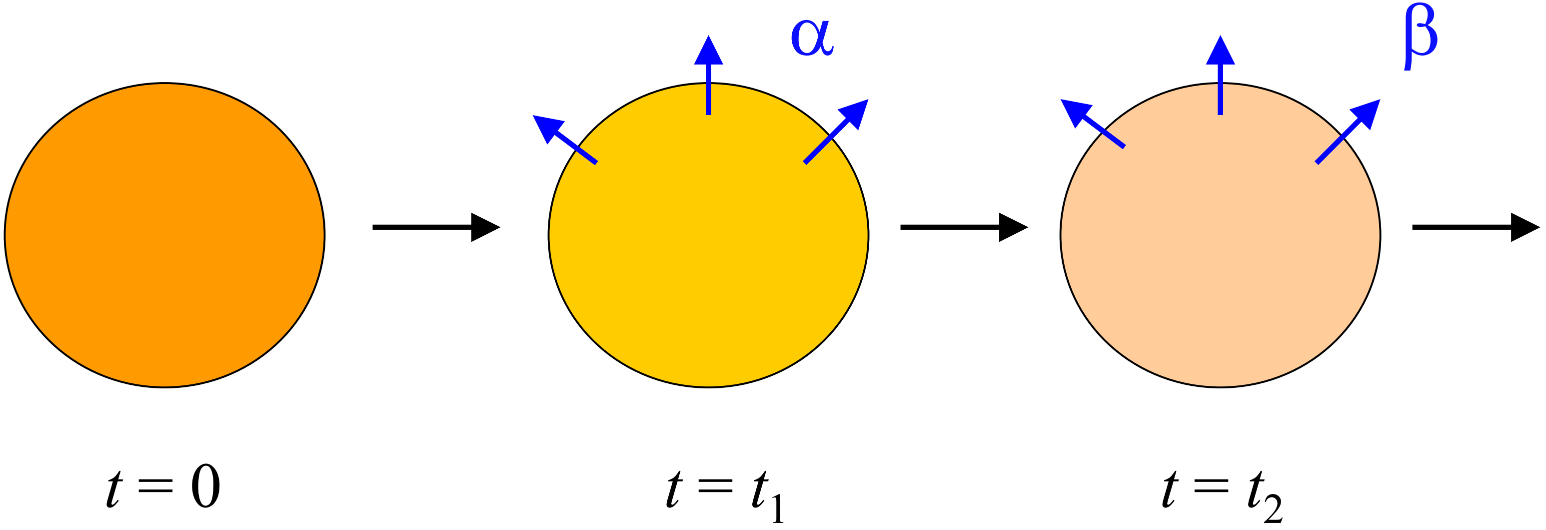
$$\frac{R\left({}^{40}\mathrm{Ar}^*\right)_{\mathrm{Mars}}}{R\left({}^{40}\mathrm{Ar}^*\right)_{\mathrm{Earth}}} = \frac{R\left({}^{36}\mathrm{Ar}\right)_{\mathrm{Mars}} \times 2257 \times \frac{40}{36}}{R\left({}^{36}\mathrm{Ar}\right)_{\mathrm{Earth}} \times 296 \times \frac{40}{36}} = 0.048.$$

Estimate of Mars degassing from radiogenic noble gas species

Radiogenic gas = Initially 0 in the atmosphere

Degassing from the interior should supply radiogenic gas into the atmosphere.

2 - Stage Degassing Model --- α, β, degassing fractions



Estimate of Mars degassing from radiogenic noble gas species

If $\tau_{1/2}({}^{129}\mathrm{Xe}) < t_1 \ll \tau_{1/2}({}^{40}\mathrm{Ar})$ and $t_2 \sim \tau_{1/2}({}^{40}\mathrm{Ar})$

$$\begin{aligned}
{}^{129}\mathrm{Xe}^* &= \alpha\,{}^{129}\mathrm{I}_0\left(1-\exp\left(-\lambda_{129}t_1\right)\right) \\
&\quad +\beta\left[(1-\alpha)^{129}\mathrm{I}_0\left(1-\exp\left(-\lambda_{129}t_1\right)\right)+{}^{129}\mathrm{I}_0\left(\exp\left(-\lambda_{129}t_1\right)-\exp\left(-\lambda_{129}t_2\right)\right)\right] \\
&\approx \alpha\,{}^{129}\mathrm{I}_0\left(1-\exp\left(-\lambda_{129}t_1\right)\right)
\end{aligned}$$

$$\begin{aligned}
{}^{40}\mathrm{Ar}^* &= \alpha\, f_{\mathrm{Ar}}\,{}^{40}\mathrm{K}_0\left(1-\exp\left(-\lambda_{40}t_1\right)\right) \\
&\quad +\beta\left[(1-\alpha) f_{\mathrm{Ar}}\,{}^{40}\mathrm{K}_0\left(1-\exp\left(-\lambda_{40}t_1\right)\right)\right. \\
&\quad \left. + f_{\mathrm{Ar}}\,{}^{40}\mathrm{K}_0\left(\exp\left(-\lambda_{40}t_1\right)-\exp\left(-\lambda_{40}t_2\right)\right)\right] \\
&\approx \beta\, f_{\mathrm{Ar}}\,{}^{40}\mathrm{K}_0\left(\exp\left(-\lambda_{40}t_1\right)-\exp\left(-\lambda_{40}t_2\right)\right).
\end{aligned}$$

$f_{\mathrm{Ar}} = 0.1048$
branching ratio

Estimate of Mars degassing from radiogenic noble gas species

$$\frac{R\left({}^{129}\mathrm{Xe}^{*}\right)_{\mathrm{Mars}}}{R\left({}^{129}\mathrm{Xe}^{*}\right)_{\mathrm{Earth}}} \approx \frac{\alpha_{\mathrm{Mars}}\left(1-\exp\left(-\lambda_{129}t_{\mathrm{M1}}\right)\right)}{\alpha_{\mathrm{Earth}}\left(1-\exp\left(-\lambda_{129}t_{\mathrm{E1}}\right)\right)} = 0.353$$

$$\frac{R\left({}^{40}\mathrm{Ar}^{*}\right)_{\mathrm{Mars}}}{R\left({}^{40}\mathrm{Ar}^{*}\right)_{\mathrm{Earth}}} \approx \frac{\beta_{\mathrm{Mars}}\left(\exp\left(-\lambda_{40}t_{\mathrm{M1}}\right)-\exp\left(-\lambda_{40}t_{\mathrm{M2}}\right)\right)}{\beta_{\mathrm{Earth}}\left(\exp\left(-\lambda_{40}t_{\mathrm{E1}}\right)-\exp\left(-\lambda_{40}t_{\mathrm{E2}}\right)\right)}$$

$$\approx \frac{\beta_{\mathrm{Mars}}\left(1-\exp\left(-\lambda_{40}t_{\mathrm{M2}}\right)\right)}{\beta_{\mathrm{Earth}}\left(1-\exp\left(-\lambda_{40}t_{\mathrm{E2}}\right)\right)} = 0.048.$$

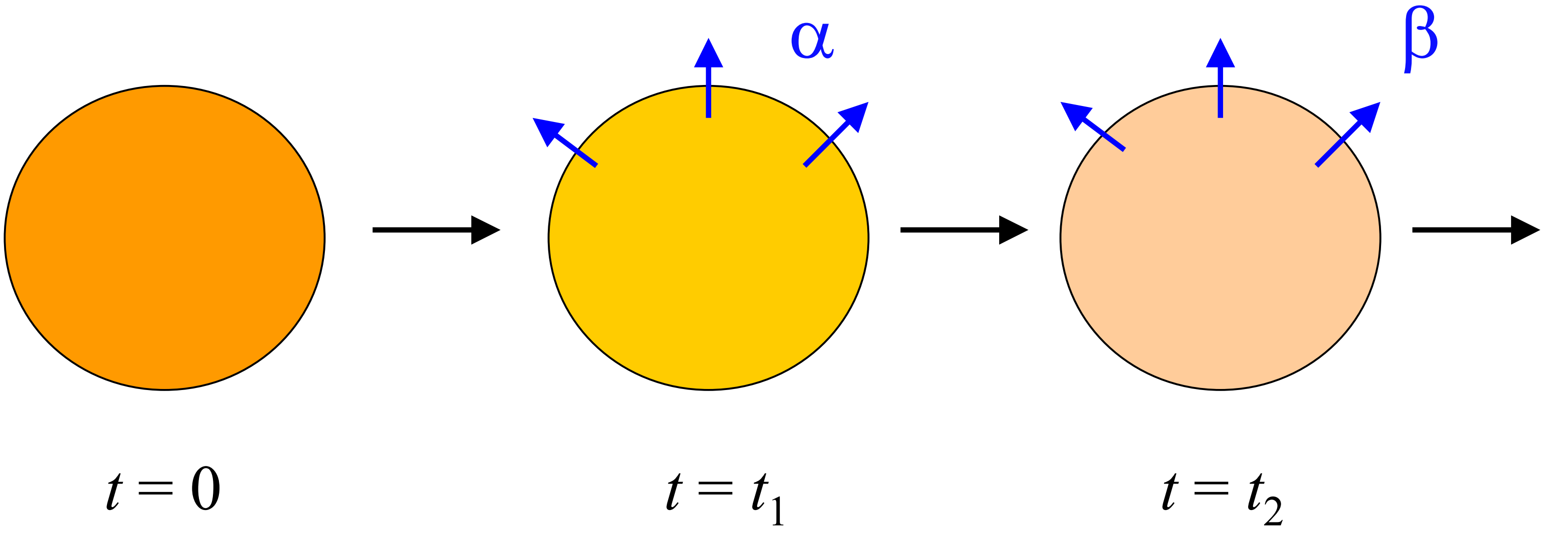
Estimate of Mars degassing from radiogenic noble gas species

If timings of degassing events are similar between the Earth and Mars,

$$\frac{\alpha_{\text{Mars}}}{\alpha_{\text{Earth}}} \approx 0.353 \quad \text{and} \quad \frac{\beta_{\text{Mars}}}{\beta_{\text{Earth}}} \approx 0.048.$$

$$\frac{\alpha_{\text{Mars}}}{\alpha_{\text{Earth}}} \approx 0.353 \quad \text{and} \quad \frac{\beta_{\text{Mars}}}{\beta_{\text{Earth}}} \approx 0.048.$$

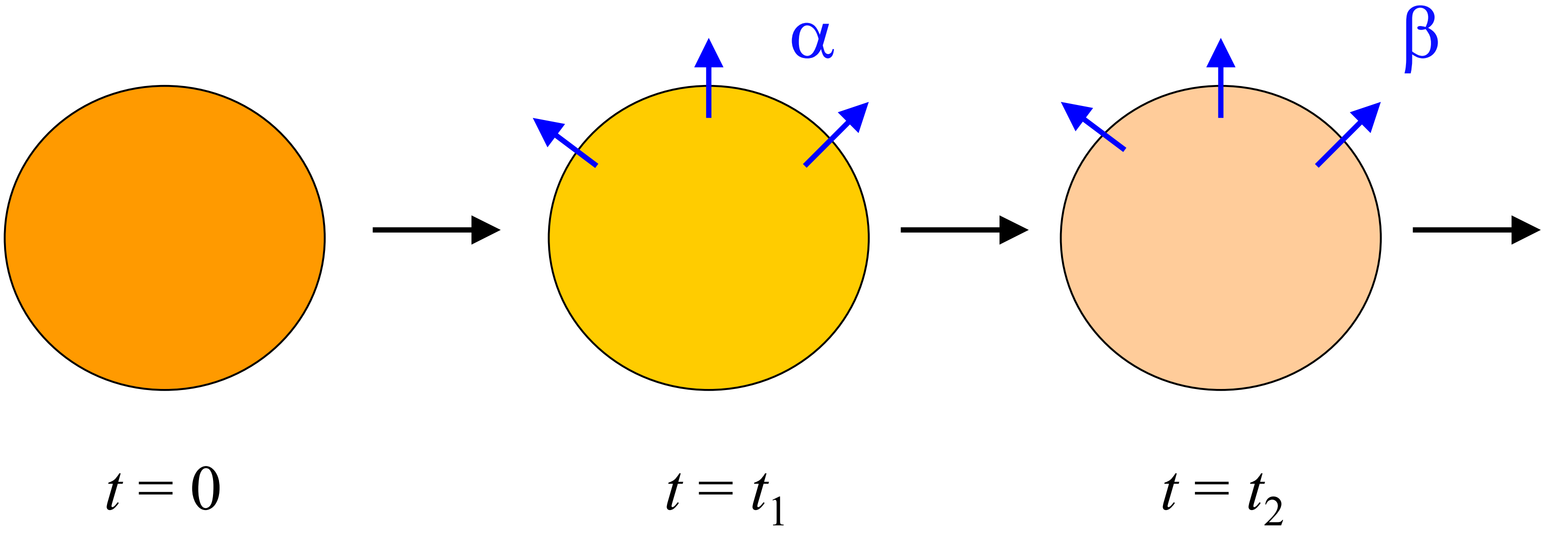
?



Early degassing 10^7-10^8yr Mars ~ Earth

Later degassing 10^8-10^9yr Mars << Earth

$$\frac{\alpha_{\mathrm{Mars}}}{\alpha_{\mathrm{Earth}}} \approx 0.353 \quad \text{and} \quad \frac{\beta_{\mathrm{Mars}}}{\beta_{\mathrm{Earth}}} \approx 0.048.$$?



Early degassing 10^7-10^8yr Mars ~ Earth

Magma ocean cooling ?

Later degassing 10^8-10^9yr Mars << Earth

Volcanic activities

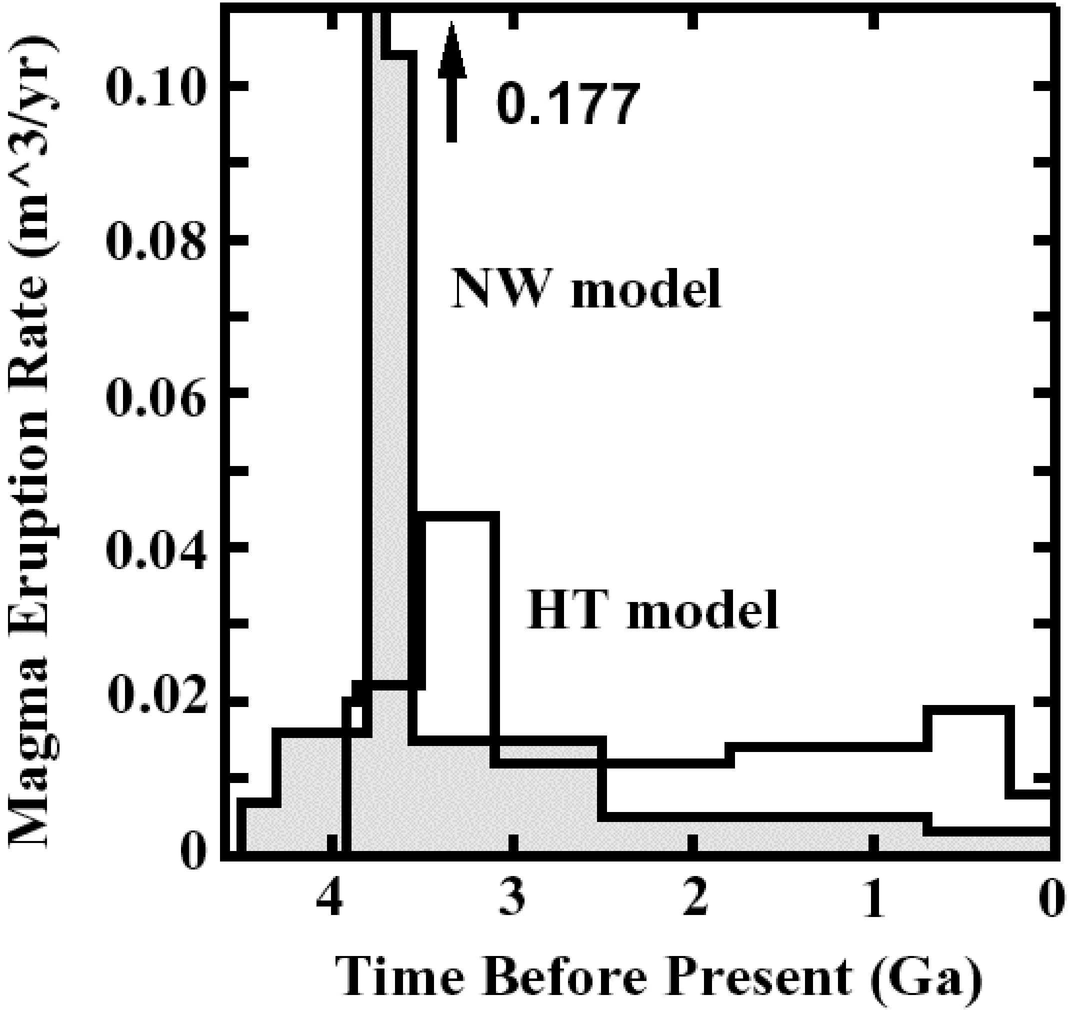
More quantitative analysis.

- Volcanic degassing

- Vocanisms in overall histories   Hot spots?
  - Estimated from the surface volcanics
  - Vocanic volume + crater age

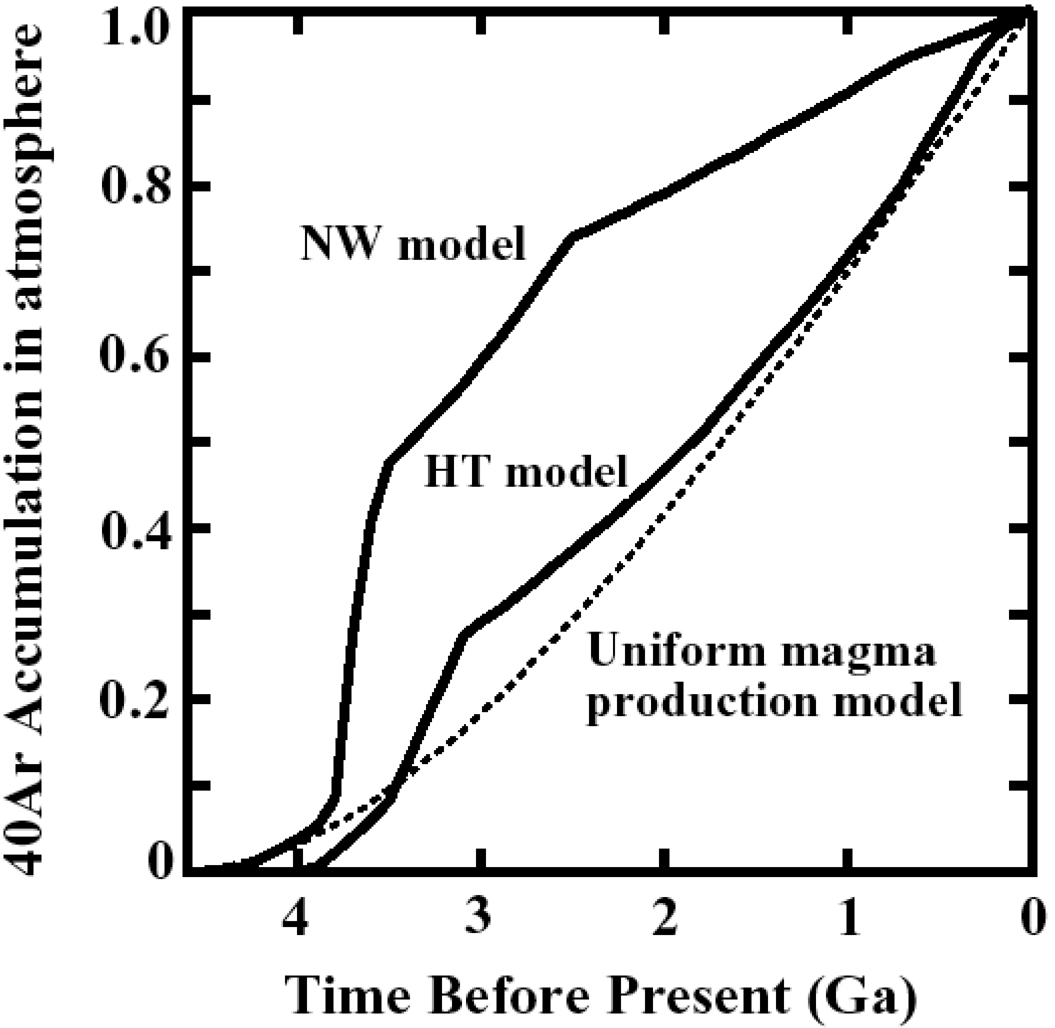
+

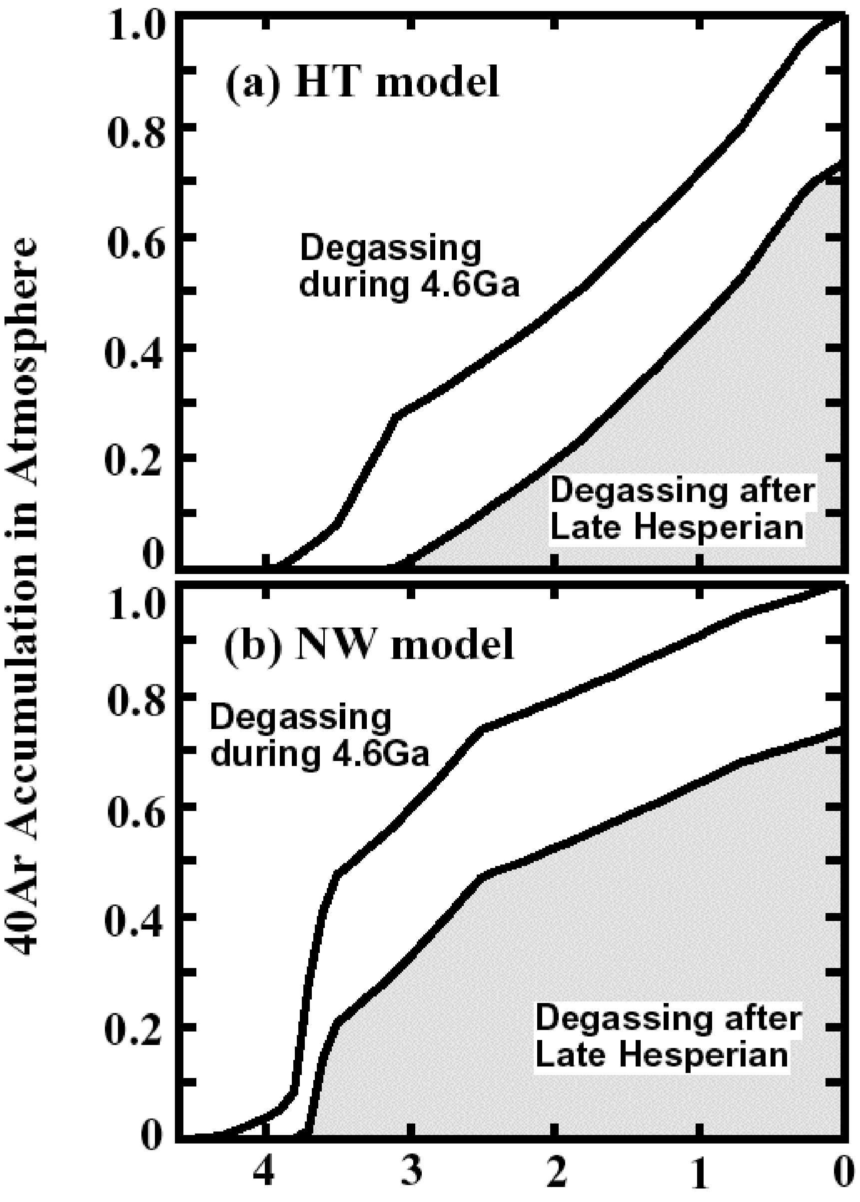
- Early (Hadean) platetectonics

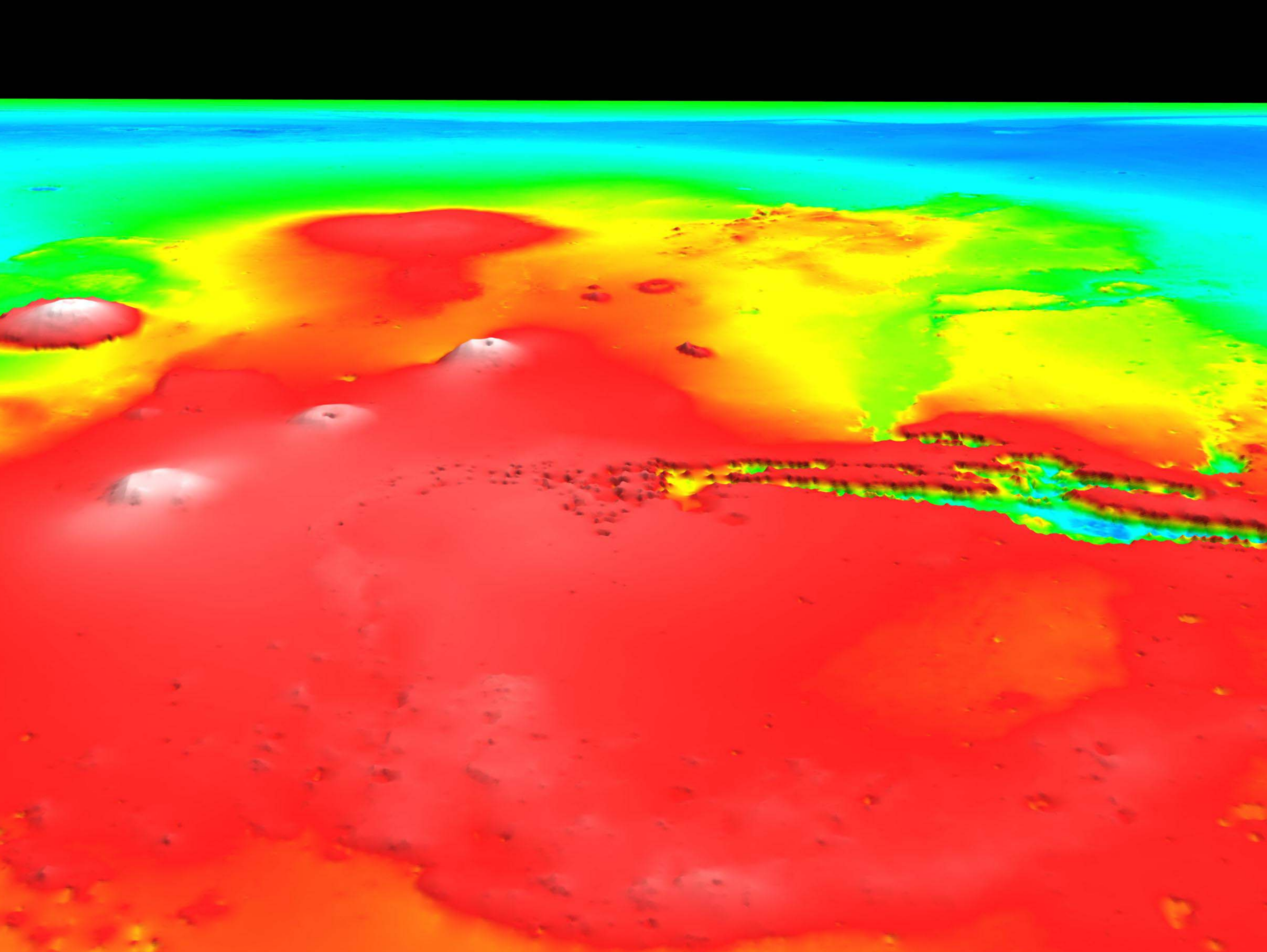


NW, HT   different crater age models

Degassing by hot-spot type volcanism from the surface area/volume

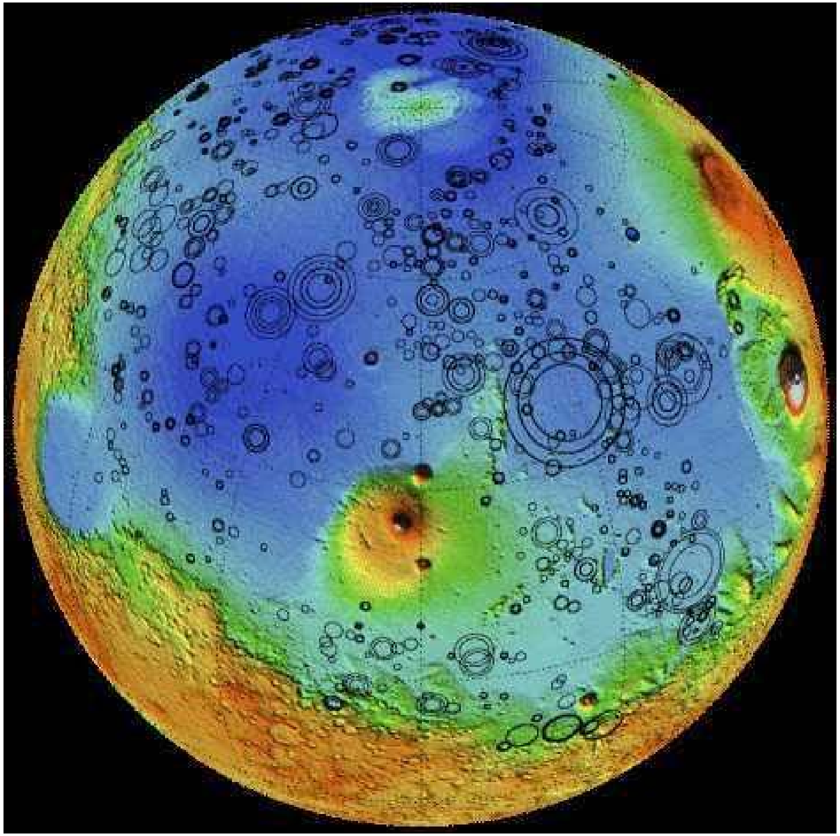



(a) HT model
Degassing during 4.6Ga
Degassing after Late Hesperian
(b) NW model
Degassing during 4.6Ga
Degassing after Late Hesperian
40Ar Accumulation in Atmosphere
1.0
0.8
0.6
0.4
0.2
0
4
3
2
1
0
Time Before Present (Ga)



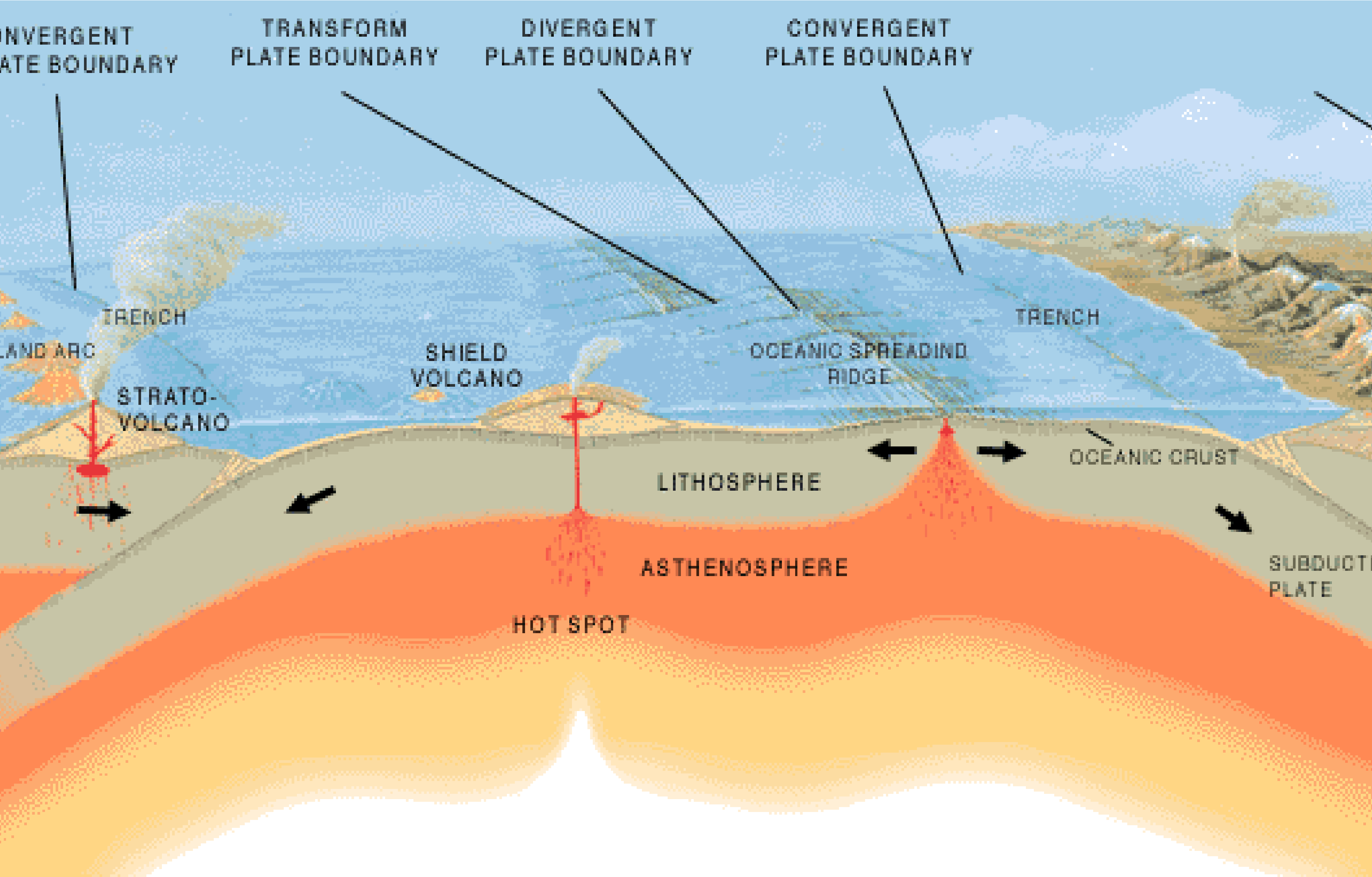
Martian platetectonics

First advocated to explain the flatness of northern lowland (Sleep, 1994)

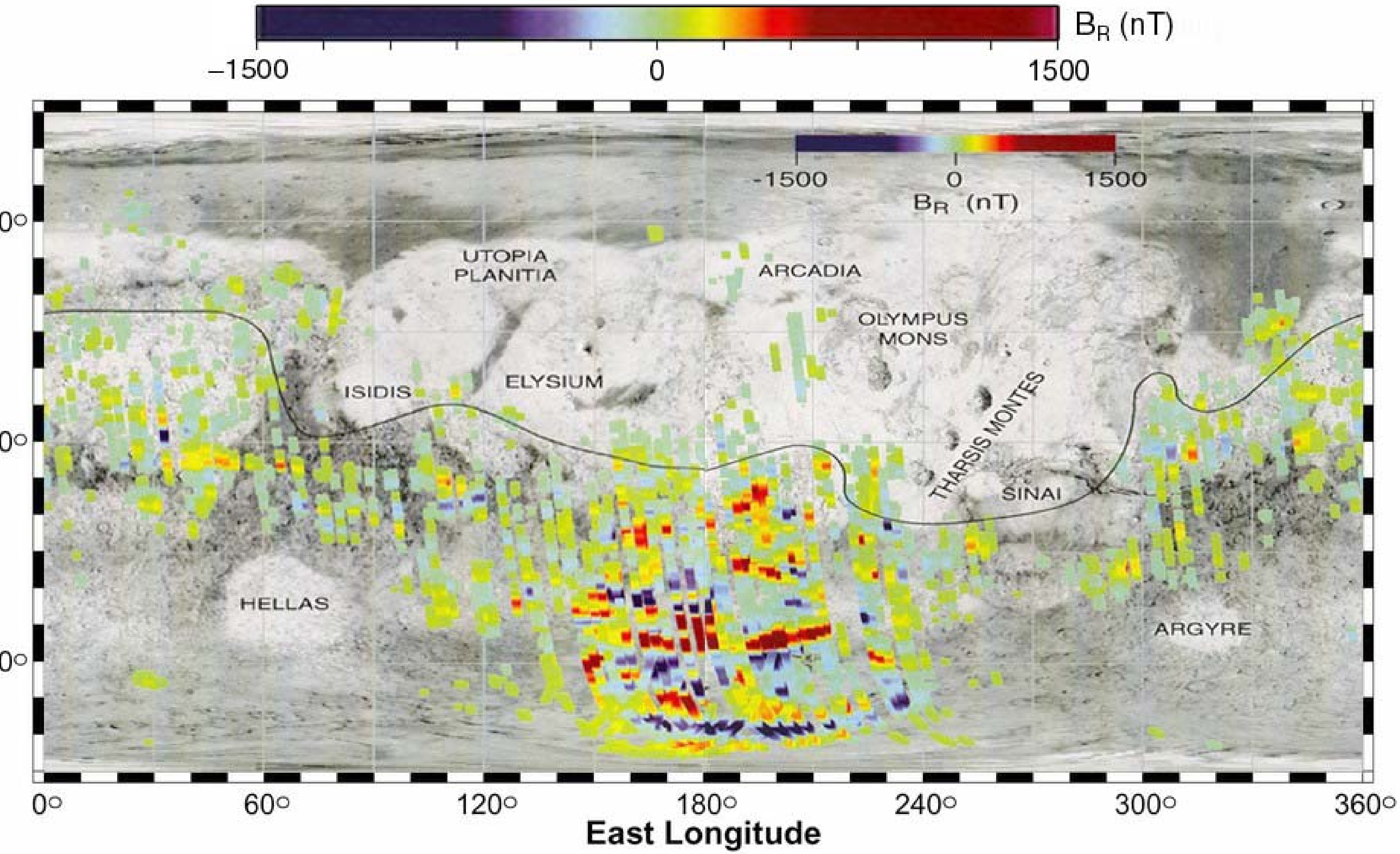


Volcanoes around the northern plane
= subduction volcanism?

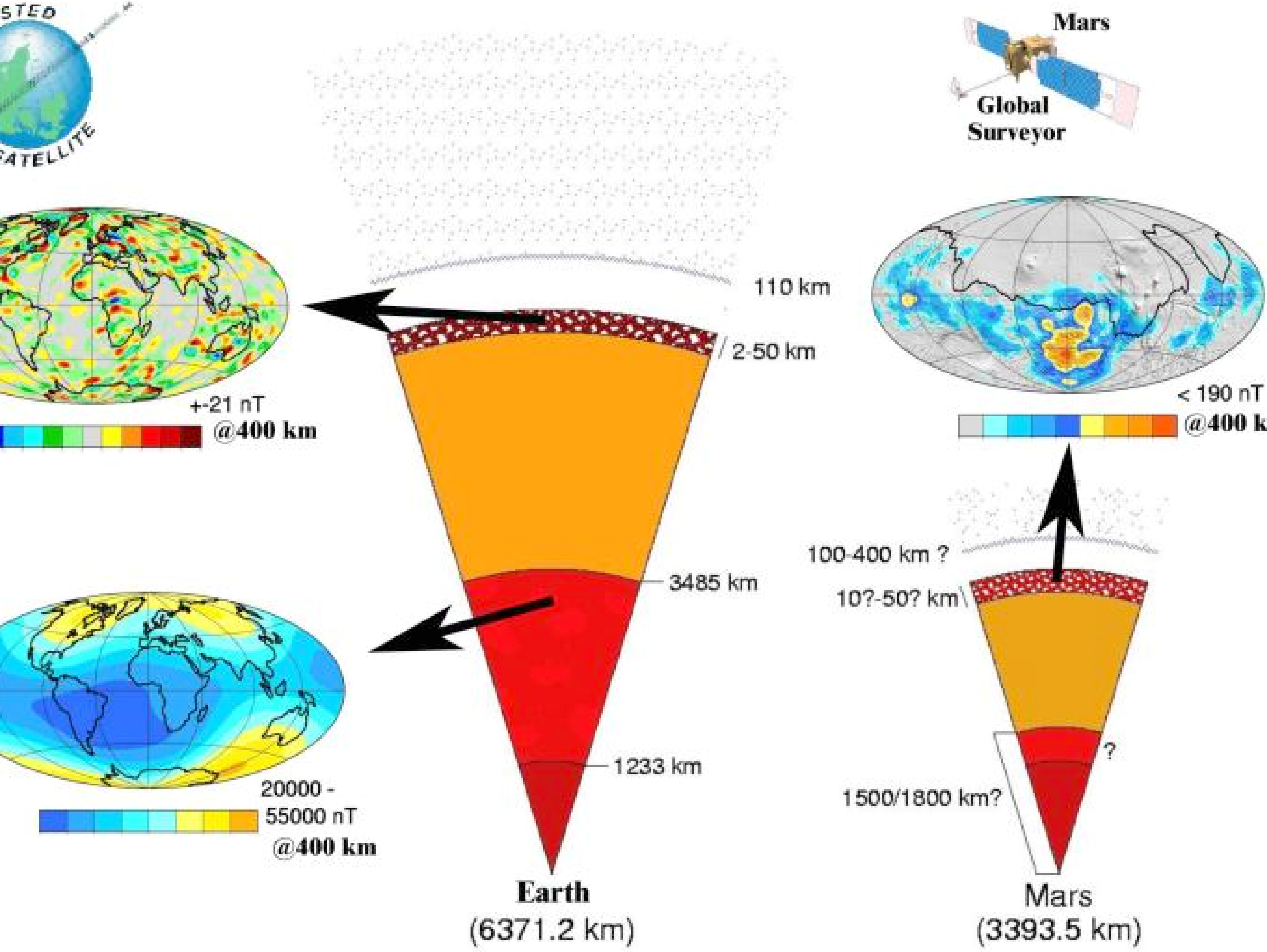
No geomorphological and other evidence.


ONVERGENT
ATE BOUNDARY
TRANSFORM
PLATE BOUNDARY
DIVERGENT
PLATE BOUNDARY
CONVERGENT
PLATE BOUNDARY
TRENCH
LAND ARC
STRATO-
VOLCANO
SHIELD
VOLCANO
OCEANIC SPREADIND
RIDGE
TRENCH
OCEANIC CRUST
LITHOSPHERE
ASTHENOSPHERE
HOT SPOT
SUBDUCTI
PLATE

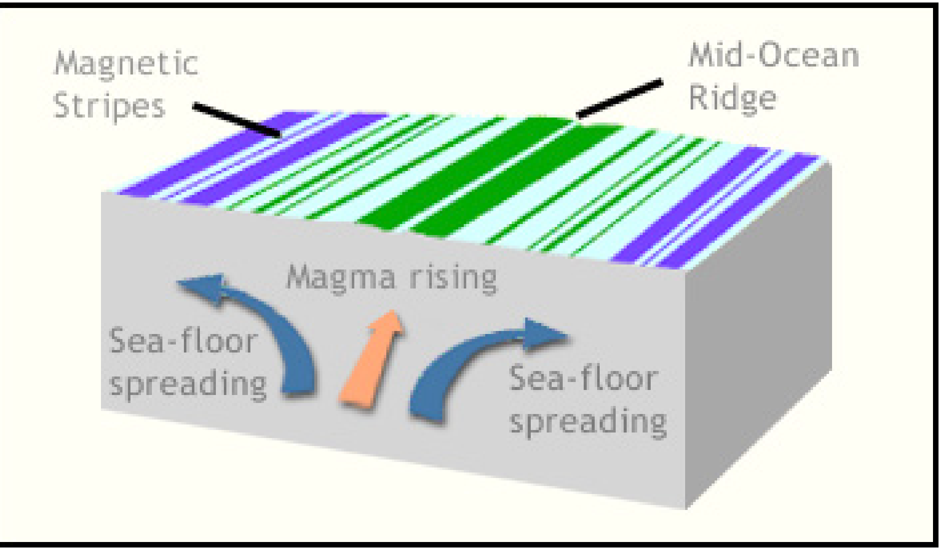
Magnetic field

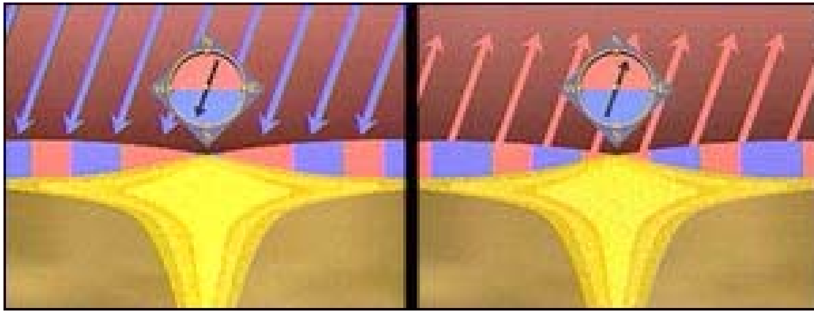


MGS/Magnetometer

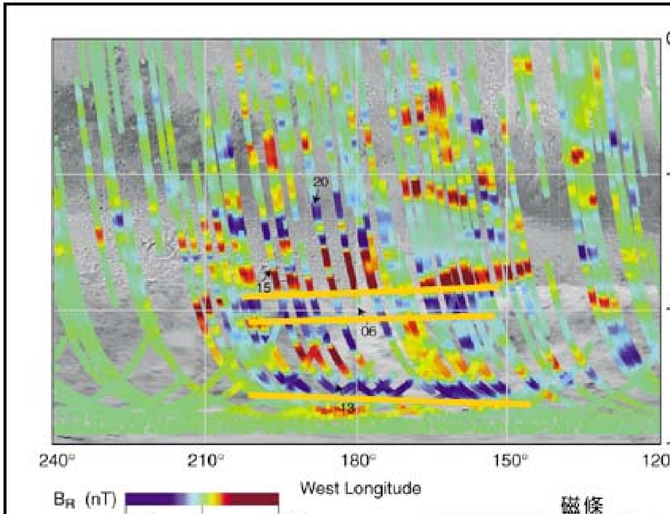

STED
SATELLITE
Mars
Global
Surveyor
110 km
2-50 km
+-21 nT
@400 km
< 190 nT
@400 k
3485 km
100-400 km ?
10?-50? km
?
1233 km
1500/1800 km?
20000 -
55000 nT
@400 km
Earth
(6371.2 km)
Mars
(3393.5 km)

Stripes of remnant magnetic fields = Evidence of ancient platetectonics ?





Sea floor spreading model
under frequent magnetic reversals.

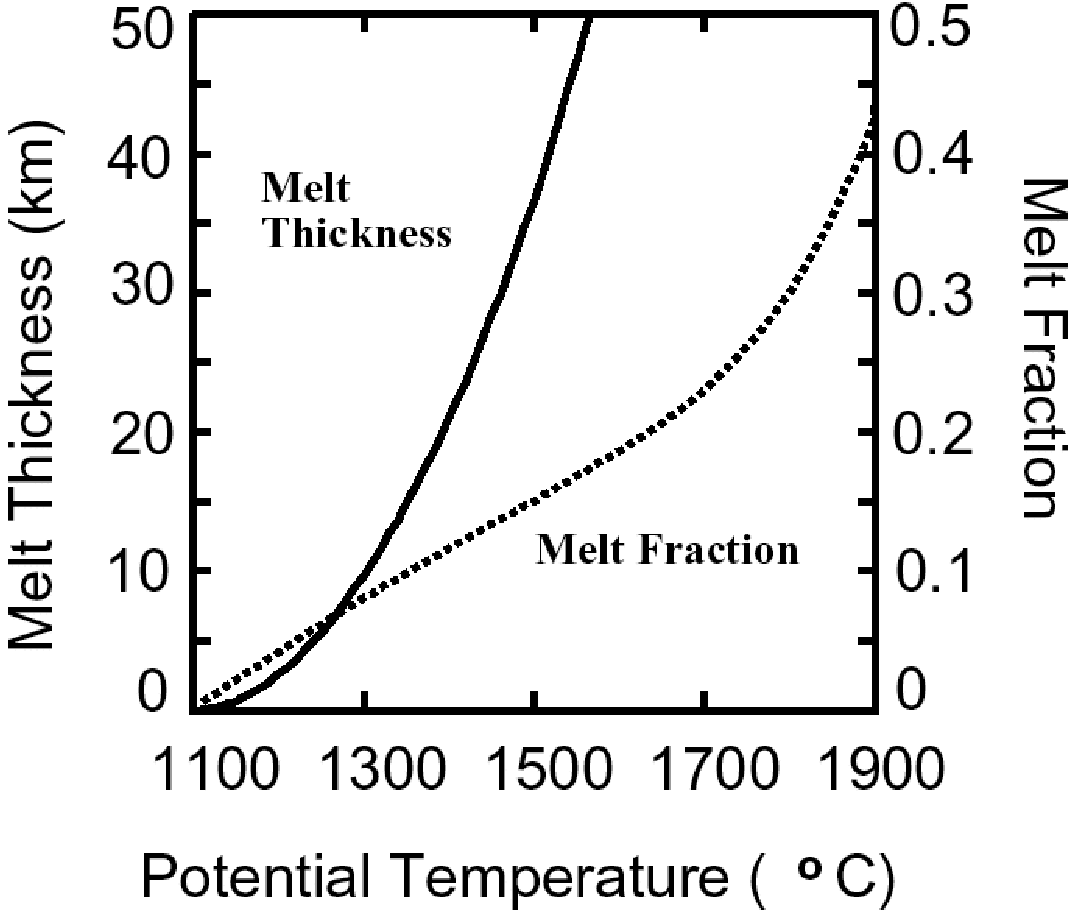


No geomorpholoriccally correlated evidence on the surface

Melt production – degassing model by platetectonics

- Case 1 Apply the Earth's melt production rate q = 2×10^{10} m^3/yr, melt fraction 0.2
- Case 2 Apply the Earth's melt production rate q = 2×10^{10} m^3/yr, melt fraction = melt fraction of hot-spot type
- Case 3 Use a detailed melt generation model from Martian mantle temperature

Case 3
Increase melt generation ~ degassing with higher mantle temperature



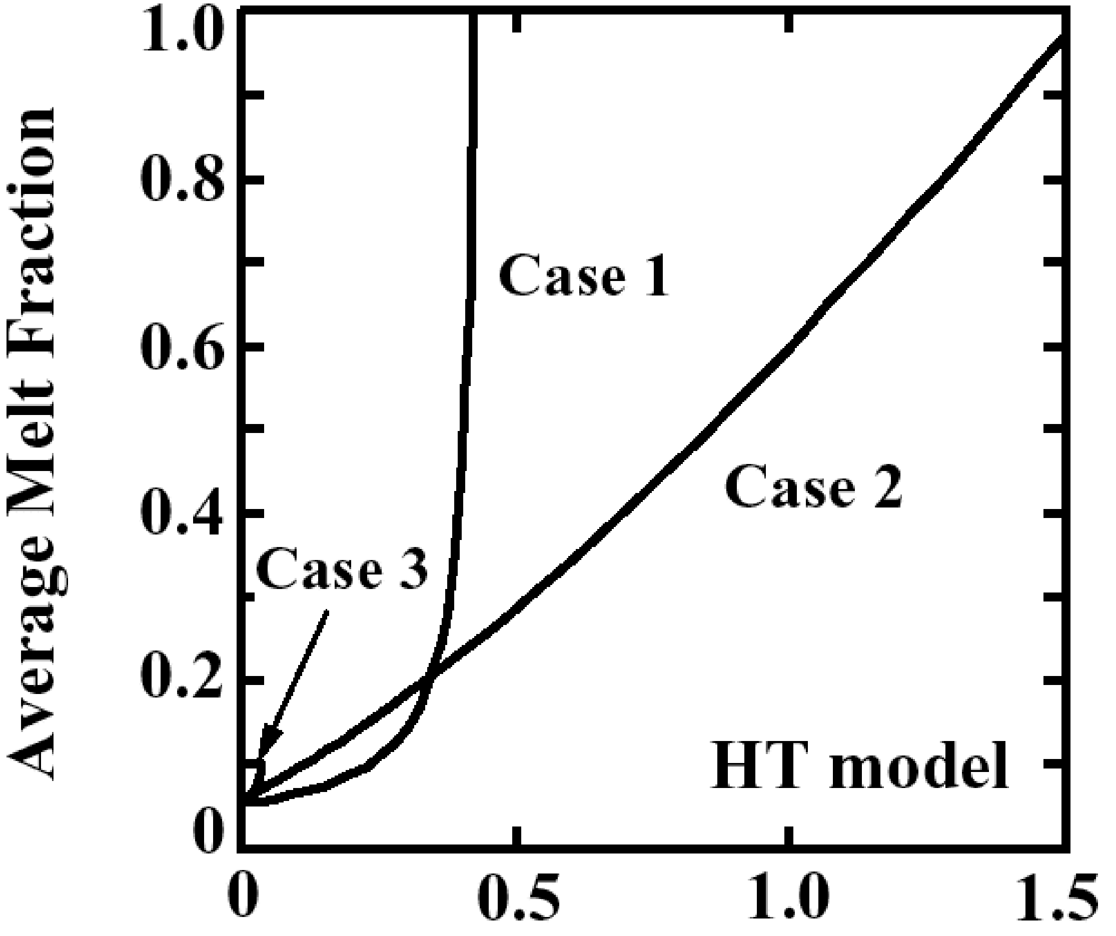
Degassing rate at ridges

- $F = K\,[^{40}Ar]_{man} = q\,[^{40}Ar]_{man} / \xi\, V_{man}$

- Case 1 $A\,(20 km^3/yr)\,[^{40}Ar]_{man} / 0.2\, V_{man}$
- Case 2 $A\,(20 km^3/yr)\,[^{40}Ar]_{man} / \xi\, V_{man}$
- Case 3 $(0.64 km^2/yr)\, d(T_p)\,[^{40}Ar]_{man} / \xi\,(T_p)\, V_{man}$

- $A = (0.3 / 0.6)\ (R_M/R_E)^2 = 0.13$
- T_p: mantle potential temperature
- $d(T_p)$: melt thickness

Under appropriate melt fraction, platetectonics duration is short



^{40}Ar in Mars atmosphere

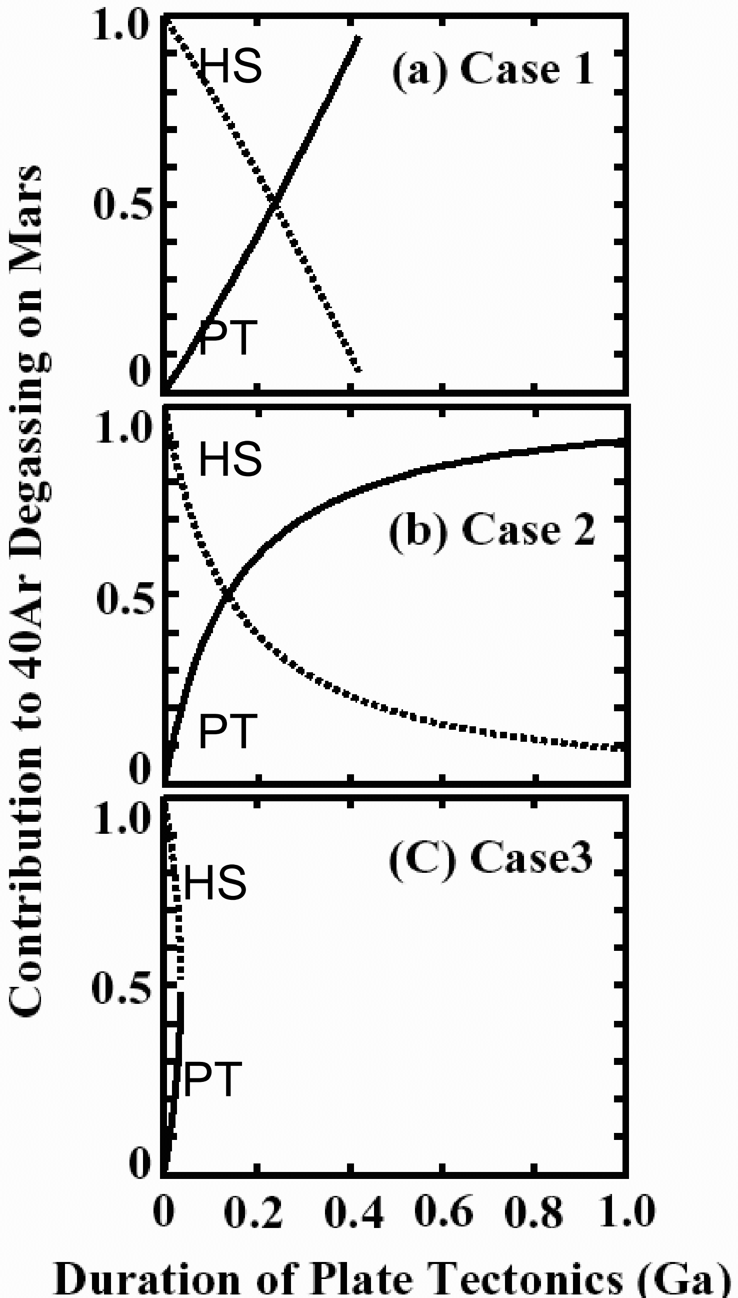
Hot spot (volcanic)

+ Platetectonics

Platetectonics

Short duration
Limited contribution in ^{40}Ar

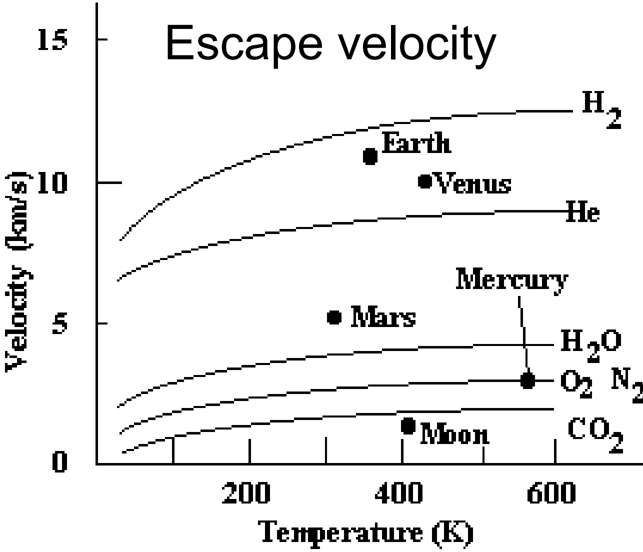
But maybe significant contribution to the atmospheric mass ($CO_2/^{40}Ar$ in degassed gas would be large in early stage)



Detection of ^{4}He

- Residence time of helium in the Martian atmosphere is considered to be order of 10^{6}yr.

- No direct deteciton at Mars
- UV observation from the Earth orbit by EUVE
  - – 43 R (1R = 10^{6} photons/cm^{2} s)   - 2 x 10^{10}kg

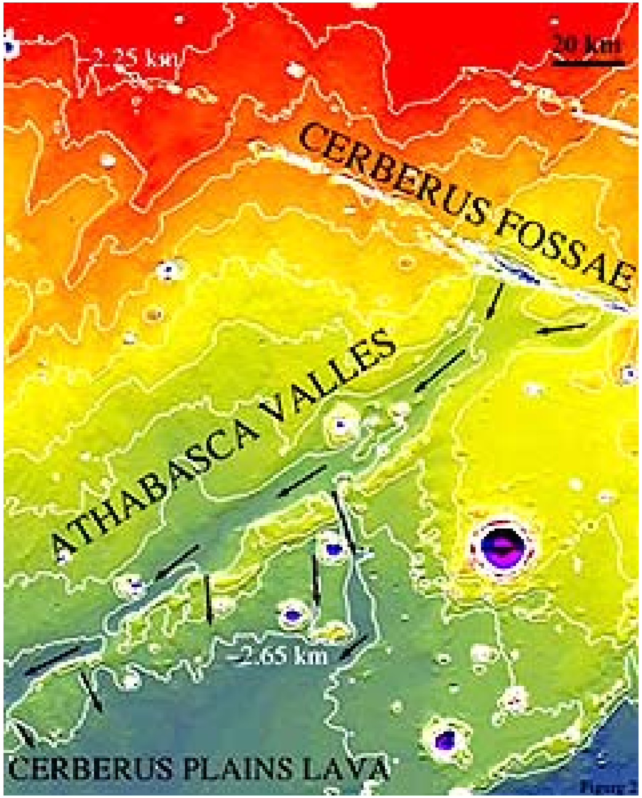

Escape velocity

^{232}Th => ^{208}Pb 6 ^{4}He   Half life 1.40x10^{10}yr

^{238}U => ^{206}Pb   8 ^{4}He   Half life 4.47x10^{9}yr

Detection of ^{4}He => Evidence of continuous volcanic activity

Recent volcanic activity on Mars

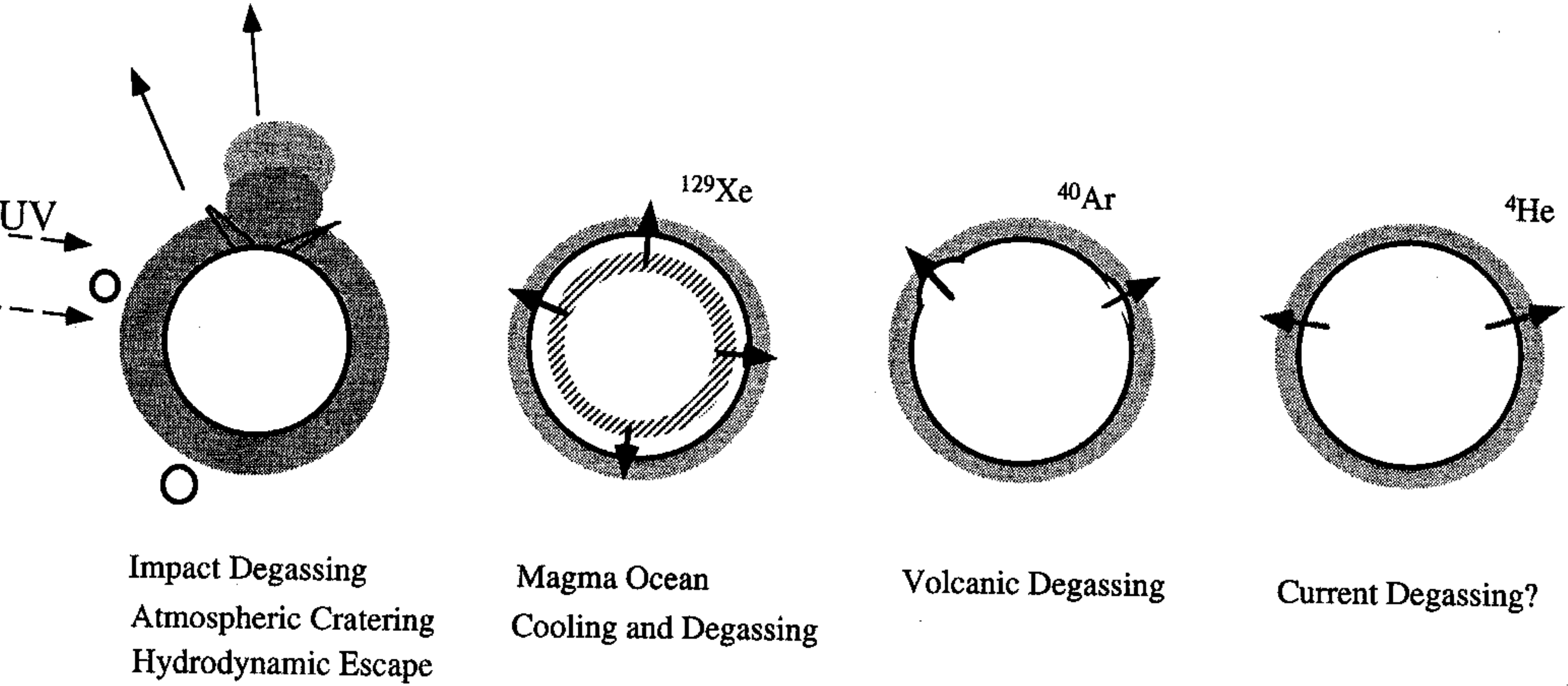


< 10^8 yr

Magma eruption and water outflow

Radiogenic noble gas isotopes

Useful to decipher the degassing from the Martian interior



Martian degassing activity from radiogenic noble gas data

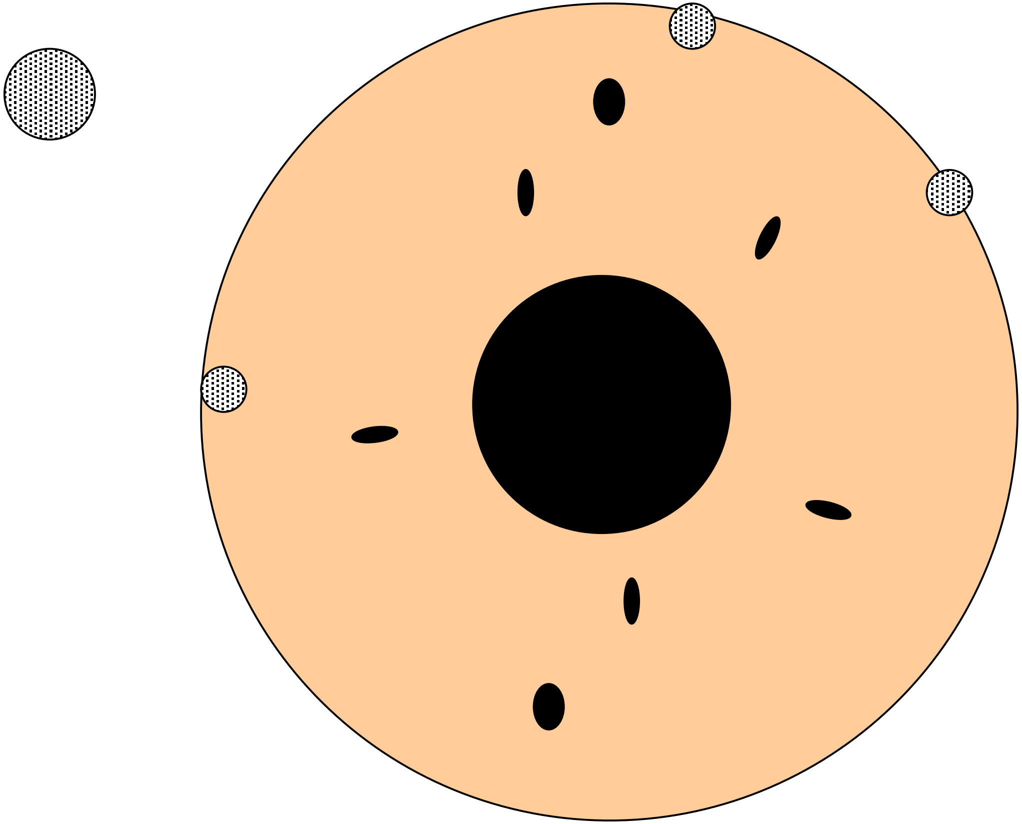
- Early degassing: Mars ~ Earth
  - Cooling of magma ocean

- Later degassing: Mars << Earth
  - Weaker volcanic activity
    - Compatible with surface morphology
  - Mars should have cooled more rapidly

- Platetectonics – short duration if existed

Martian evolution based on noble gas and other trace elements

Metal–silicate differentiation in the magma ocean => core formation

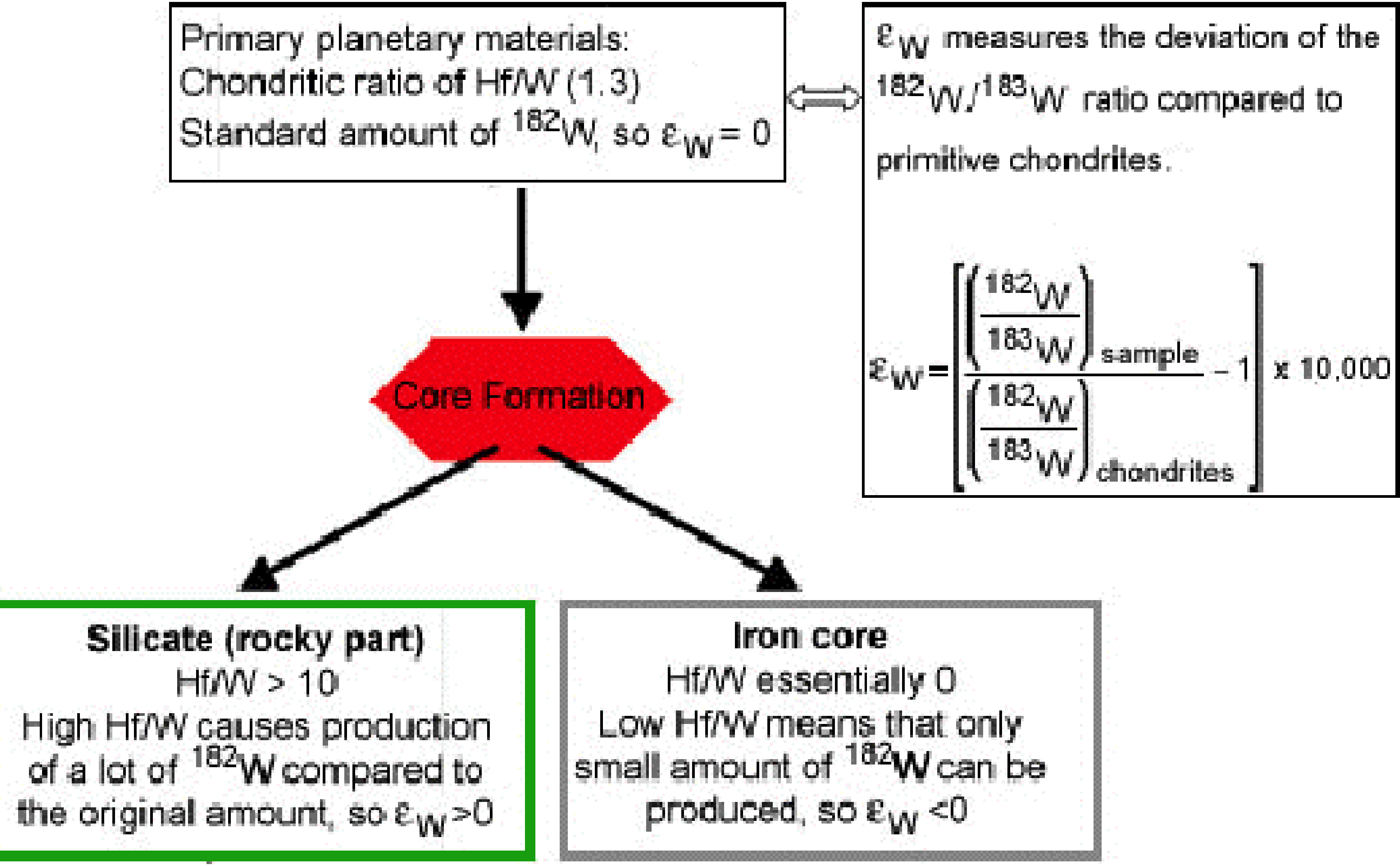


The timing is OK?

Core formation

- $^{182}Hf \Rightarrow {}^{182}W$ Half life 9×10^6 yr

- Metal-silicate fractionation
  - Hf 100% to silicate
  - W mainly to metal



Primary planetary materials:
Chondritic ratio of Hf/W (1.3)
Standard amount of ^{182}W, so $\varepsilon_W = 0$

ε_W measures the deviation of the $^{182}W/^{183}W$ ratio compared to primitive chondrites.

$$\varepsilon_W = \left[\frac{\left(\frac{^{182}W}{^{183}W} \right)_{sample}}{\left(\frac{^{182}W}{^{183}W} \right)_{chondrites}} - 1 \right] \times 10{,}000$$

Core Formation

Silicate (rocky part)
Hf/W > 10
High Hf/W causes production of a lot of ^{182}W compared to the original amount, so $\varepsilon_W > 0$

Iron core
Hf/W essentially 0
Low Hf/W means that only small amount of ^{182}W can be produced, so $\varepsilon_W < 0$

If core formation >> 10^7 yr $\varepsilon_W \sim 0$

Some Martian meteorites have $\varepsilon_W > 0$

Core formation age around 10^7yr

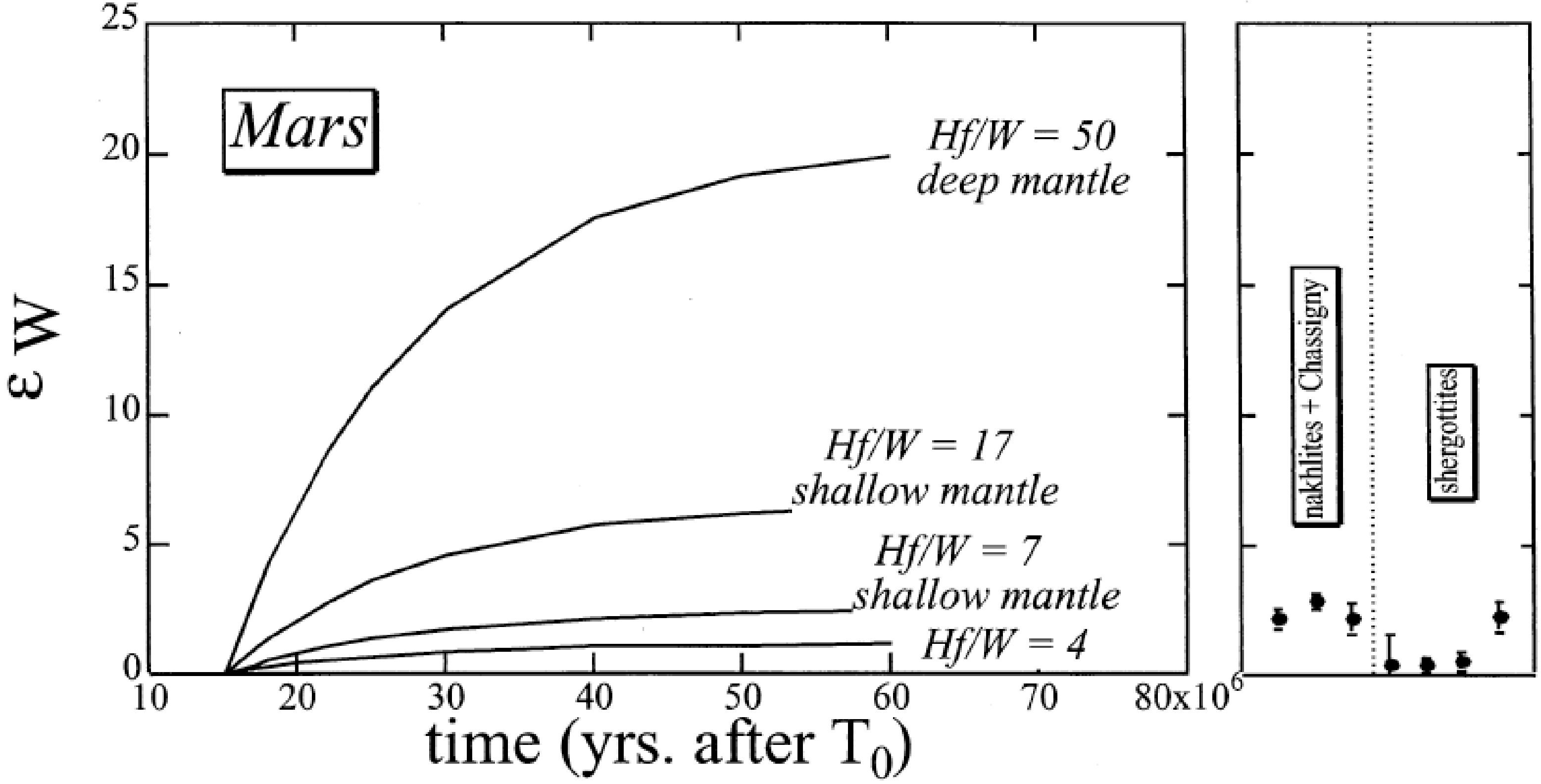


Fig. 7. Evolution of ε_W for different parts of the martian mantle, using Eqn. 3 in the text. The low curve is calculated for the martian mantle after core formation, with Hf/W = 4, and starting at 15 Ma after T_0. The highest curve was calculated for a majorite-bearing (40%) deep mantle, with a Hf/W ratio of 50. The intermediate curves were calculated for a shallow garnet-bearing mantle (Hf/W = 17) and garnet-free mantle (Hf/W = 7). Details of Eqn. 3 and values used in the equation are given in the text. The shallow and deep mineralogy of the martian mantle is taken from the Bertka and Fei (1997) mineralogic model for the interior of Mars. Data for SNC meteorites on right are from Lee and Halliday (1997).